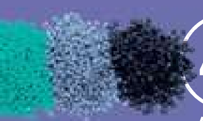
CHEMICAL REACTIONS 4

4.1 Synthesis and decomposition reactions can be represented by equations

4.2 Acid reactions depend on strength and concentration

4.3 The solubility rules predict the formation of precipitates

4.4 Combustion reactions between hydrocarbons and oxygen produce carbon dioxide, water and energy



4.5 Polymers are long chains of monomers

4.6 Temperature, concentration, surface area and stirring affect reaction rate

4.7 Catalysts increase the rate of a reaction

4.8 Green chemistry reduces the impact of chemicals on the environment

What if?

What you need:

9 V battery, wires with crocodile clips, 250 mL beaker, strip of copper foil (1 cm wide), 0.5 M copper sulfate solution, brass key (to be plated)

What to do:

1 Pour 100 mL of copper sulfate solution into the beaker.
2 Fit the copper foil inside the beaker with the top 2 cm bent back over the edge of the beaker.
3 Use a wire to connect the positive terminal of the battery to the copper foil.
4 Use a wire to connect the negative terminal of the battery to the key.
5 Place the key into the copper sulfate solution, ensuring it does not touch the copper foil.
6 Observe any changes in the key.

What if?

» What if a smaller battery was used?
» What if water was used instead of copper sulfate?
» What if a carbon rod was used instead of the copper foil?

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EXPERIMENT 4.1A: DIRECT SYNTHESIS WITH A 'POP'
GO TO PAGE 200

4.1 Synthesis and decomposition reactions can be represented by equations

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Almost every substance that you will use today was made in a chemical reaction. The role of chemists is to understand chemical reactions and the products they form. Classifying reactions into different types helps us predict the products produced by reactions and understand what reactants are required to produce particular products. To assist in classifying reactions, we can sort compounds into types, such as acids, bases, salts, hydrocarbons and polymers. Balanced chemical equations use the law of conservation of mass.

Types of chemical reactions

Classifying compounds into groups makes them easier to name and identify. Because all the compounds in the same group have similar properties, you can predict most of the properties of an unknown substance if you know to which group it belongs.

Similarly, the chemical reactions that are used to make compounds can also be classified. Reactions can be classified as synthesis, decomposition, combustion or hydrolysis (reaction with water) reactions, among others.

Synthesis reactions

Synthesis is the building up of compounds by combining simpler substances, normally elements:

$$A + B \rightarrow AB$$

This equation is a general equation and it helps you determine what will be produced in a synthesis equation. In synthesis reactions, the two reactants combine to form a new product. For example:

$$\text{sodium} + \text{chlorine} \rightarrow \text{sodium chloride}$$

WRITING CHEMICAL EQUATIONS

Once you have predicted the product that will be formed and written the word equation, you can write the chemical equation.

1 Write the symbols for the elements:

$$Na + Cl \rightarrow NaCl$$

2 Write the chemical formula for each of the molecules. Are they ionic compounds or covalent compounds? Use smaller subscript numbers to indicate the number of each atom in the molecule:

$$Na + Cl_2 \rightarrow NaCl$$

3 Count the number of atoms on each side of the equation to ensure that no atoms are created or destroyed (law of conservation of mass). If more atoms are needed, add a large number before the molecule:

$$2Na + Cl_2 \rightarrow 2NaCl$$

4 Determine if the reactants and products are solids (s), liquids (l), gases (g) or aqueous solutions (a soluble solution mixed with water) (aq):

$$2Na(s) + Cl_2(g) \rightarrow 2NaCl(s)$$

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EXPERIMENT 4.1B: DECOMPOSING A CARBONATE
GO TO PAGE 201

EXPERIMENT 4.1C: ELECTROLYSIS
GO TO PAGE 202

AMMONIA

Ammonia (NH_3) is a very important chemical produced by the direct combination of its elements, nitrogen and hydrogen. It is used in a large number of fertilisers, as well as in a range of household cleaning products. The modern method used to produce ammonia is called the Haber process, which relies on the reaction:

$$3H_2(g) + N_2(g) \rightarrow 2NH_3(g)$$

Nitrogen is not a very reactive element, so specific conditions are required for this reaction to occur. It involves heating the two gases so that the reaction will happen quickly enough.

Decomposition reactions

Decomposition reactions are the breakdown of compounds into simpler substances, either elements or more simple compounds. These reactions often require energy in the form of electricity or heat.

Electrolytic decomposition is the breakdown of a compound as a result of an electric current passing through a solution. An example is the formation of hydrogen and oxygen from water:

$$2H_2O(l) \rightarrow 2H_2(g) + O_2(g)$$

Electrolysis equipment has two diodes – an anode and a cathode. A different chemical reaction occurs at each diode (Figure 4.1). These reactions are endothermic because they need energy for the reaction to occur.

Electrolytic decomposition is used in the smelting of aluminium. Aluminium ore (bauxite) contains alumina (Al_2O_3). When an electrical current is passed through a solution of alumina, a decomposition reaction occurs:

$$2Al_2O_3 \rightarrow 4Al + 3O_2$$

Quicklime, or calcium oxide (CaO), is an important industrial product. It is used in agriculture as a fertiliser and to neutralise acidic soils. It is also a key component in building materials, such as mortar. Calcium oxide is produced by the thermal decomposition of calcium carbonate ($CaCO_3$):

copper(II) carbonate $\rightarrow$ copper(II) oxide + carbon dioxide

$$CuCO_3 \rightarrow CuO + CO_2$$

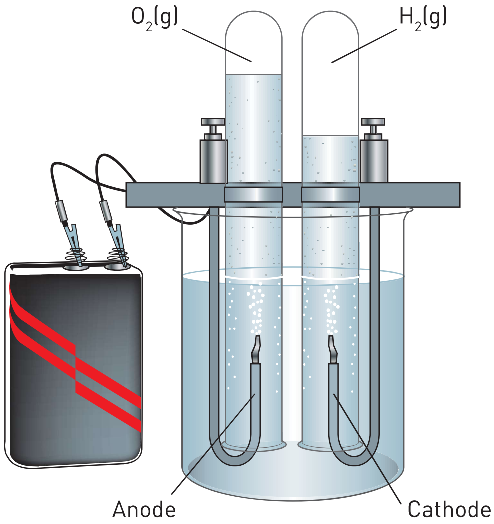

Figure 4.1 Electrolysis equipment. At the anode, water is being broken down into oxygen gas and hydrogen ions. At the cathode, hydrogen gas is being produced from hydrogen ions and electrons.

The most common and cheapest naturally occurring form of calcium carbonate is limestone. For many centuries, calcium oxide was produced from limestone in lime kilns. These stone structures were fuelled by coal, with blocks of limestone broken up, often by hand, and added to the kiln, where the temperatures could reach close to 1000°C.

Today, limestone is roasted in more modern furnaces, often fuelled by gas, where the temperature can be regulated by controlling the flow of gas and air into the furnace.

Check your learning 4.1

Remember and understand

1 What is the law of conservation of mass?
2 Why do decomposition reactions always produce more than one product?

Apply and analyse

3 Why would synthesis reactions sometimes be called combination reactions?
4 Describe, in terms of the types of chemical reactions, major differences between the reaction used to produce ammonia and the reaction used to produce calcium oxide.
5 Why is energy required in:
   a decomposition reactions?
   b direct synthesis reactions?
6 Predict the products of the following synthesis reactions and write a balanced chemical equation for each one.
   a Calcium and oxygen
   b Hydrogen and chlorine

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4.2 Acid reactions depend on strength and concentration

Acids have a pH less than 7. Bases have a pH greater than 7. Neutralisation reactions occur when acids react with a base to produce a neutral solution (pH 7). Acids react with metals to produce hydrogen and a metal salt. A **concentrated acid** has many acid molecules present with very little water. A **strong acid** readily donates a hydrogen ion to a base.

Acids

Acids are a group of chemicals with similar properties. They taste sour, turn litmus paper red and have a pH of less than 7. Strong acids are dangerous because they are corrosive and can cause severe burns. Weak acids are much less reactive and many are found in food and drinks, such as lemonade. All acids contain hydrogen. Although most acids are molecular compounds (with covalent bonding), when they dissolve in water they form ions. This is called an ionising reaction. This reaction is what gives acids their name. All acids donate a hydrogen ion (H^+) to a base. A hydrogen ion is a hydrogen atom that has lost its electron, so it is really just a proton.

Bases

A base is defined as a substance that gains a hydrogen ion. All bases have a bitter taste, turn litmus paper blue, feel slippery and have a pH of greater than 7. Bases that dissolve in water are called alkalis. Like acids, some bases are more reactive than others. Some, such as caustic soda (NaOH), can burn the skin.

Neutralisation reactions

When an acid and a base are mixed together, hydrogen ions from the acid combine with hydroxide ions (OH^-) commonly found in bases to form water. The remaining ions form a metal salt. Water is considered neutral (pH 7). This reaction is called a **neutralisation** reaction:

Figure 4.2 Zinc metal reacting in acid.

acid + base (metal hydroxide) → water + metal salt

For example:

$$HCl + NaOH \rightarrow H_2O + NaCl$$

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EXPERIMENT 4.2: ACID TITRATIONS
GO TO PAGE 203

Acid and metal reactions

The reaction between acids and metals is most obvious with acid rain. The carbon dioxide or sulfur dioxide gases in the air cause the formation of acid rain. This contributes to the corrosion of metalwork on buildings:

acid + metal → salt + hydrogen

For example:

sulfuric acid + zinc → zinc sulfate + hydrogen

$H_2SO_4(aq) + Zn(s) \rightarrow ZnSO_4(aq) + H_2(g)$

Note: Only the more reactive metals will form a metal salt and hydrogen when reacting with acids. Copper, silver and gold are unreactive metals.

Acids and metal oxides

An acid and a metal oxide react to form a metal salt and water:

acid + metal oxide → metal salt + water

For example:

nitric acid + magnesium oxide → magnesium nitrate + water

$2HNO_3(aq) + MgO(s) \rightarrow Mg(NO_3)_2(aq) + H_2O(l)$

Acids and metal carbonates

An acid and a metal carbonate react to form a metal salt, water and carbon dioxide:

acid + metal carbonate → metal salt + water + carbon dioxide

For example:

nitric acid + calcium carbonate → calcium nitrate + water + carbon dioxide

$2HNO_3(aq) + CaCO_3(s) \rightarrow Ca(NO_3)_2(aq) + H_2O(l) + CO_2(g)$

Concentrated or strong?

If you were to make a drink of cordial and not add enough water, you might describe it as 'too strong'. A chemist would describe it as 'too concentrated'. The strength and concentration of an acid or a base are two different things. So chemists need to be precise when using these terms.

The **concentration** of an acid or base is a measure of how many molecules of the acid or base are present in each litre of solution. A concentrated acid or base has very little water present: it is mostly molecules of acid or base. The labels of a container of concentrated hydrochloric acid might say, 'Conc. HCl' or '10 M HCl'. These solutions are very dangerous to handle.

The **strength** of an acid, is a measure of how readily it will give away the hydrogen ion to a base. Acid strength is compared at the same concentration, which is usually a very low concentration of 0.1 M, a very **dilute** (watered down) solution. Strong acids and strong bases are still dangerous at this concentration.

Check your learning 4.2

Remember and understand

1 What must you react with an acid to produce:
   a hydrogen gas?
   b carbon dioxide?
2 What is the reaction of an acid with a base called? Why is it given this name?

Apply and analyse

3 Write equations for:
   a dilute nitric acid (HNO_3) reacting with magnesium metal
   b dilute ethanoic acid (CH_3COOH) reacting with solid potassium carbonate (K_2CO_3)
   c dilute hydrochloric acid reacting with calcium hydroxide solution.
4 Why is it unsuitable to store acids in metal containers?
5 Would it require more, less or the same amount of base to neutralise 20 mL of 0.1 M strong acid than it would to neutralise 20 mL of 0.1 M weak acid?

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4.3 The solubility rules predict the formation of precipitates

If a compound is soluble, it can dissolve in a liquid solvent. A **precipitation reaction** involves two soluble ionic solutions being mixed to form an insoluble solid product called a precipitate. The ions that do not take part in the reaction are called spectator ions. The solubility of a compound can be predicted from the solubility rules.

Precipitation reactions

A **precipitate** is an insoluble solid that can form as part of a reaction between two ionic solutions.

This can be written in a general form:

$$AB(aq) + CD(aq) \rightarrow AD(s) + CB(aq)$$

In a water (aqueous) solution, the ions A and B separate, as do the ions C and D. Positive ion A forms a bond with negative ion D and positive ion C forms a bond with negative ion B. It is important to note that the positive ions (A and C) are always written first. This is called a double displacement reaction as both substrates change (or displace) their partners. It becomes a precipitation reaction if either AD or CB is insoluble, and forms a solid. The formation of an insoluble solid precipitate can be predicted by using a set of solubility rules. The data shown in Table 4.1 can be used to decide whether a precipitate will form.

For example, a solution of lead(II) nitrate ($Pb(NO_3)_2$) consists of lead ions (Pb^{2+}) and nitrate ions (NO_3^-) together with many water molecules.

When a solution of lead(II) nitrate is added to potassium iodide – both colourless solutions – a bright yellow precipitate of lead iodide (PbI_2) is formed. The reaction can be written as:

lead(II) nitrate + potassium iodide → lead(II) iodide + potassium nitrate

$$Pb(NO_3)_2(aq) + 2KI(aq) \rightarrow PbI_2(s) + 2KNO_3(aq)$$

The lead ions and the iodide ions have combined to form an insoluble precipitate of lead(II) iodide. This new compound forms as a solid in the solution. The potassium and nitrate ions are still dissolved in solution. They are

Table 4.1 Solubility of some common ionic compounds in water

SOLUBLE	INSOLUBLE	SLIGHTLY SOLUBLE
Group 1 elements		
All ammonium salts		
All nitrate salts		
Most chlorides, bromides and iodides	AgCl, AgI, AgBr, $PbCl_2$, PbI_2, $PbBr_2$	
	Most carbonate and phosphate compounds	
Group 1 hydroxides, $Ba(OH)_2$ and $Sr(OH)_2$	Most hydroxides and sulfates	$Ca(OH)_2$, Ag_2SO_4, $CaSO_4$

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EXPERIMENT 4.3: PRECIPITATION REACTIONS
GO TO PAGE 204

not taking part in the reaction. They are called **spectator ions**. Because of this, it is possible to write the equation in a different way that shows only those ions that are changing in the reaction:

$$Pb^{2+}(aq) + 2I^{-}(aq) \rightarrow PbI_2(s)$$

Because the lead ions and iodide ions are dissolved in the solution, they are described as aqueous (aq). This reaction is shown in Figure 4.3.

Lead compounds were used in a number of pigments until the 1970s, when it was discovered that the lead in these pigments could damage the nervous system.

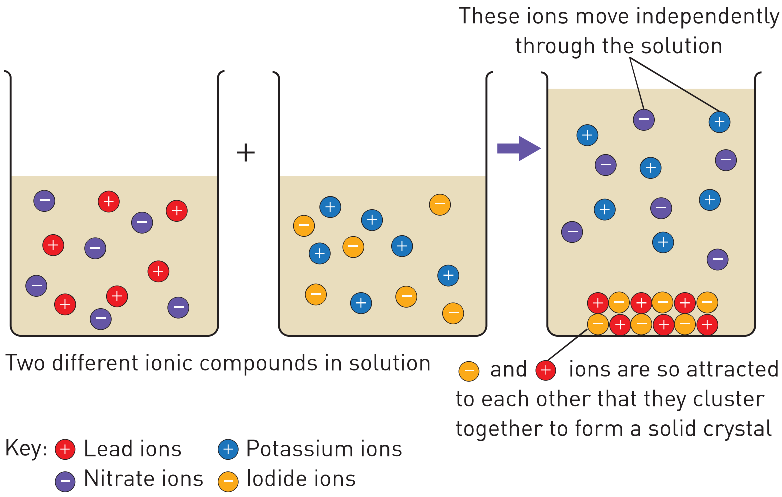

Figure 4.3 At the particle level, when a solution of lead(II) nitrate ($Pb(NO_3)_2$) is added to potassium iodide (KI), the ion partners are swapped.

Using precipitation reactions

Precipitation reactions are important for chemical analysis. PbI_2 is insoluble, so, if any soluble lead(II) compound is mixed with any soluble iodide, a precipitate of PbI_2 will form (Figure 4.4). Similarly, Table 4.1 tells us that $Cu(OH)_2$ is insoluble. This means that if any soluble hydroxide, such as NaOH, is mixed with any soluble copper(II) compound, such as $CuSO_4$, a precipitate of $Cu(OH)_2$ will form.

Chemists sometimes use precipitation reactions to find out which chemicals are present in a substance or how much is present.

Common table salt (NaCl) is essential in our diet because the sodium is needed to maintain the correct concentration of body fluids, assist in the transmission of nerve impulses and to help cells absorb nutrients.

Chemical analysis can determine the amount of salt in foods by using a precipitation reaction with silver nitrate. The salt reacts with the silver nitrate to form a precipitate of silver chloride. The amount of sodium chloride present can be calculated by using the amount of silver chloride that has been precipitated:

$$NaCl(aq) + AgNO_3(aq) \rightarrow NaNO_3(aq) + AgCl(s)$$

Figure 4.4 Yellow lead(II) iodide forming in a precipitation reaction.

Check your learning 4.3

Remember and understand

1 Draw a diagram to show which particles are present in a beaker containing a sodium chloride solution.

2 What symbol is used to show the state of an insoluble compound?

Apply and analyse

3 Which of the following substances would be insoluble?

Copper(II) chloride, calcium hydroxide, silver nitrate, magnesium bromide, silver bromide, magnesium nitrate, potassium chloride, lead(II) nitrate, potassium nitrate, lead(II) chloride

4 What precipitate would form if solutions of lead(II) nitrate and sodium sulfate were mixed?

5 Complete the following word equations and then write balanced chemical equations for each reaction.

a zinc nitrate + potassium hydroxide →

b calcium nitrate + sodium carbonate →

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4.4 Combustion reactions between hydrocarbons and oxygen produce carbon dioxide, water and energy

Oxidation reactions occur when an element reacts with oxygen. Oxidation reactions with metals produce metal oxides. Combustion reactions between non-metals and oxygen produce large amounts of energy in the form of heat and light. Combustion of **hydrocarbons** produces water and carbon dioxide.

Figure 4.5 The oxidation of magnesium is highly exothermic and produces a very bright flame.

When an element reacts with oxygen, we say that is has oxidised. This is classified as an oxidation reaction.

Oxidation reactions with metals

When metals react with oxygen, a basic metal oxide is formed:

metal + oxygen → metal oxide

As the metal has formed a compound, this is also classified as a corrosion reaction. The metal oxide produced is an ionic compound.

In the case of very reactive metals, this oxidation is highly exothermic (energy producing) and rapid. For example:

magnesium + oxygen → magnesium oxide

$$2Mg(s) + O_2(g) \rightarrow 2MgO(s)$$

In the case of moderately reactive metals, the oxidation reaction is still exothermic, but slow.

Oxidation reactions with non-metals

Group 18 non-metals do not react with oxygen. Other non-metals do react with oxygen, which is also a non-metal. Reaction results in the formation of a covalent bond. Consider the formation of water and carbon dioxide:

$$2H_2(g) + O(g) \rightarrow 2H_2O(g)$$

$$C(s) + O_2(g) \rightarrow CO_2(g)$$

Both of these reactions are highly exothermic. The first reaction can cause explosions. (This is the reaction that causes the 'pop' in the pop test for hydrogen.) Carbon is the principle constituent of coal. Both reactions produce a flame and so are classified as **combustion** reactions.

Combustion reactions require oxygen and a fuel. A fuel is a substance that will undergo a chemical reaction in which a large amount of useful energy is produced at a fast but controllable rate. According to this definition, fuels are the substances we use to produce heat and/or electricity, and to run engines and motors.

Combustion of hydrocarbons

The most common fuels we use for combustion are compounds of carbon and hydrogen (known as hydrocarbons). When pure hydrocarbons burn in unlimited oxygen, carbon dioxide and water are produced:

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EXPERIMENT 4.4: COMBUSTION OF WIRE WOOL
GO TO PAGE 205

hydrocarbon + oxygen → carbon dioxide + water

When there is less oxygen available, carbon monoxide forms:

hydrocarbon + limited oxygen → carbon monoxide + water

Carbon monoxide (CO) is a poison that binds tightly to the haemoglobin in red blood cells, much tighter than oxygen binds. Victims of carbon monoxide poisoning die because of a lack of oxygen to the brain and other body tissues.

With even less oxygen, unburnt hydrocarbon (soot) is formed, with water:

hydrocarbon + limited oxygen → carbon + water

Small particles of soot cause breathing problems, especially in people with asthma. It is important that all users of hydrocarbon fuels burn them cleanly. In addition to releasing less pollution, burning these fuels cleanly provides more energy.

Our carbon economy

The chemical fuels that our society relies upon are based on carbon. Our ancestors burnt wood, which is mainly the carbon compound cellulose. Later generations burnt coal, which is close to pure carbon. Coal is made by the dehydration and compaction of buried plant remains. Our generation uses coal to produce electricity and petroleum as a liquid fuel for transport.

All these fuels contain molecules made of carbon. Cellulose is a chain of $C_6H_{10}O_5$ units arranged end-to-end, coal is 95% pure carbon (depending on the type) and petroleum is a mixture of hydrocarbons. Petrol is mostly octane (C_8H_{18}), diesel is a mixture with the average formula $C_{12}H_{23}$, natural gas is CH_4 and liquefied petroleum gas (LPG) is propane (C_3H_8).

Petrol, diesel, natural gas and LPG are fossil fuels. They are obtained from the Earth and were formed from the fossilised remains of plants and animals. The energy in them was captured by photosynthesis millions of years ago. This carbon has been locked away out of the atmosphere for millions of years. Even renewable fuels, such as biodiesel and ethanol, contain carbon atoms. The carbon atoms in renewable fuels were captured by photosynthesis in the last growing season.

It is fair to say that our society runs on carbon. It is a very important fuel. Carbon is the mainstream of our economy. This is why it is called a carbon economy.

Figure 4.6 In oil refineries, distillation towers are used to isolate the different liquid fractions in crude oil.

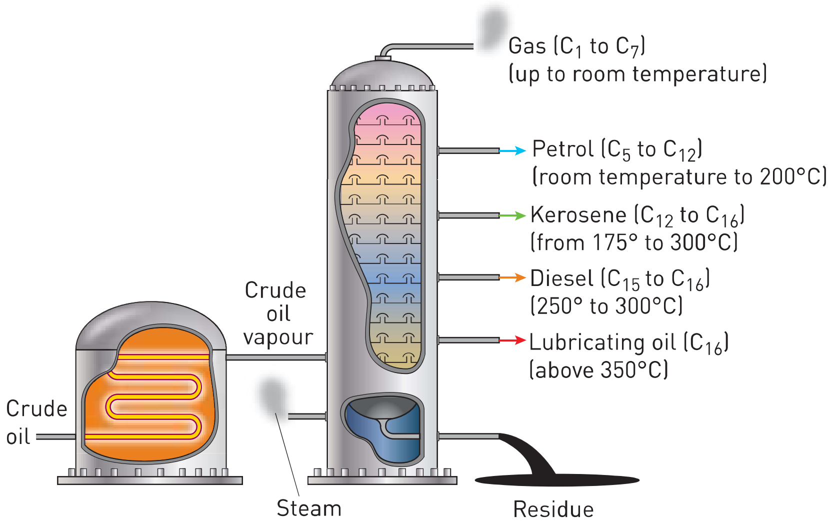

Figure 4.7 As the crude oil is slowly heated, vapour (gases) form. As the vapour rises, it cools. When the vapour reaches the height where the temperature is equal to the fraction's boiling point, it condenses into a liquid.

Check your learning 4.4

Remember and understand

1 Why are carbon fuels so important to our society?
2 Why does the amount of oxygen available affect the products formed in the combustion process?
3 Which group of elements do not react with oxygen?
4 Why is it important to burn hydrocarbons in a well-ventilated area?

Apply and analyse

5 Give an example of a substance that might be considered a fuel by a:
 a firefighter
 b chemist.
6 Write a balanced equation for the combustion of each of the following hydrocarbons in excess oxygen.
 a Petrol
 b LPG
 c Natural gas
 d Diesel
7 Which fuel in question 6 requires the most oxygen to burn cleanly?

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4.5 Polymers are long chains of monomers

Polymerisation is the process of forming a long chain **polymer** from smaller **monomer** molecules. Elastomers are bound to each other and will return to their original shape when stretched. **Cross-linked polymers** are giant lattices with many random linkages. **Thermoplastic polymers** will soften when heated. Thermoset plastics will not melt or change shape when heated.

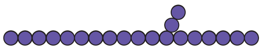

Figure 4.8 The basic structure of a linear polymer. The small circles represent small groups of atoms.

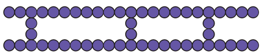

Figure 4.9 The basic structure of an elastomer.

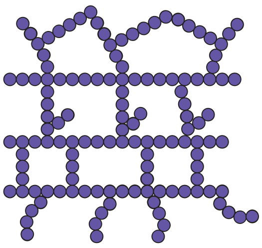

Figure 4.10 A cross-linked polymer.

Figure 4.11 Plastic film is a thermoplastic material.

Different types of polymers

The plastics we use every day are a result of polymerisation. A polymer is a giant molecule that has been produced by joining many, many smaller molecules together – often thousands! Polymer means 'many parts'. The small molecules from which the polymers are made are called monomers.

If the polymer has been produced by chemists or chemical engineers, it is called a synthetic polymer. An example of a synthetic polymer is nylon. Before nylon was created, stockings were made from silk, which is a natural fibre produced by silkworms. Apart from being expensive, stockings made from silk easily developed holes and 'ladders'. Toothbrush bristles were made from another natural fibre – the fine hairs from boars! Nylon could replace both silk and boar bristles because nylon fibre is much tougher and more suitable for these applications.

There are three types of polymer structures: linear polymers, occasionally cross-linked polymers (also known as elastomers) and cross-linked polymers.

Linear polymers are in the form of long chains (Figure 4.8). Generally, the chains consist of carbon atoms held together by covalent bonding, with other atoms or groups attached to the carbon atoms. In some linear polymers, the atoms of another non-metal are found at regular intervals along the chain of carbon atoms. For example, in nylon a nitrogen atom is found about every tenth atom along the chain. There may also be 'branches' hanging off the main chain.

The structure of elastomers is like a ladder (Figure 4.9). **Elastomers** are in the form of long chains that are connected every now and then with a small chain of atoms. They are termed 'elastomers' because they are elastic. That is, they can be stretched and, when you let them go, they spring back into shape.

Cross-linked polymers are giant covalent lattices (Figure 4.10). Generally, they are largely made up of carbon atoms, although the atoms are much more haphazardly arranged than the carbon atoms in other covalent lattices, such as diamonds.

Apart from being classified according to their structure, polymers are classified according to how they respond to heat. This is a very important property.

Thermoplastic polymers soften when heated gently and solidify again when cooled. They can be readily worked into different shapes by warming and pressing them, squeezing them through holes or even blowing them into the required shape. 'Plastic' means being able to have its shape changed.

So, these are the only polymers that really should be described as 'plastic'. Plastic film is a thermoplastic polymer (Figure 4.11).

Thermosetting polymers do not melt or change shape when heated. If heated very strongly, they may char (turn black). These polymers must be produced in a mould because once they are formed they will not change shape again. Once formed, they are hard and rigid (Figure 4.12).

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EXPERIMENT 4.5: POLYMERISATION OF CASEIN
GO TO PAGE 206

Formation of polymers

There are many different types of **polymerisation** reactions, but they all follow the same process, with the small molecules being reacted under conditions (i.e. specific temperature and/or pressure) that allow them to join together in a chain reaction to form giant molecules that can contain thousands of atoms. Polyethene is produced in this way, with molecules of ethene (C_2H_4) reacting together to form long-chain molecules of polyethene. This process can be represented using a diagram, as shown in Figure 4.13.

This polymerisation reaction requires high temperature and pressure, as well as a chemical catalyst.

How we use polymers today

Many different polymers are used today.

More and more designer polymers are being developed and modified to suit particular applications. Many tents are made from nylon, which produces a lightweight, tear-resistant fabric (Figure 4.14). Bigger tents are made of cotton polyester. The bases of the tents are made of polyurethane, another useful, waterproof polymer.

Most people have at least one piece of clothing made of polar fleece, which is warm and yet lightweight. Polar fleece is a synthetic wool made from PET, or PETE (polyethylene terephthalate). PET is a thermoplastic polymer and, for polar fleece, is sourced from recycled plastic bottles that have been processed into a clothing fabric. PET gives polar fleece its soft, warm, durable and fast-drying properties, which make it perfect for camping and other outdoor activities (Figure 4.15).

Figure 4.12 The plastics that make up the cover of a PlayStation are made of thermosetting polymers.

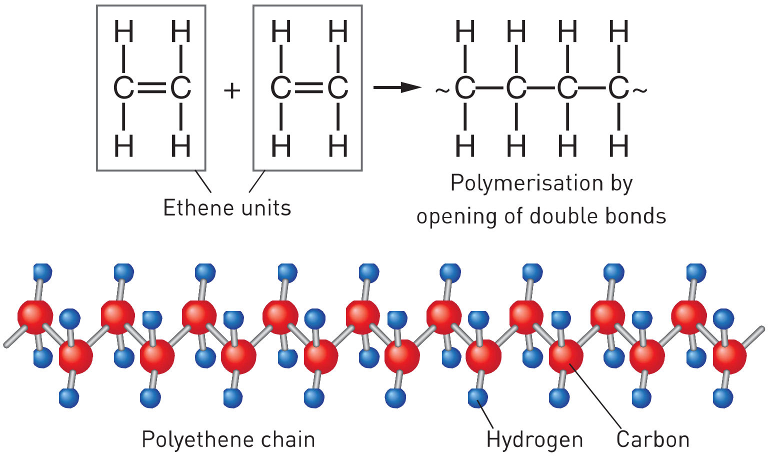

Figure 4.13 The formation of polyethene from ethene molecules.

Figure 4.14 Tents are made of nylon, which makes them lightweight.

Check your learning 4.5

Remember and understand

1 What are the differences between a linear polymer and a cross-linked polymer?

2 What is the monomer unit of polyethene?

3 What are the properties of elastomers? Use their structure to explain their properties.

Apply and analyse

4 For each of the following applications, state whether it would be better to make the object from a thermosetting polymer or a thermoplastic polymer.
   a Food wrap
   b Light switch
   c Disposable cup for soft drinks
   d Wash bottle for a science laboratory
   e Handles of barbecue tongs

5 Which would you expect to be a thermosetting plastic: a linear polymer or a cross-linked one? State your reasoning.

Figure 4.15 Polar fleece is warm and light, which makes it very suitable for outdoor activities such as camping.

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4.6 Temperature, concentration, surface area and stirring affect reaction rate

The speed at which a reaction occurs is called the rate of a reaction. For a reaction to occur, the reactants must collide in the correct orientation. This is called **collision theory**. The rate of a reaction can be increased by increasing the temperature, concentration, surface area or stirring the reactants.

Why reaction rates are important

A **reaction rate** is how fast a reaction proceeds. It is important to realise that this does not mean more products are formed in the reaction. This can be illustrated by a 100-metre race. A runner can run fast or slow; the only difference is how quickly the runner finishes the 100 metres. A fast reaction has a high reaction rate; a slow reaction has a low reaction rate.

In the chemical industry, controlling the rate of a reaction is vital. Reactions that are too slow are not economic, because equipment is tied up for a long time. Reactions that are too fast need to be controlled. Chemists and chemical engineers have the role of making chemical reactions as cheap as possible. A large part of this is achieved by controlling the rate of the reaction.

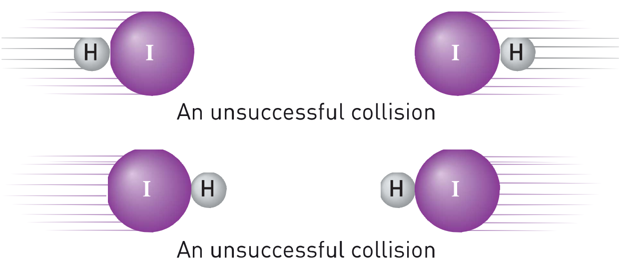

Figure 4.16 Not all collisions result in a chemical reaction.

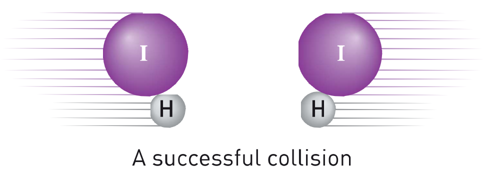

Figure 4.17 When the collisions between particles have enough energy, and the particles are aligned correctly, a reaction may occur.

Collision theory

For a chemical reaction to occur, the atoms or ions or molecules must collide with enough energy for that reaction to occur. This model is known as collision theory.

One reaction that has been studied is the decomposition reaction of hydrogen iodide. The reaction, in symbols, is:

$$2HI(g) \rightarrow H_2(g) + I_2(g)$$

Hydrogen iodide is a gas and its molecules travel quickly. Each hydrogen iodide molecule must collide with another hydrogen iodide molecule in order to react.

Some collisions do not result in a reaction. In these unsuccessful collisions, the hydrogen iodide molecules bounce apart with no reaction, as shown in Figure 4.16.

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EXPERIMENT 4.6A: EFFECT OF TEMPERATURE ON REACTION RATE
GO TO PAGE 207

EXPERIMENT 4.6B: FACTORS AFFECTING REACTION RATE
GO TO PAGE 208

In the collision shown in Figure 4.17, there is a reaction. A weak chemical bond forms between the iodide ions and between the hydrogen ions. This intermediate substance is unstable and only exists for a short period of time before it breaks apart. Only some collisions result in a reaction. The molecules must collide in the correct orientation for a reaction to occur.

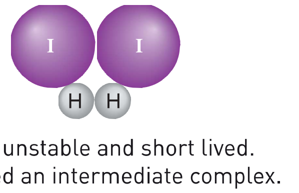

Figure 4.18 An intermediate stage during the reaction. The products of this reaction move apart. (This is partly due to electrical repulsion.)

Increasing the rate of collisions

To increase the rate of a reaction, you need to increase the number of collisions occurring. This can be done by increasing the:

- surface area of the particles reacting
- concentration of the reactants
- temperature of the reaction.

Figure 4.19 The final products are formed.

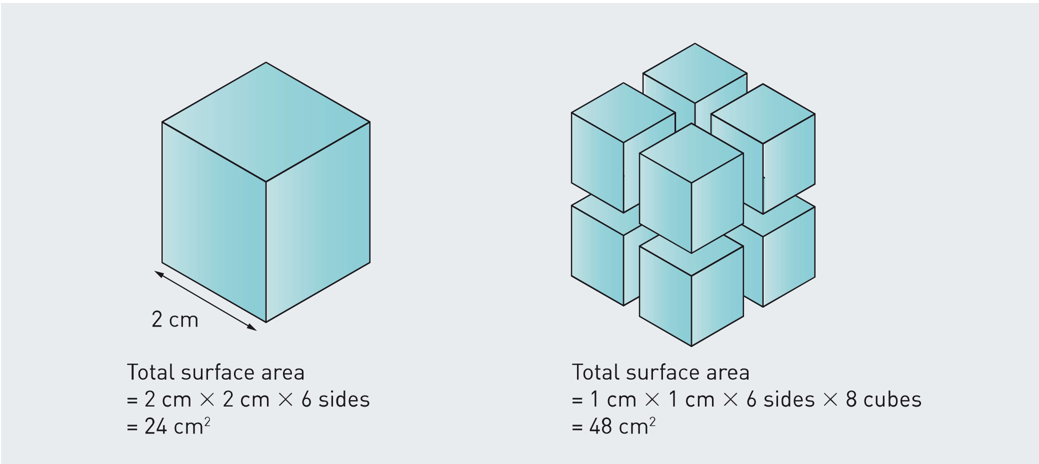

Figure 4.20 Many small particles have a larger surface area than a single large particle of the same volume.

INCREASE THE SURFACE AREA

A metal such as magnesium reacts with dilute hydrochloric acid. For a reaction to occur, hydrogen ions in the acid have to collide with magnesium atoms. There are more metal atoms exposed to the hydrogen ions if the metal is in small pieces. Because the reaction occurs on the surface of the magnesium, breaking it up into smaller pieces provides a larger surface area on which the reaction can occur.

Powders have a much larger surface area than large-sized bits of material. The surface area is not the size of the pieces, but the total area exposed to possible collisions (Figure 4.20).

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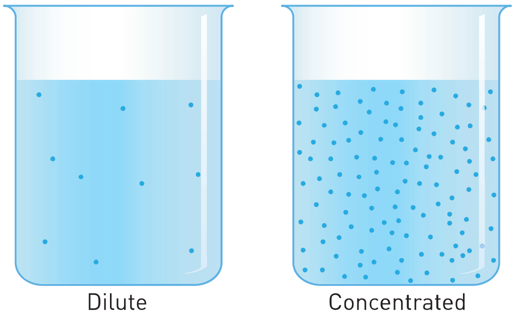

Figure 4.21 A concentrated solution will contain more dissolved particles than a dilute solution.

INCREASE THE CONCENTRATION

In a dilute solution, the particles (molecules or ions) of the reactant are spread out in a solvent, such as water. There is a lot of space between the reactant particles. In a concentrated solution, there are many more reactant particles in the same volume, so they are much closer together (Figure 4.21).

In the reaction between magnesium and hydrogen ions, the reaction will occur faster if there are more hydrogen ions in a given volume. So, using a hydrochloric acid solution with a higher concentration (i.e. more hydrogen ions in a given volume) will speed up the reaction. When there are more particles, there are more collisions and therefore a higher reaction rate.

INCREASE THE TEMPERATURE

Particles in a hot substance have more kinetic energy than particles in a cold substance. This means that the particles in a hot substance travel faster than the particles in a cold substance (Figure 4.22).

Particles in hot substances will collide faster and more often than cold particles will. A higher frequency of collisions, with a greater energy, means a greater proportion of collisions will result in a reaction.

Slow-moving gas molecules will be pushed apart by the repulsion of the electrons that orbit the atoms: they never come close enough to form new chemical bonds. Fast-moving molecules can ‘push through’ the repulsion and their electrons can orbit around a different atom. The faster the molecules, the higher the proportion of molecules with sufficient energy to change into products.

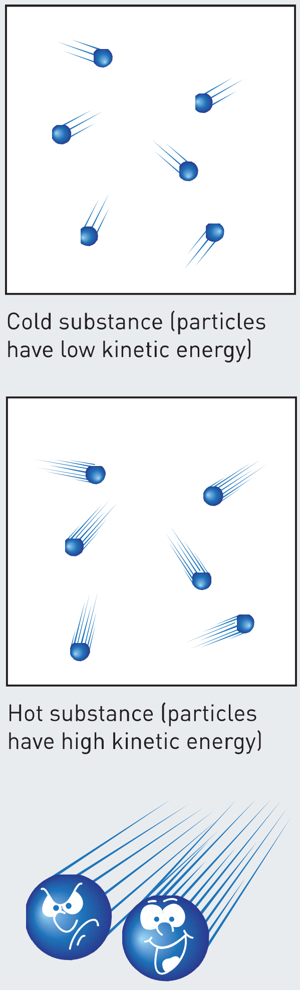

Figure 4.22 At higher temperatures, the average energy of the particles is increased and the particles travel faster.

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Stir and mix

As a chemical reaction proceeds, the particles of the reactants get used up: when there are fewer particles of reactants, there are fewer collisions and so the reaction rate slows. To maintain the reaction rate, the products of the reaction should be removed and replaced with more particles of reactants. A basic way of doing this is by stirring or mixing the reactants.

In the reaction between magnesium and acid, one of the products is hydrogen gas. The gas forms bubbles that gather on the surface of the magnesium, covering the unreacted magnesium (Figure 4.23). This prevents the reaction from continuing. Stirring sweeps the hydrogen gas away so that more hydrogen ions can react with the fresh magnesium surface.

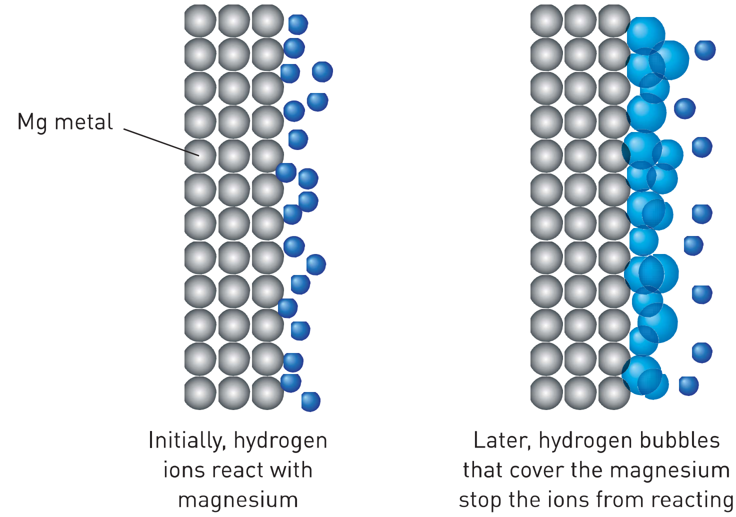

Figure 4.23 Sometimes the presence of the product can slow down a chemical reaction.

Check your learning 4.6

Remember and understand

1. Are products formed every time molecules of reactants collide? Explain your answer.
2. Why does increasing the surface area increase the rate of reaction?
3. Why does diluting a solution decrease the rate of reaction?
4. Why does a reaction occur faster when the reactants are stirred together?
5. How does collision theory explain the dramatic increase in the rate of a reaction as the reactants are heated?

Apply and analyse

6. A reaction is carried out in a well-ventilated environment with outside air regularly circulating. A chemical engineer noticed that a reaction that gave a high yield of a product in winter gave a low yield of that same product in summer, despite the reagents and concentrations being identical. What is a possible explanation for the different yields?

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4.7 Catalysts increase the rate of a reaction

Catalysts increase the rate of a chemical reaction without being permanently changed. Some catalysts provide a surface on which the two reactants can meet in the correct orientation, allowing the products to be formed. The products are then released. Other catalysts take part in the initial reaction and are regenerated in the final reaction.

A **catalyst** is a substance that speeds up a chemical reaction but is not used up in the reaction. Catalysts work in many different ways.

Solid catalysts provide a surface on which the reaction can occur. The particles of reactants get adsorbed (stuck onto) the surface, where they react to form the products. The products are then released from the surface of the catalyst. This frees up the catalyst to be used again by other reactant molecules.

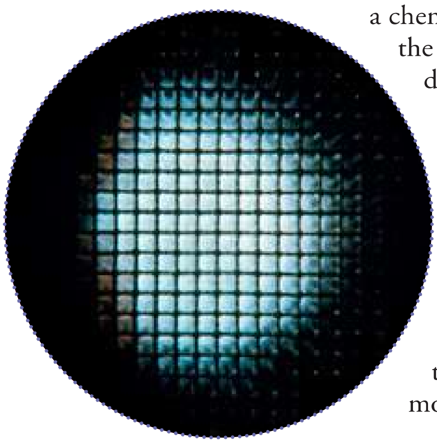

Figure 4.24 Catalysts are often used in the form of a grid to maximise the surface area.

Pollution control in cars

Solid catalysts are used in the catalytic converters of cars. A honeycomb-like grid of metals provides a large surface area (Figure 4.24). As the exhaust gases pass through the converter, they react on the surface of the metals to form harmless gases. The metals adsorb pollutant gases, but not clean gases such as nitrogen and carbon dioxide. These clean gases are passed through the car exhaust. The metals that act as catalysts are platinum, palladium and rhodium.

The overall reaction that occurs in the catalytic converter is:

$$2CO(g) + 2NO(g) \rightarrow 2CO_2(g) + N_2(g)$$

Sometimes these catalysts are poisoned. This is when an impurity prevents the catalyst from functioning fully. Impurities in petrol can poison a car catalyst.

Figure 4.25 Ozone offers some protection from some harmful ultraviolet radiation.

Figure 4.26 Catalytic converters are used to reduce pollution from exhaust gases.

Reactions in the ozone layer

Another way in which catalysts work is to take part in the reaction and be regenerated later. This occurs in the destruction of ozone by chlorofluorocarbons (CFCs).

The ozone layer is part of the stratosphere. It is the region in the stratosphere from 10 to 50 km high, with the greatest concentration at an altitude of 30 km. Ozone in this region absorbs the ultraviolet (UV) light that would otherwise cause many more skin cancers and eye problems.

CFCs are the main destroyers of ozone. CFCs were developed as refrigerants for use in refrigerators. CFCs are non-flammable, non-toxic, cheap to manufacture, easy to store and chemically stable and were used in aerosol cans (Figure 4.27), fire extinguishers and asthma inhalers, as well as in foam insulation for furniture, bedding, coffee cups and hamburger containers.

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EXPERIMENT 4.7: USING A CATALYST
GO TO PAGE 209

CFCs such as CCl_3F (trichlorofluoromethane or freon-11) are broken apart by the UV rays from the Sun, releasing a free chlorine atom. This chlorine atom catalyses the destruction of ozone and is regenerated.

In this way, one chlorine atom from the original CFC can destroy up to 10 000 ozone molecules. The reactions occurring can be shown as follows.

CCl_3F breaks down to produce a chlorine atom:

$$CCl_3F \xrightarrow{\text{UV light}} CCl_2F + Cl$$

The chlorine atom reacts with ozone:

$$Cl + O_3 \rightarrow ClO + O_2$$

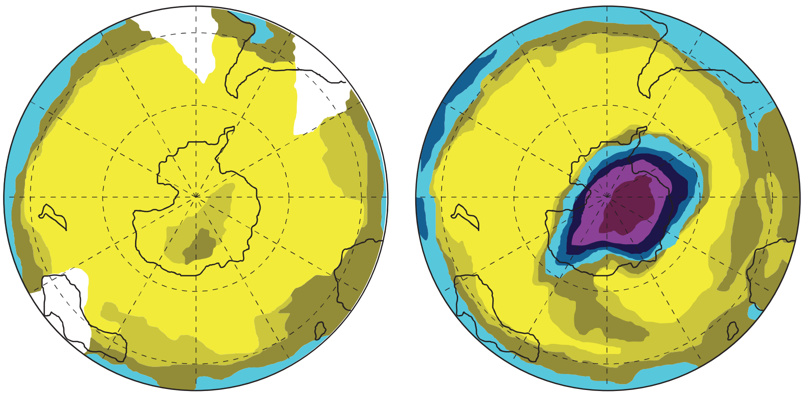
ClO reacts with by O atoms, making more Cl:

$$ClO + O \rightarrow Cl + O_2$$

The Cl atoms are then free to react with more ozone.

In 1987, the Montreal Protocol (an agreement made in Montreal, Canada) phased out the use of CFCs. Chemicals that were 'ozone friendly' were developed and used as replacements for the ozone-depleting substances.

Figure 4.27 Chlorofluorocarbons (CFCs) were used to pressurise the gas used in aerosol cans before it was proven that the CFCs damaged the ozone layer.



1 November 1978 1 November 1992

Figure 4.28 Ozone levels reduce over the southern hemisphere every year. The darker colours show where the 'hole' in the ozone layer has grown.

Enzymes as catalysts

An enzyme is a catalyst made and used in living cells. Enzymes play an important part in all cellular processes. All the reactions that occur inside a cell are catalysed by enzymes. There are numerous enzymes in our bodies to help speed up reaction rates. For example, enzymes in the digestive system help break down food. Enzymes only work with specific reactants and so will only catalyse certain reactions.

Check your learning 4.7

Remember and understand

1. What is a catalyst?
2. Explain the two ways in which catalysts can work.
3. What is a catalytic converter? Why are they used?

Apply and analyse

4. Why is it important that the amount of ozone in the atmosphere remains stable?
5. What has caused a change in the amount of ozone in the atmosphere over time?
6. Which part of the CFC molecule destroys ozone? How does this atom become detached?

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//SCIENCE AS A HUMAN ENDEAVOUR//

4.8 Green chemistry reduces the impact of chemicals on the environment

Being 'green' means doing something positive for the environment. Scientists with special knowledge in ecology, biochemistry, zoology and botany study the environment and how it responds to changes. These scientists detect changes caused by natural events, as well as by human actions. They monitor the environment for changes that may have been caused by the actions of society.

Low-impact chemicals

Some chemicals have a negative impact on the environment and living things. When these substances are identified, scientists act to reduce their use and prevent them from entering the environment. Some substances are banned altogether.

New chemical products and processes are described as 'green' if they have less impact on the environment than the product or process they replace. The study and development of new substances that have a low impact on the environment is called '**green chemistry**'.

Some examples of the development of 'green' alternatives are described below.

Pesticides and herbicides

Pesticides and herbicides have been used to kill organisms that eat our food crops and the plants that compete with these crops for sunlight and nutrients. In the past, some of these products killed all living things, not just the target species. Most were **non-degradable** (did not break down) and remained in the environment long after they were no longer needed. These substances are now banned and have been replaced with **biodegradable** poisons. In many cases, chemical poisons have been replaced with new farming practices, such as crop rotation and planting pest-resistant crop varieties.

Heavy metals

Heavy metals include lead, mercury and cadmium. Heavy metals had many uses, especially in dyes, and were used in chemical processes as catalysts. But these metals accumulated in the bodies of living things, including people.

The most dramatic example is that of Minamata disease, caused when people in Minamata, Japan, in 1956, were poisoned by mercury after eating contaminated seafood. The use of these metals in situations where they could enter the environment has been largely stopped. They have been replaced by different catalysts and even different production processes.

Solvent-based paints

Acrylic paints have replaced solvent-based enamel paints and lacquers. The solvent used in the old paints was a hydrocarbon, such as turpentine, and it evaporated as the paint dried. The hydrocarbon solvents in enamel paint were toxic to aquatic life in waterways and the fumes from the paint caused 'painter's disease' in the workers who inhaled them.

These solvent-based paints have been replaced with acrylic paints, which are water based and set by polymerisation of the paint, not by evaporation of a solvent.

Green chemistry is sometimes called 'sustainable chemistry'. It is about reducing the impact of chemicals on the environment – chemists produce substances in processes that have less impact on the environment than the substances they replace.

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How science can help

You can help protect the environment and the planet by adapting the slogans 'Reduce, Reuse, Recycle' and 'Act Local, Think Global' to reduce your footprint on the environment by:

> using your own shopping bag instead of plastic bags
> composting grass clippings and food scraps and using this compost instead of chemical fertilisers
> using trigger-action spray bottles, not aerosols
> avoiding non-degradable products, such as some biocides
> leaving the car at home for short journeys, catching public transport or riding a bike
> using natural cleaning products and avoiding chlorine-based cleaners.

Figure 4.29 There are many ways in which you can reduce your impact on the environment.

Extend your understanding 4.8

1. How do scientists determine how safe a product is?
2. The 'old masters', the painters of the 1600s to 1800s, used pigments made of compounds of lead, mercury and cadmium. Why are these paints no longer available to today's artists?
3. If you discovered an important new chemical, could you be responsible for any consequences that occurred 30 years in the future? Could the people who are affected in 30 years' time blame you?
4. What other materials can be recycled to reduce the risk of chemical pollution?
5. What are the properties of substances that would make them suitable for recycling?
6. What other actions can you take to reduce your impact on the environment? Your actions will make a small difference, but when others join you, the effect is quite dramatic.

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* REVIEW

4

Remember and understand

1 Describe the differences between decomposition reactions and direct synthesis reactions.

2 What types of products are formed when acids react with metals, carbonates or bases?

3 Describe two different types of reactions that produce carbon dioxide.

4 In terms of particles, what is required for a chemical reaction to take place?

5 List four factors that will affect the rate of a chemical reaction.

6 Describe two ways that the rate of chemical reactions can be measured.

7 Describe one situation where it could be dangerous if a reaction occurs too quickly.

8 What is the link between CFCs and the ozone layer?

Apply and analyse

9 Polypropylene is a plastic that can be easily melted and formed into a range of products. Describe the likely structure of polypropylene and explain how its structure allows the plastic to be moulded into a range of shapes.

10 A student mixed the following solutions together in a beaker: ammonium nitrate, sodium chloride, lead(II) nitrate, sodium sulfate. Describe what would be seen in the beaker. Explain your answer using a chemical equation.

11 Sodium metal was used to produce aluminium from purified bauxite (Al_2O_3).

a What type of reaction would be occurring?

b Write a chemical equation for the process, ensuring that the law of conservation of mass is applied to the equation.

12 Describe two examples of the use of catalysts in the production of chemical products.

13 In many industrial environments, the presence of a fine dust is regarded as an explosion hazard. Why is coal dust more likely to explode than chunks of coal?

14 What are some examples of green chemistry that you could apply at home?

Evaluate and create

15 How does the particle model of matter help us understand the rate of reactions?

16 The reaction $2SO_2(g) + O_2(g) \rightarrow 2SO_3(g)$ is very slow at room temperature. The reaction occurs in two steps, which are shown below. The reaction occurs more quickly in the presence of nitrogen dioxide gas.

Step 1
$2SO_2(g) + 2NO_2(g) \rightarrow 2SO_3(g) + 2NO(g)$

Step 2
$2NO(g) + O_2(g) \rightarrow 2NO_2(g)$

Explain two reasons why the nitrogen dioxide is regarded as a catalyst.

Ethical understanding

17 In the 1920s, the compound tetraethyl lead was developed to prevent 'knocking' in car engines. ('Knocking' is where the spark plugs fire too early, resulting in loss of power and possible engine damage.) Adding tetraethyl lead saved the cost of additional refining of petrol, which reduced costs for consumers and motorists. However, some people were concerned about the use of a lead compound that was being released from the exhaust of cars. If you had been part of the debate in the 1920s, what arguments would you make against the use of tetraethyl lead?

Critical and creative thinking

18 Some catalysts work by providing a surface on which reactions can occur. These surface catalysts work by allowing the reacting particles to interact together on the surface of the catalyst.

a Why would attracting particles onto a surface of another chemical encourage a chemical change to occur?

b Why would a substance that actually bonded chemically to the reacting particles not make a good catalyst?

c Give an example of the use of a surface catalyst, describing in detail the chemical reaction.

d Use your knowledge of collision theory to explain why most catalysts are used in the form of a powder or fine mesh.

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19 Haemoglobin is responsible for the transport of oxygen in the bloodstream from your lungs to the cells in your body, where respiration takes place. The oxygen molecules interact with the haemoglobin and combine to form oxyhaemoglobin. When the blood reaches the cells (having been pumped through the heart), the oxyhaemoglobin releases the oxygen. If carbon monoxide molecules are breathed into the lungs, they can attach themselves permanently to haemoglobin molecules, thus preventing the essential transfer of oxygen. Carbon monoxide poisoning is a very real danger and many Australians are killed by it each year.

a Use a diagram to represent the transfer of oxygen from the lungs to body cells.

b Explain why the chemical changes occurring between haemoglobin and oxygen need to be reversible.

c Do you think that the reaction between carbon monoxide and haemoglobin is reversible? Explain your answer.

d Suggest two ways that carbon monoxide poisoning can be prevented.

Research

20 Choose one of the following topics for a research project. Present your report in a format of your own choosing.

> **Rare metals**
>
> A range of rare metals is used in microelectronic devices. Many of these metals, such as tantalum and niobium, are sourced from Australia. Find out more about where these metals are found in Australia, in what form they occur naturally and what chemical processes are used to extract the pure metals.

> **Minamata disease**
>
> Minamata disease is caused by people eating seafood contaminated with a compound containing mercury. The condition was called a 'disease' because when it was first described no one knew its cause. Research this disease and present your findings using the following headings.
> - Symptoms
> - Cause
> - Action taken
> - Lasting consequences (for the people affected, chemical industry and the world)

> **Ozone and CFCs**
>
> Although governments limited the use of CFCs to reduce the damage to the ozone layer, it took time for many countries to recognise the risks and act on the advice from scientists. Investigate how evidence for ozone depletion was discovered and how countries responded to the evidence, and discuss implications for possible future action (or inaction) of governments based on scientific advice.

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KEY WORDS

4

biodegradable
this means an object or a substance can be broken down by bacteria, fungi and other living organisms

catalyst
a substance that increases the rate of a reaction but is not used up in the reaction

collision theory
a theory that states the particles involved in a chemical reaction must collide in order to react

combustion
a reaction that involves oxygen and releases light and heat energy

concentrated acid
this refers to an acid solution with a high concentration of hydrogen ions

concentration
the number of active molecules in a set volume of solution

decomposition
a reaction that involves the breakdown of a compound into simpler substances

dilute
a small number of active molecules (such as acid) in a solution

green chemistry
this is a branch of chemistry that deals with developing processes and products to reduce or remove hazardous substances and minimise impact on the environment

hydrocarbon
a molecule that contains only carbon and hydrogen atoms

monomer
a small molecule from which polymers are made

neutralisation
a reaction in which an acid and a base combine to produce a metal salt and water

non-degradable
not subject to or capable of decomposition

oxidation reaction
a reaction that involves the combination of oxygen with a fuel or metal

polymer
giant molecule formed by the joining of many smaller repeating molecules (monomers) together

polymerisation
process of joining of smaller units (monomers) to form a long-chain molecule (polymer)

precipitate
an insoluble compound formed in a precipitation reaction

precipitation reaction
a reaction that is used to produce solid products from solutions of ionic substances

reaction rate
how fast or slow a reaction proceeds

solution
a mixture of a solute dissolved in a solvent such as water

spectator ion
an ion that does not take part in a chemical reaction

strength
a strong acid readily releases a hydrogen ion in a chemical reaction. 'Strength' can also be used to describe the bond between different atoms

strong acid
an acid which most of its molecules release hydrogen ions into solution

synthesis
a reaction that involves the building up of compounds by combining simpler substances, normally elements

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