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Chemistry

Fourth Edition

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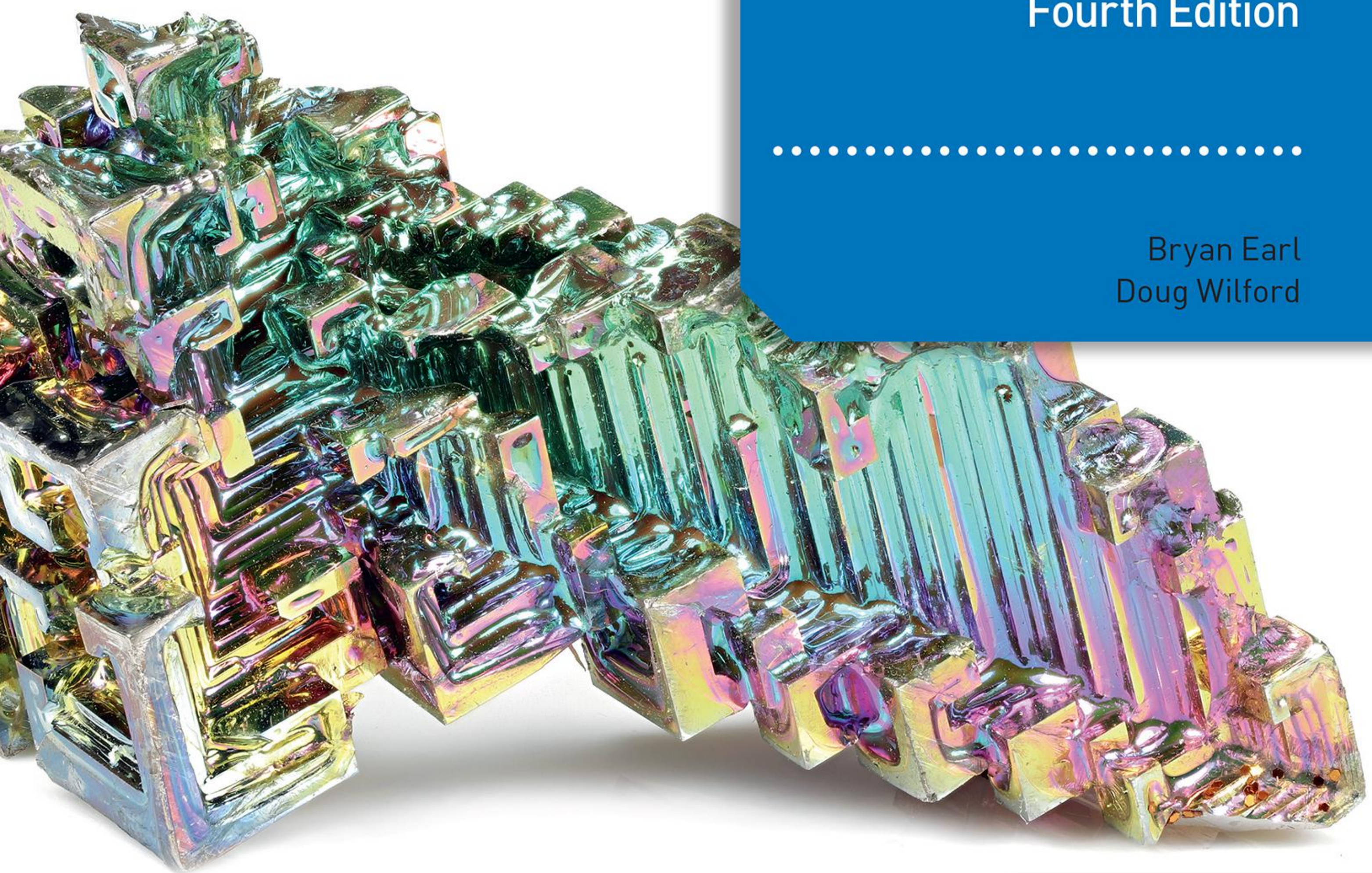

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1 States of matter

FOCUS POINTS

★ What is the structure of matter?
★ What are the three states of matter?
★ How does kinetic particle theory help us understand how matter behaves?

In this first chapter, you will look at the three states of matter: solids, liquids and gases. The structure of these states of matter and how the structures can be changed from one to another is key to understanding the states of matter.

You will use the kinetic particle theory to help explain how matter behaves, so you can understand the difference in the properties of the three states of matter and how the properties are linked to the strength of bonds between the particles they contain. Why, for example, can you compress gases but cannot compress a solid? By the end of this chapter, you should be able to answer this question and use the ideas involved to help you to understand many everyday observations, such as why car windows mist up on a cold morning or why dew forms on grass at night.

1.1 Solids, liquids and gases

Chemistry is about what **matter** is like and how it behaves, and our explanations and predictions of its behaviour. What is matter? This word is used to cover all the substances and materials from which the physical universe is composed. There are many millions of different substances known, and all of them can be categorised as solids, liquids or gases (Figure 1.1). These are what we call the three states of matter.

a Solid

b Liquid

c Gas

▲ **Figure 1.1** Water in three different states

A **solid**, at a given temperature, has a definite volume and shape which may be affected by changes in temperature. Solids usually increase slightly in size when heated, called **expansion** (Figure 1.2), and usually decrease in size if cooled, called **contraction**.

A **liquid**, at a given temperature, has a fixed volume and will take up the shape of any container into which it is poured. Like a solid, a liquid's volume is slightly affected by changes in temperature.

A **gas**, at a given temperature, has neither a definite shape nor a definite volume. It will take up the shape of any container into which it is placed and will spread out evenly within it. Unlike solids and liquids, the volumes of gases are affected greatly by changes in temperature.

Liquids and gases, unlike solids, are compressible. This means that their volume can be reduced by the application of pressure. Gases are much more compressible than liquids.

▲ **Figure 1.2** Without expansion gaps between the rails, the track would buckle in hot weather

1.2 The kinetic particle theory of matter

The **kinetic particle theory** helps to explain the way that matter behaves. It is based on the idea that all matter is made up of tiny particles. This theory explains the physical properties of matter in terms of the movement of the particles from which it is made.

The main points of the theory are:

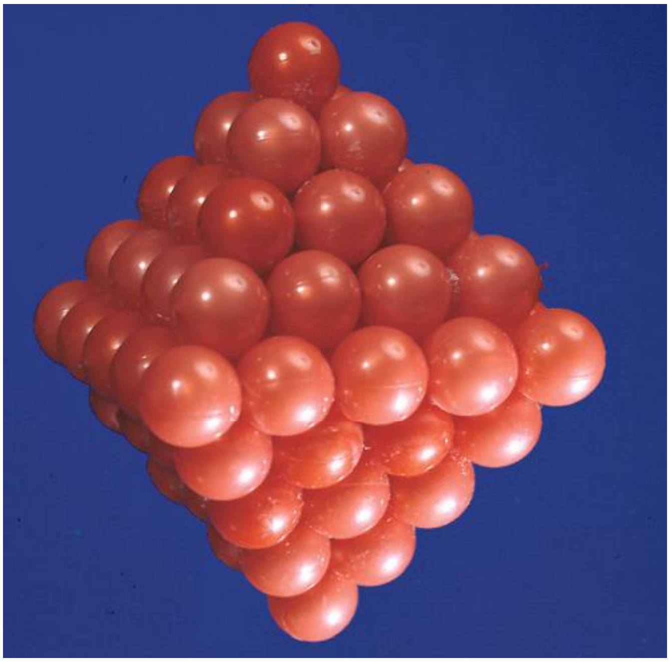
- All matter is made up of tiny, moving particles, invisible to your eye. Different substances have different types of particles (atoms, molecules or ions) of varying sizes.
- The particles move all the time. The higher the temperature, the faster they move on average.
- Heavier particles move more slowly than lighter ones at a given temperature.

The kinetic particle theory can be used as a scientific model to explain how the arrangement of particles relates to the properties of the three states of matter.

Explaining the states of matter

In a solid, the particles attract one another. There are attractive forces between the particles which hold them close together. The particles have little freedom of movement and can only vibrate about a fixed position. They are arranged in a regular manner, which explains why many solids form **crystals**.

It is possible to model such crystals by using spheres to represent the particles. For example, Figure 1.3a shows spheres built up in a regular way to represent the structure of a chrome alum crystal. The shape is very similar to that of a part of an actual chrome alum crystal (Figure 1.3b).

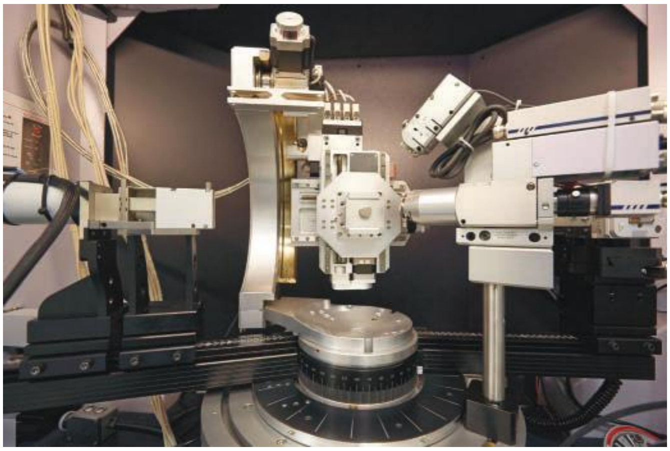


a A model of a chrome alum crystal

b An actual chrome alum crystal

▲ **Figure 1.3**

Studies using X-ray crystallography (Figure 1.4) have confirmed how particles are arranged in crystal structures. When crystals of a pure substance form under a given set of conditions, the particles are always arranged (or packed) in the same way. However, the particles may be packed in different ways in crystals of different substances. For example, common salt (sodium chloride) has its particles arranged to give cubic crystals as shown in Figure 1.5.



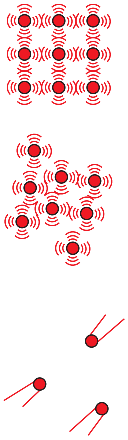
▲ **Figure 1.4** A modern X-ray crystallography instrument used for studying crystal structure

▲ **Figure 1.5** Sodium chloride crystals

In a liquid, the particles are still close together but they move around in a random way and often collide with one another. The forces of attraction between the particles in a liquid are weaker than those in a solid. Particles in the liquid form of a substance have more energy on average than the particles in the solid form of the same substance.

In a gas, the particles are relatively far apart. They are free to move anywhere within the container in which they are held. They move randomly at very high velocities, much more rapidly than those in a liquid. They collide with each other, but less often than in a liquid, and they also collide with the walls of the container. They exert virtually no forces of attraction on each other because they are relatively far apart. Such forces, however, are very significant. If they did not exist, we could not have solids or liquids (see Changes of state, p. 4).

The arrangement of particles in solids, liquids and gases is shown in Figure 1.6.



Solid
Particles only vibrate about fixed positions. Regular structure.

Liquid
Particles have some freedom and can move around each other. Collide often.

Gas
Particles move freely and at random in all the space available. Collide less often than in liquid.

▲ **Figure 1.6** The arrangement of particles in solids, liquids and gases

Test yourself

1 When a metal (such as copper) is heated, it expands. Explain what happens to the metal particles as the solid metal expands.

1.3 Changes of state

The kinetic particle theory model can be used to explain how a substance changes from one state to another. If a solid is heated, the particles vibrate faster as they gain energy. This makes them 'push' their neighbouring particles further away. This causes an increase in the volume of the solid, such that the solid expands, and we can say that expansion has taken place.

Eventually, the heat energy causes the forces of attraction to weaken. The regular pattern of the structure breaks down, and the particles can now move around each other. The solid has melted. The temperature at which this takes place is called the **melting point** of the substance. The temperature of a melting pure solid will not rise until it has all melted. When the substance has become a liquid, there are still very significant forces of attraction between the particles, which is why the substance is a liquid and not a gas.

Solids which have high melting points have stronger forces of attraction between their particles than those which have low melting points. A list of some substances with their corresponding melting and boiling points is shown in Table 1.1.

▼ **Table 1.1** Melting points and boiling points of substances

Substance	Melting point/°C	Boiling point/°C
Aluminium	661	2467
Ethanol	–117	79
Magnesium oxide	827	3627
Mercury	–30	357
Methane	–182	–164
Oxygen	–218	–183
Sodium chloride	801	1413
Sulfur	113	445
Water	0	100

If a liquid is heated, the average energy of the particles increases and the particles will move around even faster. Some particles at the surface of the liquid have enough energy to overcome the forces of attraction between themselves and the other particles in the liquid and they escape to form a gas. The liquid begins to **evaporate** as a gas is formed.

Eventually, a temperature is reached at which the particles are trying to escape from the liquid so quickly that bubbles of gas actually start to form inside the liquid. This temperature is called the **boiling point** of the substance. At the boiling point, the pressure of the gas created above the liquid equals that of the air, which is **atmospheric pressure**.

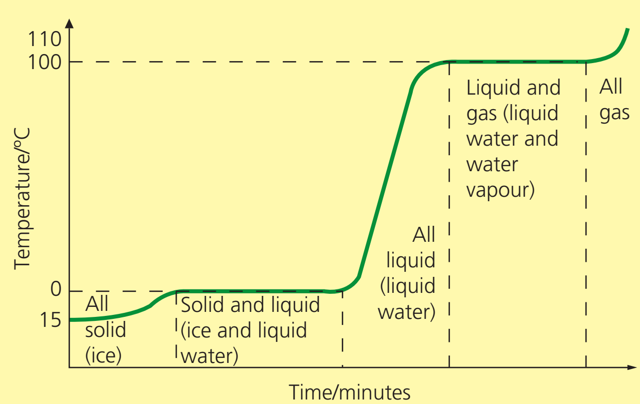
Liquids with high boiling points have stronger forces between their particles than liquids with low boiling points.

When a gas is cooled, the average energy of the particles decreases and the particles move closer together. The forces of attraction between the particles now become significant and cause the gas to **condense** into a liquid. When a liquid is cooled, it freezes to form a solid. Energy is released in each of these changes.

Changes of state are examples of physical changes. Whenever a physical change of state occurs, the temperature remains constant during the change. During a physical change, no new substance is formed.

Heating and cooling curves

The graph shown in Figure 1.7 was drawn by plotting the temperature of water as it was heated steadily from –15°C to 110°C. You can see from the curve that changes of state have taken place. When the temperature was first measured, only ice was present. After a short time, the curve flattens showing that even though heat energy is being put in, the temperature remains constant.



▲ **Figure 1.7** Graph of temperature against time for the change from ice at –15°C to water to steam

Practical skills

Changes of state

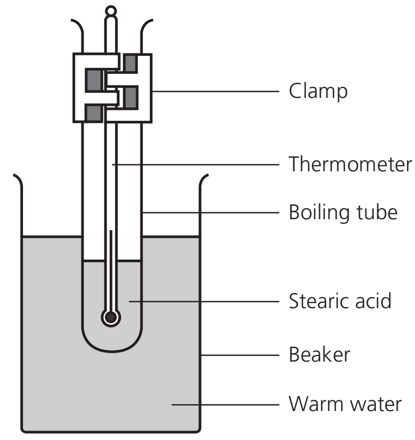
For safe experiments/demonstrations which are related to this chapter, please refer to the *Cambridge IGCSE Chemistry Practical Skills Workbook*, which is also part of this series.

Safety

- Eye protection must be worn.
- Take care when handling and using hot water.

The apparatus on the right was set up to obtain a cooling curve for stearic acid. The stearic acid was placed into a boiling tube which was then placed in a beaker of water that was heated to 80°C, which is above the melting point of stearic acid.

The boiling tube was then removed from the beaker and the temperature of the stearic acid was recorded every minute for 12 minutes using the thermometer to stir the stearic acid while it was a liquid.



1 Why was it important to remove the boiling tube with the stearic acid from the water?
2 Why was the stearic acid stirred with the thermometer?
3 Why were temperature readings taken every minute for 12 minutes?

The following data was obtained from the experiment:

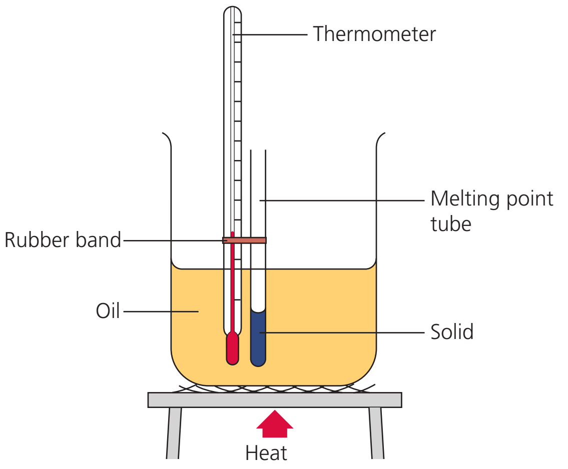
Time/mins	0	1	2	3	4	5	6	7	8	9	10	11	12
Temperature/°C	79	76	73	70	69	69	69	69	69	67	64	62	60

4 Draw and label axes for plotting this data.
5 Plot the points and draw a line of best fit.
6 a At what temperature did the stearic acid begin to change state?
  b How could you tell this from your graph?
  c Explain what is happening at this temperature.

In ice, the particles of water are close together and are attracted to one another. For ice to melt, the particles must obtain sufficient energy to overcome the forces of attraction between the water particles, so that relative movement can take place. The heat energy is being used to overcome these forces.

The temperature will begin to rise again only after all the ice has melted. Generally, the heating curve for a pure solid always stops rising at its melting point and gives rise to a sharp melting point. A sharp melting point therefore indicates that it is a pure sample. The addition or presence of impurities lowers the melting point.

You can find the melting point of a substance using the apparatus shown in Figure 1.8. The addition or presence of impurities lowers the melting point. A mixture of substances also has a lower melting point than a pure substance, and the melting point will be over a range of temperatures and not sharp.



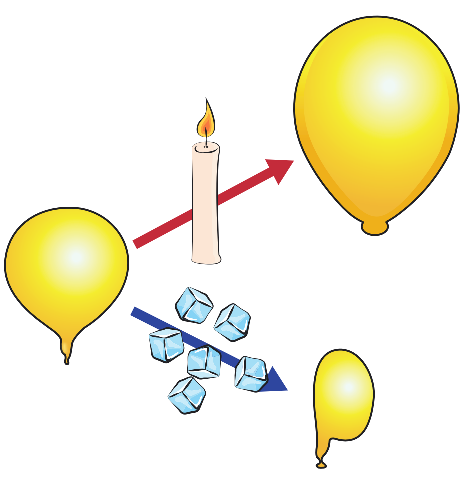
▲ **Figure 1.8** If a substance, such as the solid in the melting point tube, is heated slowly, this apparatus can be used to find the melting point of the substance

In the same way, if you want to boil a liquid, such as water, you have to give it some extra energy. This can be seen on the graph in Figure 1.7, where the curve levels out at 100°C – the boiling point of water.

Solids and liquids can be identified from their characteristic melting and boiling points.

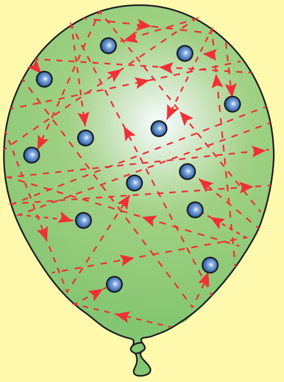
The reverse processes of condensing and freezing occur when a substance is cooled. Energy is given out when the gas condenses to the liquid and the liquid freezes to give the solid.

1.4 The effects of temperature and pressure on the volume of a gas



▲ **Figure 1.9** Temperature changes the volume of the air in a balloon. Higher temperatures increase the volume of the balloon and cold temperatures reduce its volume.

What do you think has caused the difference between the balloons in Figure 1.9? The pressure inside a balloon is caused by the gas particles striking the inside surface of the balloon. At a higher temperature, there is an increased pressure inside the balloon (Figure 1.10). This is due to the gas particles having more energy and therefore moving around faster, which results in the particles striking the inside surface of the balloon more frequently, which leads to an increase in pressure.



▲ **Figure 1.10** The gas particles striking the surface create the pressure

Since the balloon is made from an elastic material, the increased pressure causes the balloon to stretch and the volume increases. An increase in volume of a gas with increased temperature is a property of all gases. French scientist J.A.C. Charles made an observation like this in 1781 and concluded that when the temperature of a gas increased, the volume also increased at a fixed pressure. We can extend this idea to suggest that changing the pressure of a fixed volume of a gas must have an effect on the temperature of the gas. If you have ever used a bicycle pump to blow up a bicycle tyre then you may have felt the pump get hotter the more you used it. As you use the pump you increase pressure on the air in the pump. Such an increase in pressure causes the gas molecules to move closer together so the molecules to collide more frequently and more frictional forces come into play, which causes the temperature to rise. In addition, as the molecules are forced closer to one another, intermolecular bonds form, again increasing the temperature of the gas. As the temperature of the gas increases, this also causes the molecules to move faster, causing even more collisions.

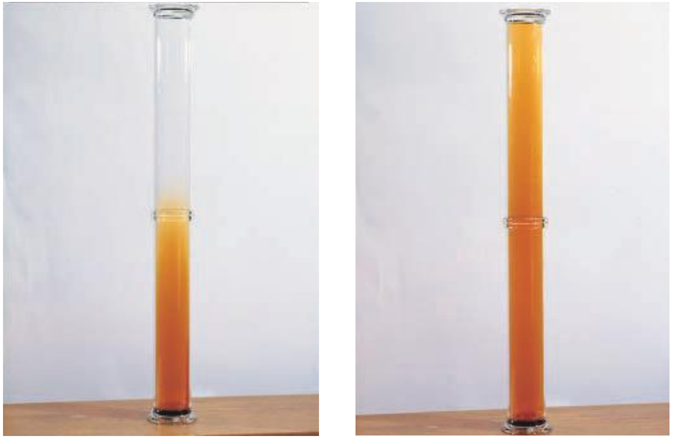
Test yourself

2 Why do gases expand more than solids for the same increase in temperature?
3 Ice on a car windscreen will disappear as you drive along, even without the heater on. Explain why this happens.
4 When salt is placed on ice, the ice melts. Explain why this happens.
5 Draw and label a graph of water at 100°C being allowed to cool to −5°C.

1.5 Diffusion

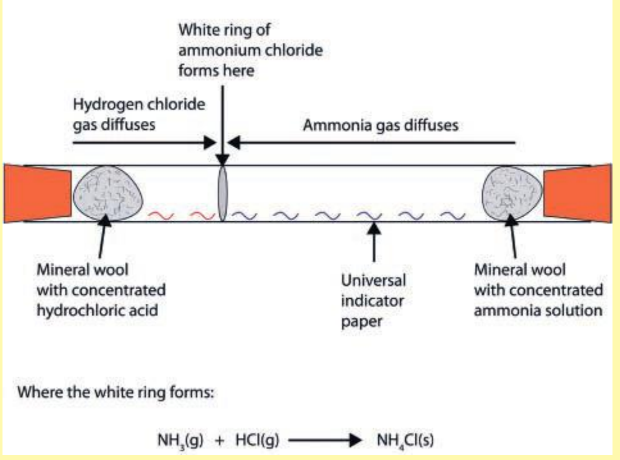
When you go through the door of a restaurant, you can often smell the food being cooked. For this to happen, gas particles must be leaving the pans the food is being cooked in and be spreading out through the air in the restaurant. This spreading out of a gas is called **diffusion** and it takes place in a haphazard and random way.

All gases diffuse to fill the space available. Figure 1.11 shows two gas jars on top of each other. Liquid bromine has been placed in the bottom gas jar (left photo) and then left for a day (right photo). The brown-red fumes are gaseous bromine that has spread evenly throughout both the gas jars from the liquid present in the lower gas jar.



▲ **Figure 1.11** After 24 hours the bromine fumes have diffused throughout both gas jars

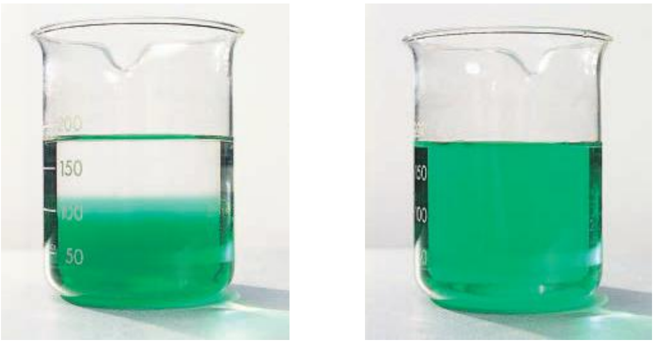
Diffusion can be explained by the **kinetic particle theory**. This theory states that all matter is made up of many small particles which are constantly moving. In a solid, as we have seen, the particles simply vibrate about a fixed point. However, in a gas, the particles move randomly past one another, colliding with each other.



▲ **Figure 1.12** Hydrochloric acid (left) and ammonia (right) diffuse at different rates

Gases diffuse at different rates. If one piece of cotton wool is soaked in concentrated ammonia solution and another is soaked in concentrated hydrochloric acid and these are put at opposite ends of a dry glass tube, then after a few minutes a white cloud of ammonium chloride appears. Figure 1.12 shows the position at which the two gases meet and react. The white cloud forms in the position shown because the ammonia particles are lighter; they have a smaller relative molecular mass (Chapter 4, p. 54) than the hydrogen chloride particles (released from the hydrochloric acid) and so move faster, such that the gas diffuses more quickly. (See *Chemistry Practical Skills Workbook* for more detail of this experiment.) This experiment is a teacher demonstration only, which must be carried out in a fume cupboard. If considering carrying out this practical, teachers should refer to the *Practical Skills Workbook* for full guidance and safety notes.

Diffusion also takes place in liquids (Figure 1.13) but it is a much slower process than in gases. This is because the particles of a liquid move much more slowly.



▲ **Figure 1.13** Diffusion of green food colouring can take days to reach the stage shown on the right

When diffusion takes place between a liquid and a gas, it is known as intimate mixing. Kinetic particle theory can be used to explain this process. It states that collisions are taking place randomly between particles in a liquid or a gas and that there is sufficient space between the particles of one substance for the particles of the other substance to move into.

Test yourself

6 When a jar of coffee is opened, people can often smell it from anywhere in the room. Use the kinetic particle theory to explain how this happens.
7 Describe, with the aid of diagrams, the diffusion of a drop of green food colouring added to the bottom of a beaker.
8 Explain why diffusion is faster in gases than in liquids.

9 Explain why a gas with a low relative molecular mass can diffuse faster than a gas with a high relative molecular mass at the same temperature.

Revision checklist

After studying Chapter 1 you should be able to:

- ✔ State the three states of matter and describe the structure arrangement of the particles in each.
- ✔ Explain the properties of the three states of matter using ideas about the separation and movement of particles.
- ✔ Name the changes of state and describe what happens to the particles in a substance when they occur.

- ✔ Explain what is happening when a substance changes state.
- ✔ Describe what happens to a given amount of gas when temperature and/or pressure decreases and increases.
- ✔ Use the kinetic particle theory to explain the effects of pressure and temperature on the volume of a gas.
- ✔ Describe the process of diffusion and explain why gases diffuse.
- ✔ Describe and explain the rate of diffusion of a gas in terms of its relative molecular mass.

Exam-style questions

1 **a** Sketch diagrams to show the arrangement of particles in:
- **i** solid oxygen [1]
- **ii** liquid oxygen [1]
- **iii** oxygen gas. [1]

b Describe how the particles move in these three states of matter. [3]

c Explain, using the kinetic particle theory, what happens to the particles in oxygen as it is cooled down. [3]

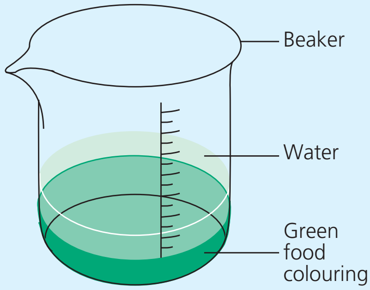
2 Explain the meaning of each of the following terms. In your answer include an example to help with your explanation.
- **a** expansion [2]
- **b** contraction [2]
- **c** physical change [2]
- **d** diffusion [2]
- **e** random motion [2]

3 **a** Explain why solids do not diffuse. [2]

b Give two examples of diffusion of gases and liquids found in your house. [2]

4 Explain the following, using the ideas you have learned about the kinetic particle theory:
- **a** When you take a block of butter out of the fridge, it is quite hard. However, after 15 minutes it is soft enough to spread. [2]
- **b** When you come home from school and open the door, you can smell food being cooked. [2]
- **c** A football is blown up until it is hard on a hot summer's day. In the evening the football feels softer. [2]
- **d** When a person wearing perfume enters a room, it takes several minutes for the smell to reach the back of the room. [2]

5 Some green food colouring was carefully added to the bottom of a beaker of water using a syringe. The beaker was then covered and left for several days.

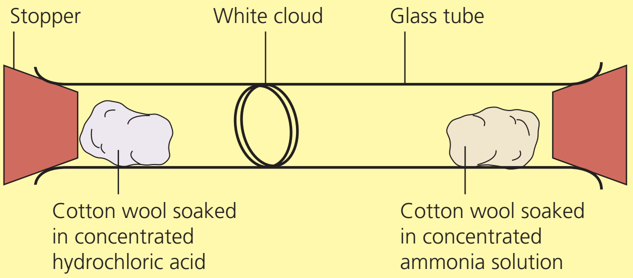


a Describe what you would observe after:
- **i** a few hours [1]
- **ii** several days. [1]

b Explain your answer to Question 5a using your ideas of the kinetic particle theory. [2]

c State the physical process that takes place in this experiment. [1]

6 The apparatus shown below was set up.



When this apparatus is used, the following things are observed. Explain why each of these is observed.
- **a** A white cloud is formed. [1]
- **b** It took a few minutes before the white cloud formed. [1]
- **c** The white cloud formed further from the cotton wool soaked in ammonia than that soaked in hydrochloric acid. [2]
- **d** Cooling the concentrated ammonia and hydrochloric acid before carrying out the experiment increased the time taken for the white cloud to form. [1]

2 Atoms, elements and compounds

FOCUS POINTS

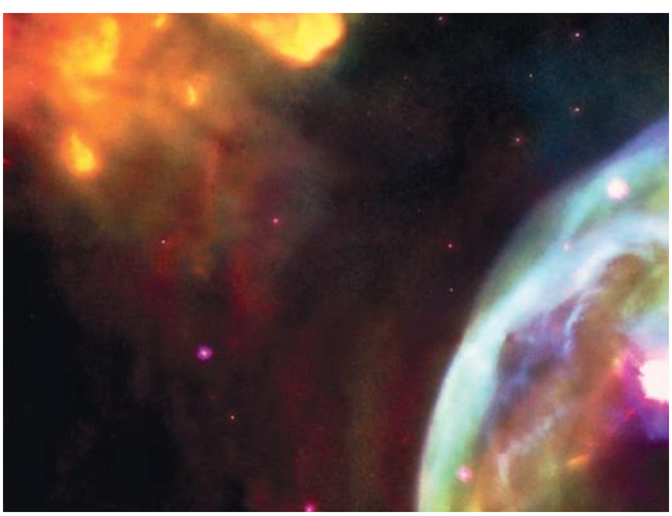
★ How are elements, molecules, ions, compounds and mixtures different from each other?
★ How do the properties of the particles in an atom lead to an atom's structure?
★ What do oxidation and reduction mean?
★ What is an isotope?

In Chapter 1, you saw that all matter is made up of particles. In this chapter you will look closely at these particles and see that they are made up of atoms. Atoms are the smallest part of elements. An element is made up of one type of atom and can be either a metal or a non-metal. Metals and non-metals have different properties.

You will look at how atoms of different elements can combine to form substances called compounds, and how this combining occurs in a chemical reaction. By the end of the chapter you should be able to write a simple word or symbol equation to represent these reactions.

You will see that although atoms are the smallest part of an element that shares the chemical properties of that element, they are made from even smaller particles. By learning about the properties and behaviour of these smaller particles (electrons, protons and neutrons), you will be able to see how they affect the chemical properties of elements and compounds.

The universe is made up of a very large number of substances (Figure 2.1), and our own part of the universe is no exception. When we examine this vast array of substances more closely, it is found that they are made up of some basic substances which were given the name **elements** in 1661 by Robert Boyle.



▲ **Figure 2.1** Structures in the universe, such as stars, planets and meteorites, are made of millions of substances. These are made up mainly from just 91 elements, all of which occur naturally on the Earth

In 1803, John Dalton suggested that each element was composed of its own kind of particles, which he called **atoms**. Atoms are much too small to be seen. We now know that about 20×10^6 of them would stretch over a length of only 1 cm.

2.1 Elements

As well as not being able to be broken down into a simpler substance, each element is made up of only one kind of atom. The word atom comes from the Greek word *atomos* meaning 'unsplittable'. For example, aluminium is an element which is made up of only aluminium atoms. It is not possible to obtain a simpler substance chemically from the aluminium atoms. You can only combine it with other elements to make more complex substances, such as aluminium oxide, aluminium nitrate or aluminium sulfate.

One hundred and eighteen elements have now been identified. Twenty of these do not occur in nature and have been made artificially by scientists. They include elements such as curium and flerovium. Ninety-eight of the elements occur naturally and range from some very reactive gases, such as fluorine and chlorine, to gold and platinum, which are unreactive elements. A physical property is any characteristic of a substance that we can measure. The elements have different properties that we can measure, and we can then classify them according to those properties.

All elements can be classified according to their various properties. A simple way to do this is to classify them as **metals** or **non-metals** (Figures 2.2 and 2.3). Table 2.1 shows the physical property data for some common metallic and non-metallic elements. You will notice from Table 2.1 that many metals have high densities, high melting points and high boiling points, and that most non-metals have low densities, low melting points and low boiling points. Table 2.2 summarises the different properties of metals and non-metals.

a Gold is very decorative

b Aluminium has many uses in the aerospace industry

c These coins contain nickel

▲ **Figure 2.2** Some metals

▼ **Table 2.1** Physical data for some metallic and non-metallic elements at room temperature and pressure

Element	Metal or non-metal	Density/ g cm^{-3}	Melting point/°C	Boiling point/°C
Aluminium	Metal	2.70	660	2580
Copper	Metal	8.92	1083	2567
Gold	Metal	19.29	1065	2807
Iron	Metal	7.87	1535	2750
Lead	Metal	11.34	328	1740
Magnesium	Metal	1.74	649	1107
Nickel	Metal	8.90	1453	2732
Silver	Metal	10.50	962	2212
Zinc	Metal	7.14	420	907
Carbon	Non-metal	2.25	Sublimes at 3642	
Hydrogen	Non-metal	0.07[a]	–259	–253
Nitrogen	Non-metal	0.88[b]	–210	–196
Oxygen	Non-metal	1.15[c]	–218	–183
Sulfur	Non-metal	2.07	113	445

Source: Earl B., Wilford L.D.R. Chemistry data book. Nelson Blackie, 1991 a: at –254°C; b: at –197°C; c: at –184°C.

The elements also have chemical properties, which are characteristics or behaviours that may be observed when the substance undergoes a chemical change or reaction. A discussion of the chemical properties of some metals and non-metals is given in Chapters 9 and 10.

▼ **Table 2.2** How the properties of metals and non-metals compare

Property	Metal	Non-metal
Physical state at room temperature	Usually solid (occasionally liquid)	Solid, liquid or gas
Malleability	Good	Poor – usually soft or brittle
Ductility	Good	
Appearance (solids)	Shiny (lustrous)	Dull
Melting point	Usually high	Usually low
Boiling point	Usually high	Usually low
Density	Usually high	Usually low
Conductivity (thermal and electrical)	Good	Very poor

Test yourself

1 Using Tables 2.1 and 2.2, pick the 'odd one out' in the following group and explain why it is different from the others.
zinc copper oxygen lead

2 Using Tables 2.1 and 2.2, pick the 'odd one out' in the following group and explain why it is different from the others.
carbon nitrogen iron sulfur

3 Using Tables 2.1 and 2.2, pick the 'odd one out' in the following group of properties of metals and explain why it is different from the others.
- high melting point
- high density
- soft or brittle
- good electrical conductivity

a A premature baby needs oxygen

b Artists often use charcoal (carbon) to produce an initial sketch

c Neon is used in advertising signs

▲ **Figure 2.3** Some non-metals

Atoms – the smallest particles

Everything is made up of billions of extremely small atoms. The smallest atom is hydrogen, and we represent each hydrogen atom as a sphere having a diameter of 0.000 000 07 mm (or 7×10^{-8} mm) (Table 2.3). Atoms of different elements have different diameters as well as different masses.

▼ **Table 2.3** Sizes of atoms

Atom	Diameter of atom/mm	Masses/g
Hydrogen	7×10^{-8}	1.67×10^{-24}
Oxygen	12×10^{-8}	2.66×10^{-23}
Sulfur	20.8×10^{-8}	5.32×10^{-23}

Chemists use shorthand symbols to label the elements and their atoms. The symbol consists of one, two or three letters, the first of which is always a capital. The initial letter of the element's name is often used and, where several elements have the same initial letter, another letter from the name is added. For example, **C** is used for **carbon**, **Ca** for **calcium** and **Cl** for **chlorine**. Some symbols seem to have no relationship to the name of the element, for example, **Na** for **sodium** and **Pb** for **lead**. These symbols come from their Latin names: **na**trium for sodium and **pl**um**b**um for lead. A list of some common elements and their symbols is given in Table 2.4.

▼ **Table 2.4** Some common elements and their symbols. The Latin names of some of the elements are given in brackets

Element	Symbol	Physical state at room temperature and pressure
Aluminium	Al	Solid
Argon	Ar	Gas
Barium	Ba	Solid
Boron	B	Solid
Bromine	Br	Liquid
Calcium	Ca	Solid
Carbon	C	Solid
Chlorine	Cl	Gas
Chromium	Cr	Solid
Copper (Cuprum)	Cu	Solid
Fluorine	F	Gas
Germanium	Ge	Solid
Gold (Aurum)	Au	Solid
Helium	He	Gas
Hydrogen	H	Gas
Iodine	I	Solid
Iron (Ferrum)	Fe	Solid
Lead (Plumbum)	Pb	Solid
Magnesium	Mg	Solid
Mercury (Hydragyrum)	Hg	Liquid
Neon	Ne	Gas
Nitrogen	N	Gas
Oxygen	O	Gas
Phosphorus	P	Solid
Potassium (Kalium)	K	Solid
Silicon	Si	Solid
Silver (Argentum)	Ag	Solid
Sodium (Natrium)	Na	Solid
Sulfur	S	Solid
Tin (Stannum)	Sn	Solid
Zinc	Zn	Solid

Molecules

The atoms of some elements are joined together in small groups. These small groups of atoms are called **molecules.** The atoms of some elements are always joined in pairs, for example, hydrogen, oxygen, nitrogen, fluorine, chlorine, bromine and iodine. They are known as **diatomic** molecules. In chemical shorthand the molecule of chlorine shown in Figure 2.4 is written as Cl_2. The atoms of some other elements, such as phosphorus and sulfur, join in larger numbers, four and eight respectively, which we write as P_4 and S_8.

The complete list of the elements with their corresponding symbols is shown in the **Periodic Table** on p. 135.

The gaseous elements helium, neon, argon, krypton, xenon and radon (which are all gases at 0°C at sea level and atmospheric pressure) are composed of separate, individual atoms. When an element exists as separate atoms, then the molecules are said to be **monatomic**. In chemical shorthand these monatomic molecules are written as He, Ne, Ar, Kr, Xe and Rn respectively.

Cl——Cl

a Represented by a letter-and-stick model

b Represented by a space-filling model

▲ **Figure 2.4** A chlorine molecule

Molecules are not always formed by atoms of the same type joining together as elemental molecules. Most molecules consist of atoms of different elements, for example, water exists as molecules containing oxygen and hydrogen atoms. We will learn more about these in the next section.

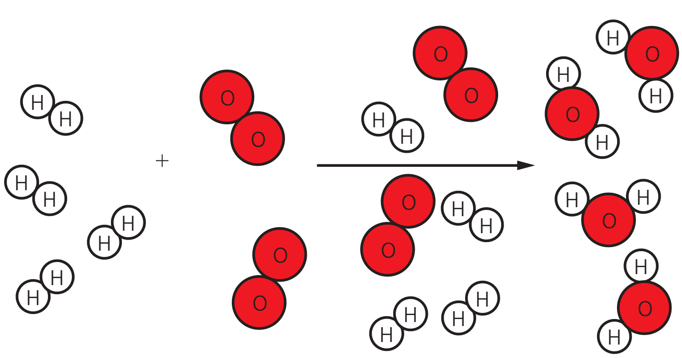
Test yourself

4 How many atoms of hydrogen would have to be placed side by side along the edge of your ruler to fill just one of the 1 mm divisions?
5 How would you use chemical shorthand to write a representation of the molecules of iodine and fluorine?
6 Using the Periodic Table on p. 135, write down the symbols for each of these elements and give their physical state at room temperature.
   a chromium
   b krypton
   c osmium

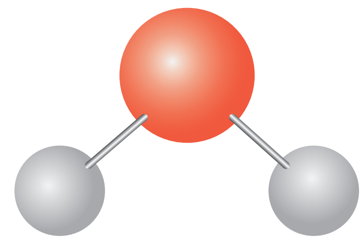
2.2 Compounds

Compounds are pure substances which are formed when two or more elements chemically combine together. A **pure substance** is a material that has a constant composition (is homogeneous) and has consistent properties throughout. Water is a simple compound formed from the elements hydrogen and oxygen (Figure 2.5). This combining of the elements can be represented by a word equation:

hydrogen +	oxygen	→	water
Hydrogen a pure element	Oxygen a pure element	Hydrogen and oxygen mixed together	Water a pure compound formed from hydrogen burning in oxygen



a The element hydrogen reacts with the element oxygen to produce the compound water



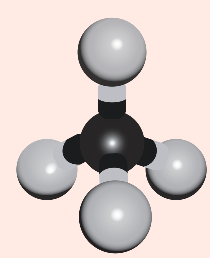
b A model of water showing 2 H atoms and one O atom. Models such as this can be built to show what a compound looks like

▲ **Figure 2.5**

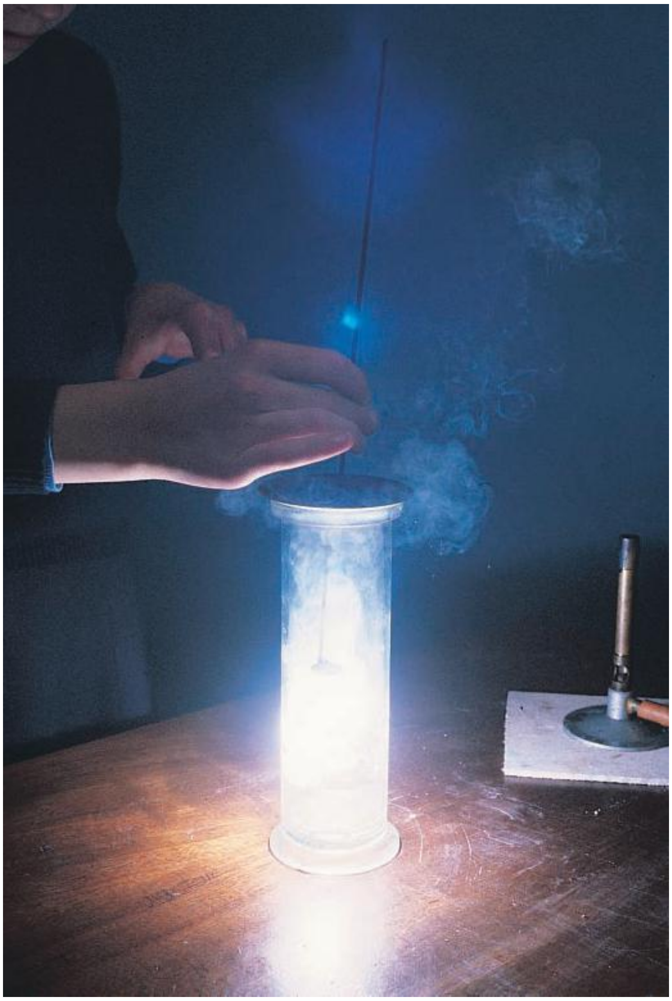
Water molecules contain two atoms of hydrogen and one atom of oxygen, and water has the **chemical formula** H_2O. If there is only one atom of an element in the molecule, no number is required in the formula, only its symbol, as in the case of oxygen in the water molecule H_2O.

Test yourself

7 What is the formula for the molecule shown in the diagram which contain carbon (black sphere) and hydrogen (white spheres)?



Elements other than hydrogen will also react with oxygen to form compounds called oxides. For example, magnesium reacts violently with oxygen gas to form the white powder magnesium oxide (Figure 2.6). This reaction is accompanied by a release of energy as new chemical bonds are formed.



▲ **Figure 2.6** Magnesium burns brightly in oxygen to produce magnesium oxide

When a new substance is formed during a chemical reaction, a **chemical change** has taken place.

magnesium + oxygen → magnesium oxide

When substances such as hydrogen and magnesium combine with oxygen in this way, they are said to have been oxidised, and this process is known as **oxidation**.

Reduction is the opposite of oxidation. In this process oxygen is removed rather than added.

Key definitions

Oxidation is gain of oxygen.

Reduction is loss of oxygen.

Any chemical process that involves reduction and oxidation is known as a **redox** reaction. For example, to extract iron from iron(III) oxide, the oxygen has to be removed. The reduction of iron(III) oxide can be done in a **blast furnace** using carbon monoxide. The iron(III) oxide loses oxygen to the carbon monoxide and is reduced to iron.

Carbon monoxide is the **reducing agent**. A reducing agent is a substance that reduces another substance during a redox reaction. In the reaction, carbon monoxide is oxidised to carbon dioxide by the iron(III) oxide. In this process, the iron(III) oxide is the **oxidising agent**. An oxidising agent is a substance which oxidises another substance during a redox reaction.

We can write the redox reaction as:

iron(III) oxide + carbon monoxide → iron + carbon dioxide

Test yourself

8 Zinc is extracted from its ore zinc blende in a furnace by a redox reaction. What does the term 'redox reaction' mean?

9 Identify the oxidising and reducing agents in each of the following reactions:

a copper(II) oxide + hydrogen → copper + water

b tin(II) oxide + carbon → tin + carbon dioxide

c $PbO(s) + H_2(g) \rightarrow Pb(s) + H_2O(l)$.

For a further discussion of oxidation and reduction see Chapter 3 (p. 31) and Chapter 5 (p. 71).

Key definitions

Redox reactions involve simultaneous oxidation and reduction.

An **oxidising agent** is a substance that oxidises another substance and is itself reduced.

A **reducing agent** is a substance that reduces another substance and is itself oxidised.

Practical skills

Heating copper

For safe experiments/demonstrations which are related to this chapter, please refer to the *Cambridge IGCSE Chemistry Practical Skills Workbook*, which is also part of this series.

Safety

- Eye protection must be worn.
- Take care when handling hot apparatus.
- Handle the copper with tongs or tweezers, not your fingers.

A student wants to find out what happens when copper is heated in air. In order to do this, they carried out the following experiment and recorded their results.

- First, they found the mass of an empty crucible (a suitably prepared beer-bottle top (metal) is an alternative to a porcelain crucible).
- They added a piece of copper to the crucible and found the mass again.
- They then heated the crucible strongly for approximately two minutes.
- After they allowed it to cool, they then found the mass after heating.

Mass of crucible = 12.90 g
Mass of crucible + copper = 14.18 g

Mass of copper = __________ g
Mass of crucible + contents after heating = 14.30 g

Colour of contents after heating = black

1. Draw a labelled diagram of the experimental set-up used in this experiment.
2. Calculate the change in mass that has taken place during the heating.
3. Explain what has caused the change in mass.
4. What is the black substance left on the copper after heating?
5. Write a word and balanced chemical equation to show the process that has taken place.
6. a How could you modify the experiment to ensure there was no loss of substance taking place during the heating process?
   b What are the other possible sources of error?
7. Predict what would happen, in terms of mass change and colour change, if calcium were heated in air in the same way as the copper.

Formulae

The formula of a compound is made up from the symbols of the elements that make up the compound and numbers that show the ratio of the different atoms the compound is made from. Carbon dioxide has the formula CO_2, which tells you that it contains one carbon atom for every two oxygen atoms. The 2 in the formula indicates that there are two oxygen atoms present in each molecule of carbon dioxide.

Worked example

Write the ratio of atoms in sodium sulfate – Na_2SO_4.

Substance	Formula	Ratio of atoms
Sodium sulfate	Na_2SO_4	Na : S : O 2 : 1 : 4

Test yourself

10 Write down the ratio of the atoms present in the formula for each of the compounds shown in Table 2.5.

Table 2.5 Names and formulae of some common compounds

Compound	Formula
Ammonia	NH_3
Calcium hydroxide	$Ca(OH)_2$
Carbon dioxide	CO_2
Copper sulfate	$CuSO_4$
Ethanol (alcohol)	C_2H_5OH
Glucose	$C_6H_{12}O_6$
Hydrochloric acid	HCl
Nitric acid	HNO_3
Sodium carbonate	Na_2CO_3
Sodium hydroxide	$NaOH$
Sulfuric acid	H_2SO_4

The ratio of atoms within a chemical compound is usually constant. Compounds are made up of fixed proportions of elements: they have a fixed composition. Chemists call this the **Law of constant composition.**

For further discussion of formulae, see p. 35.

Balancing chemical equations

Word equations are a useful way of representing chemical reactions, but a better and more useful way of seeing what happens during a chemical reaction is to produce a balanced chemical equation. This type of equation gives the formulae of the substances that are reacting, the reactants, and the new substances formed during the chemical reaction, the products, as well as showing the relative numbers of each of the particles involved.

Balanced equations often include symbols that show the physical state of each of the reactants and products:

(s) = solid
(l) = liquid
(g) = gas
(aq) = aqueous (water) solution

We can use the reaction between iron and sulfur as an example. The word equation to represent this reaction is:

$$\text{iron} + \text{sulfur} \xrightarrow{\text{heat}} \text{iron(II) sulfide}$$

When we replace the words with symbols for the reactants and the products, and include their physical state symbols, we get:

$$Fe(s) + S(s) \xrightarrow{\text{heat}} FeS(s)$$

Since there is the same number of each type of atom on both sides of the equation, this is a balanced chemical equation.

Worked example

Write, for the reaction between magnesium and oxygen producing magnesium oxide:

a the word equation
b the balanced chemical equation.

a The word equation is:

$$\text{magnesium} + \text{oxygen} \xrightarrow{\text{heat}} \text{magnesium oxide}$$

b When we replace the words with symbols for the reactants and the products and include their physical state symbols, it is important to remember that oxygen is a diatomic molecule:

$$Mg(s) + O_2(g) \xrightarrow{\text{heat}} MgO(s)$$

In the equation there are two oxygen atoms on the left-hand side (O_2) but only one on the right (MgO). We cannot change the formula of magnesium oxide, so to produce the necessary two oxygen atoms on the right-hand side, we will need 2MgO – this means 2 × MgO formula units. The equation now becomes:

$$Mg(s) + O_2(g) \xrightarrow{\text{heat}} 2MgO(s)$$

There are now two atoms of magnesium on the right-hand side and only one on the left. To balance the equation, we place a 2 in front of the magnesium, and obtain the following balanced chemical equation:

$$2Mg(s) + O_2(g) \xrightarrow{\text{heat}} 2MgO(s)$$

This balanced chemical equation now shows us that two atoms of magnesium react with one molecule of oxygen gas when heated to produce two units of magnesium oxide.

Test yourself

11 Write the word and balanced chemical equations for the reactions which take place between:
a calcium and oxygen
b copper and oxygen.

Going further

Instrumental techniques

Elements and compounds can be detected and identified by a variety of instrumental methods. Scientists have developed instrumental techniques that allow us to probe and discover which elements are present in a substance as well as how the atoms are arranged within the substance.

Many of the instrumental methods that have been developed are quite sophisticated. Some methods are suited to identifying elements. For example, atomic absorption spectroscopy allows the element to be identified and also allows the quantity of the element that is present to be found.

Some methods are particularly suited to the identification of compounds. For example, infrared spectroscopy is used to identify compounds by showing the presence of particular groupings of atoms.

Infrared spectroscopy is used by the pharmaceutical industry to identify and discriminate between drugs that are similar in structure, for example, penicillin-type drugs. Used both with organic and inorganic molecules, this method assumes that each compound has a unique infrared spectrum. Samples can be solid, liquid or gas and are usually tiny. However, Ne, He, O_2, N_2 or H_2 cannot be used.

This method is also used to monitor environmental pollution and has biological uses in monitoring tissue physiology including oxygenation, respiratory status and blood-flow damage.

Forensic scientists make use of both these techniques because they are very accurate, but they only require tiny amounts of sample – often only small amounts of sample are found at crime scenes. Other techniques utilised are nuclear magnetic resonance spectroscopy and ultraviolet/visible spectroscopy.

2.3 Mixtures

Many everyday things are not pure substances: they are **mixtures**. A mixture contains more than one substance, which could be elements and/or compounds. Examples of common mixtures are:

- sea water (Figure 2.7)
- air, which is a mixture of elements such as oxygen, nitrogen and neon, and compounds such as carbon dioxide (see Chapter 11, p. 178)
- alloys such as brass, which is a mixture of copper and zinc (for a further discussion of alloys, see Chapter 10, p. 165).

▲ **Figure 2.7** Sea water is a common mixture. It is a water solution of substances such as sodium chloride as well as gases such as oxygen and carbon dioxide

The difference between mixtures and compounds

There are differences between compounds and mixtures, which can be seen by looking at the reaction between iron filings and sulfur. A mixture of iron filings (powdered iron) and sulfur (Figure 2.8 bottom right), looks different from either of the individual elements (Figure 2.8 top). This mixture has the properties of both iron and sulfur; for example, a magnet can be used to separate the iron filings from the sulfur (Figure 2.9).

▲ **Figure 2.8** The elements sulfur and iron at the top of the photograph, and (below) black iron(II) sulfide on the left and a mixture of the two elements on the right

Substances in a mixture have not undergone a chemical reaction and it is possible to separate them, provided that there is a suitable difference in their physical properties. If the mixture of iron and sulfur is heated, a chemical reaction occurs and a new substance is formed. The product of the reaction is iron(II) sulfide (Figure 2.8 bottom left), and the word equation for this reaction is:

$$\text{iron} + \text{sulfur} \xrightarrow{\text{heat}} \text{iron(II) sulfide}$$

▲ **Figure 2.9** A magnet will separate the iron from the mixture

During the reaction, heat energy is given out as new chemical bonds are formed. This is called an **exothermic reaction** and accompanies a chemical change (Chapter 6, p. 92). The iron(II) sulfide formed has very different properties to the mixture of iron and sulfur (Table 2.6); for example, iron(II) sulfide would not be attracted towards a magnet. Some chemical reactions take in heat during the reaction, which is called an **endothermic reaction** (Chapter 6, p. 92). You will learn more about the different types of reactions in Chapter 6.

▼ **Table 2.6** Different properties of iron, sulfur, an iron/sulfur mixture and iron(II) sulfide

Substance	Appearance	Effect of a magnet	Effect of dilute hydrochloric acid
Iron	Dark grey powder	Attracted to it	Very little action when cold. When warm, a gas is produced with a lot of bubbling (effervescence)
Sulfur	Yellow powder	None	No effect when hot or cold
Iron/sulfur mixture	Dirty yellow powder	Iron powder attracted to it	Iron powder reacts as above
Iron(II) sulfide	Black solid	No effect	A foul-smelling gas is produced with some effervescence

In iron(II) sulfide, FeS, one atom of iron has combined with one atom of sulfur. In a mixture of iron and sulfur, no such ratio exists as the atoms have not chemically combined. Table 2.7 compares mixtures and compounds. Some common mixtures are discussed in Chapter 10 (p. 165) and Chapter 11 (p. 177).

▼ **Table 2.7** The major differences between mixtures and compounds

Mixture	Compound
It contains two or more substances.	It is a single substance.
The composition can vary.	The composition is always the same.
No chemical change takes place when a mixture is formed.	When the new substance is formed it involves chemical change.
The properties are those of the individual elements/compounds.	The properties are very different to those of the component elements.
The components may be separated quite easily by physical means.	The components can only be separated by one or more chemical reactions.

Test yourself

12 Make a list of some other common mixtures and then use your research to find out and state what they are mixtures of.

13 Which of the following are not mixtures: milk, tin, sulfur, cough linctus, brass, gold?

Going further

Other types of mixtures

There are mixtures which are formed by mixing two substances (or phases) which cannot mix. Gels, sols, foams and emulsions are all examples of just such mixtures. Look closely at the substances in Figure 2.10, which shows examples of these different types of mixture.

a


b


c

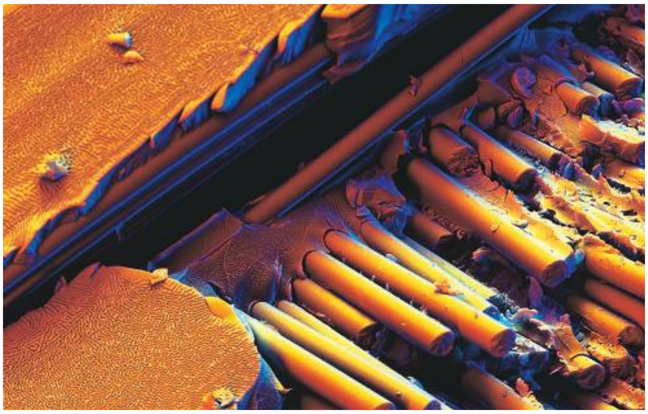

d


a This jelly is an example of a 'gel'
b Emulsion paint is an example of a 'sol'
c These foams have been formed by trapping bubbles of gas in liquids
d Emulsions are formed by mixing immiscible liquids

▲ **Figure 2.10**

Composite materials are those that combine the properties of two constituents in order to get the exact properties needed for a particular job. Glass-reinforced fibre is an example of a composite material combining the properties of two different materials. It is made by embedding short fibres of glass in a matrix of plastic.

The glass fibres give the plastic extra strength so that it does not break when it is bent or moulded into shape. The finished material has the strength and flexibility of the glass fibres as well as the lightness of plastic (Figure 2.11).



a Glass-reinforced plastic (GRP) consists of glass fibres (rod shapes) embedded in plastic, in this case polyester

b The glass-reinforced plastic used to make boats like this is a composite material

▲ **Figure 2.11**

2.4 Inside atoms

Everything you see around you is made out of tiny particles, which we call atoms (Figure 2.12). When John Dalton developed his atomic theory, over 200 years ago, he stated that the atoms of any one element were identical and that each atom was 'indivisible'. Scientists in those days also believed that atoms were solid particles, like marbles.

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