CURRICULUM FOR WALES

SCIENCE AND TECHNOLOGY

Science

FOR 11–14 YEARS

BOOK 3

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IN COLLABORATION WITH
Gwasg Prifysgol Cymru
University of Wales Press

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Contents

1 Representing chemical reactions

Atoms are the building blocks of matter. They can be combined in many different ways. It is essential for chemists to understand what happens when a chemical compound is formed – which atoms combine, how many of each different type and in what ratios. When reactions happen, we need to be able to show clearly what substances we started with and what new substances form. This allows chemists to communicate clearly, and to predict if chemical reactions will occur and what products will form.

Understanding the difference between a reaction and a physical change such as dissolving is important in helping chemists know how easily a change can be reversed or if new substances are made.

- Oxygen atoms are found in a wide range of different substances with unique properties. How many substances do you know that contain oxygen atoms?
- Why do chemists need a universal code for writing chemical formulae?

Atoms, molecules, elements, compounds and mixtures

To understand chemical change, we must first review the atomic nature of matter. Next, we consider the way atoms are combined in the starting substances and the new atomic arrangements in the products.

Atoms

We must first review the atomic structure of matter from earlier in your course. You should remember that an **atom** is the smallest part of a substance that has the properties of that substance. It is the basic particle from which all substances are built up. The desk, the air and even you are made up of atoms.

Atoms are far too small to see, even with a light microscope. It can be really difficult to picture the size of a single atom. Imagine the point of a very sharp needle – there are approximately one million atoms in that tiny space.

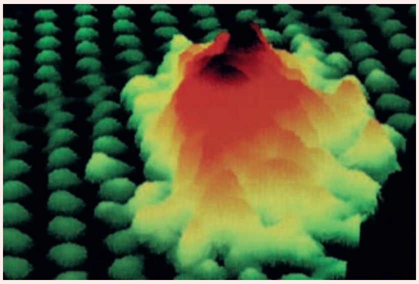


Figure 1 A scanning tunnelling microscope allows a computer to build an image based on tiny electrical currents detected near the surface of a sample. This image shows a sample of gold just three atoms thick on a sheet of carbon. Individual carbon atoms are shown as green.

Making links

This topic builds on earlier work on separating mixtures in the topics on **Extraction, refinement and analysis** and **Physical and chemical changes**. In your course you have studied the particle model of matter and learnt how physical changes, such as change of state and dissolving, are different from chemical changes where new substances are made.

Key term

Atom – the simplest unit of matter. All substances are made out of atoms.

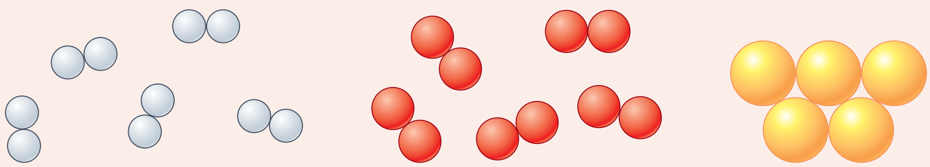
Scientists have used the atomic model for over 200 years. The model shows that different substances are made out of different atoms. Models are accepted when they explain observations. For example, the atomic model explains:

- why some new materials can be made by combining other materials
- how some chemical substances can be split into other simpler substances
- why substances are different from each other.

Elements

An **element** is a pure substance that cannot be split up into simpler substances. Each element contains only one type of atom. Elements are divided into three categories. These are metals, non-metals and metalloids. Metals are hard, shiny substances that conduct electricity and transfer energy by heating easily. Non-metals are brittle, dull and poor conductors by heating and of electricity. They are also often gases at room temperature. Metalloids are substances which have properties of both typical metals and non-metals.

These elements are listed in the Periodic Table. Every element has different properties, such as hardness or melting point. You cannot make elements out of other materials.

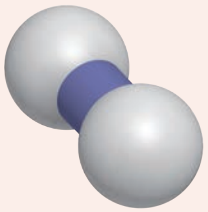


▲**Figure 2** An element is made up of atoms of the same type.

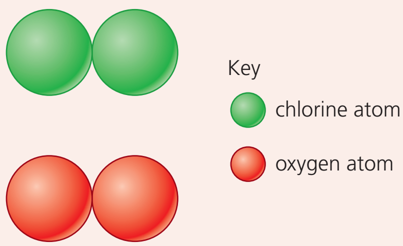
Molecules

Some non-metal elements exist as atoms and others as **molecules**. These non-metals exist in their elemental state as molecules made of two atoms joined together. These **diatomic molecules** include hydrogen, nitrogen, oxygen and the Group 7 elements (the halogens: fluorine, chlorine, bromine and iodine). They are molecular elements because both atoms are the same element.

We can use molecular models to show the types of atoms and the order in which they are joined together.



▲**Figure 3** A molecular model of hydrogen.



▲**Figure 4** Particle diagrams for the diatomic molecules chlorine and oxygen.

In order to recognise atoms of various elements in models and diagrams, we use different colours to represent different atoms.

When a substance burns, it reacts with oxygen. When carbon is burnt, individual carbon and oxygen atoms are joined together in a **chemical bond** to make a carbon dioxide molecule.

Making links

You have studied elements earlier in your course in the topic on **Atomic structure and the Periodic Table**, and you should recall that elements are arranged on the Periodic Table in order of increasing atomic number (number of protons).

Key terms

Element – a substance that is made up of only one type of atom.

Molecule – made up of two or more atoms chemically joined together. The atoms can be the same, as in a molecule of an element, or different to make up a molecule of a compound.

Diatomic molecule – molecule of an element that is made up of two atoms of the same element combined.

Chemical bond – formed when two particles combine.

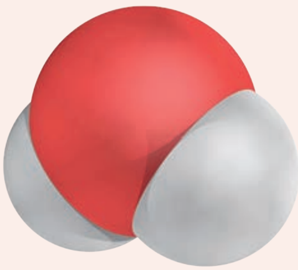
The carbon dioxide molecule has the same mass as the carbon and oxygen atoms added together. No atoms have been gained or lost.

Compounds

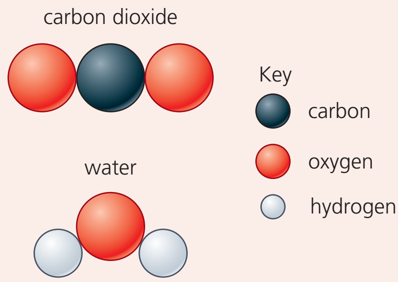
Compounds are made from more than one element chemically joined together in a chemical reaction. When a new substance is formed, this is a chemical change and bonds are made.

Key term

Compound – substance made up of two or more different types of atoms or ions, chemically joined together in a fixed ratio.



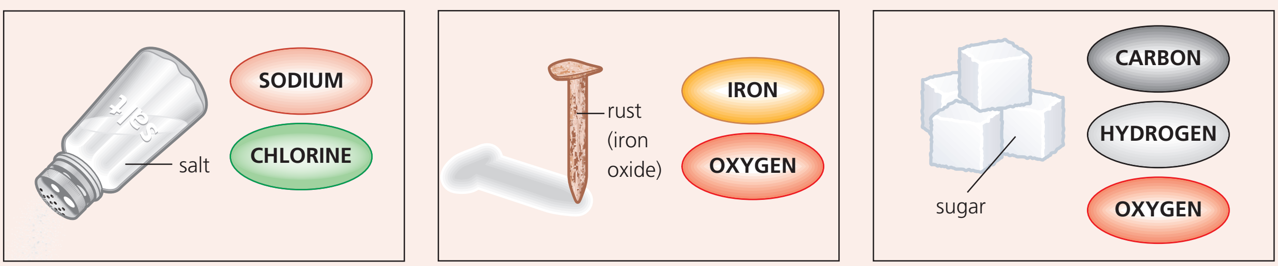
▲**Figure 5** A molecular model of water.



▲**Figure 6** Particle diagrams of the compounds carbon dioxide and water.

A particular compound always contains the same set of elements combined in the same way. Some examples of compounds include:

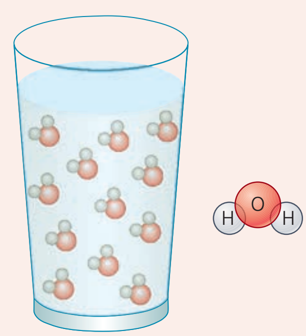
- sodium chloride
- copper sulfate
- carbon dioxide
- hydrochloric acid
- sodium hydroxide
- water.



▲**Figure 7** These examples show a range of chemical compounds and the names of the elements that combine to make them.

Non-metal compounds are made up of molecules; a molecule is the smallest part of a compound that has the properties of that compound. Molecules are made from atoms joined together by chemical bonds. All the molecules of a particular compound contain the same combination of atoms. Different compounds have different molecules, with different combinations of atoms.

Compounds can be made when chemicals react together. Reactions may happen in a laboratory, in a kitchen or inside a living organism, for example. The right conditions are needed for a bond between atoms to break, allowing them to combine in a new way in the product of the reaction. Often the input of energy required to break bonds is provided by heating.



▲**Figure 8** The molecules in the compound water all have one atom of oxygen in the middle, bonded to two hydrogen atoms.

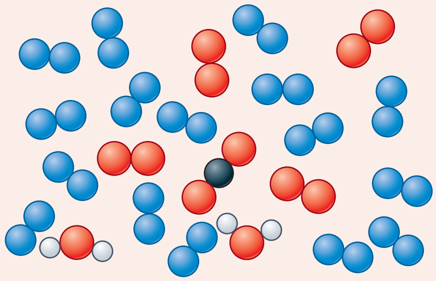
Mixtures

You have a mixture when two or more substances are mixed together without any chemical reaction taking place. These substances could be elements or compounds. The substances in a mixture are not chemically bonded together.

Air is a mixture. It contains several different gases, including:

- nitrogen
- carbon dioxide
- oxygen
- water vapour.

These gases stay separate from each other. They do not normally react to form new compounds.



▲**Figure 9** Air is a mixture of many different substances, including the compounds carbon dioxide and water, and the elements nitrogen and oxygen.

Science in context

The nitrogen and the oxygen in the air can be made to react at high temperatures, by the energy in a lightning bolt for example. The product of the reaction is the compound nitrous oxide (N_2O). Nitrous oxide is sometimes called 'laughing gas' and was used by doctors and dentists for many years to relax patients. However, it is also a greenhouse gas and causes global warming. A very similar reaction occurs inside car engines where the temperature is also very high. The product in this case is nitrogen dioxide (NO_2), which is a major air pollutant leading to acid rain and smog.

▶ Comparing a compound to the elements it is formed from

Compounds have their own properties. These are not necessarily the same as, or even a combination of, the properties found when the atoms existed as elements. This is because when a compound forms in a chemical reaction, the atoms that make it are combined in a new way. This gives the new substance its own unique properties.

One example is copper sulfate, which contains copper, sulfur and oxygen. A comparison of the appearance of the compound and its elements can be made:

- copper sulfate is made of bright blue crystals
- copper is a shiny orange–brown metal
- sulfur is a yellow solid
- oxygen is a colourless gas.

Making links

Mixtures can be separated easily by physical methods (no chemical reaction is needed). The range of methods used to separate the substances in mixtures was described earlier in your course in the topic on **Extraction, refinement and analysis**.

▲**Figure 10** The metal copper and the non-metal sulfur.

Worked example

A scientific leaflet aims to share a lot of scientific facts in a small space. The layout should be easy to read and the text easy to understand. The leaflet also needs to capture the reader's attention by being visually attractive.

Create a leaflet of your research into the properties and uses of copper sulfate compared to those of the elements that it is formed from (copper, sulfur and oxygen).

▶ **STEP 1** Collect all of your research, keeping a note of each source.

Copper sulfate is made of blue solid crystals. Melting point 150 °C. It is an irritant and dangerous for the environment. It can be used to kill algae and fungi.

Source: https://kids.kiddle.co/Copper(II)_sulfate

Copper is a reddish-gold metal. Melting point 1085 °C. Easily worked and drawn into wires.

Used in electrical equipment such as wiring and motors because it conducts electricity very well. Also used in roofing and plumbing.

Source: www.rsc.org/periodic-table/element/29/copper

▲**Figure 11** Blue crystals of copper sulfate.

Sulfur is a brittle, pale yellow solid. It is a poor conductor of electricity, and insoluble in water. Melting point 119 °C.

Most is converted into sulfuric acid, to make fertilisers. Sulfuric acid is also used in pigments, detergents, explosives and storage batteries.

Article by Robert Brasted (2020) www.britannica.com/science/sulfur

Oxygen is a colourless gas at room temperature. Liquid oxygen is pale blue. Melting point −219 °C.

Used in the manufacture of steel, to make rocket fuel and to treat those with breathing problems and as life support for astronauts and scuba divers.

Source: www.littlehouseofscience.com/20_fascinating__fun_science_facts_oxygen

▶ **STEP 2** Select key headings; in this case use headings for each of the elements and the compound they form: Copper, Sulfur, Oxygen and Copper sulfate.

▶ **STEP 3** Create a simple summary for each heading – bullet points are useful. Use scientific terms for the properties you describe. For example, under the heading 'Copper' you might write:

Copper is:

- a reddish metal
- solid
- ductile
- a good electrical conductor.

It is used for:

- roofing and plumbing
- wiring.

Select images to illustrate these properties and uses.

▶ **STEP 4** Design the front page – include a title that shows what the leaflet is about and a main image.

▶ **STEP 5** At the end, list any sources of information as a suggested list for further research:

Schmit, A. and Pollard, J. (2016) *WJEC GCSE Chemistry*, Hodder Education

'Copper(II) sulfate facts for kids', https://kids.kiddle.co/Copper(II)_sulfate (accessed on 05.09.21)

Royal Society of Chemistry interactive Periodic Table, www.rsc.org/periodic-table/element/29/copper (accessed on 05.09.21)

Brasted, R. 'Sulfur'. *Encyclopedia Britannica* www.britannica.com/science/sulfur (accessed 05.09.21)

www.littlehouseofscience.com/20_fascinating__fun_science_facts_oxygen (accessed 05.09.21)

1 In your own words, write **three** bullet points to summarise the information on the properties of copper sulfate and **two** bullet points for its uses.

2 In your own words, write **three** bullet points to summarise the information on the properties of sulfur and **two** bullet points for its uses.

3 Create a table to compare the melting points of all the substances mentioned in the leaflet.

4 Design the front page for this leaflet.

Water

Think about the properties of water:

- melting point 0 °C
- boiling point 100 °C
- liquid at room temperature.

These properties of water differ from the properties of the two elements in water, hydrogen and oxygen, which are both gases at room temperature.

The main uses of hydrogen are in oil refineries to process crude oil and as a reactant in some important industrial reactions, such as the production of ammonia in the Haber process. A new use for hydrogen is as fuel for vehicles, thanks to the fuel cell.

In addition to household uses of water for drinking and washing, it is used as a solvent in many industrial processes. Water dissolves more substances than any other solvent.

▲**Figure 12** Crystals of sodium chloride.

Sodium chloride

Also known as common table salt, sodium chloride forms white solid crystals (Figure 12). They have a very high melting point (801 °C) but dissolve very easily in water.

Sodium is a very reactive Group 1 metal and chlorine is a toxic non-metal gas.

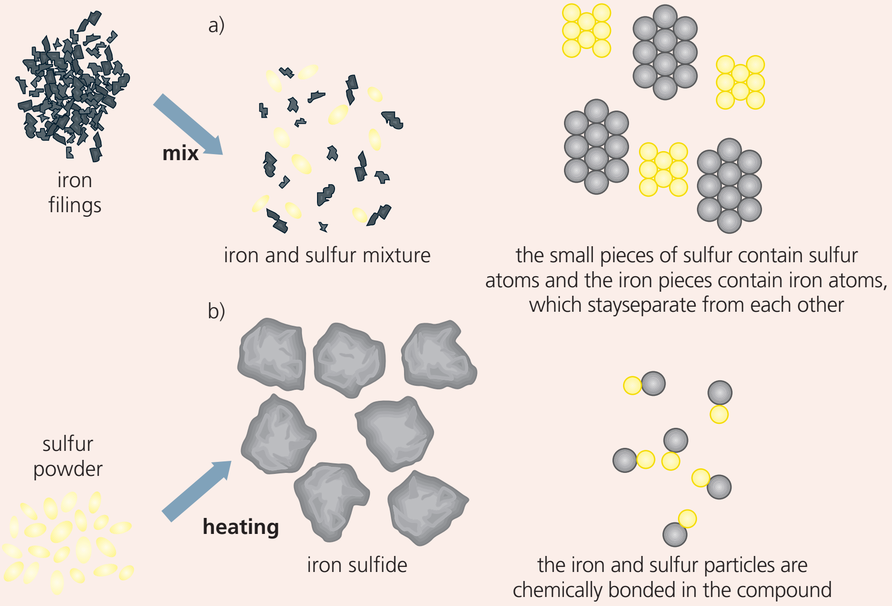
Sodium metal is used in many industrial reactions, such as in the production of dyes and in reactions to make perfumes. Molten sodium metal is also used as a coolant in nuclear reactors. Chlorine is commonly used as a disinfectant, for example to treat drinking water and swimming pools. Sodium chloride is used as a food flavouring and preserver (it prevents food from rotting). It is also used in many industrial processes, such as in the manufacture of soap and glass, and in hospitals (you may have heard nurses mention 'saline') for rinsing wounds.

Making links

You studied Group 1 (alkali metals) and Group 7 (halogens) in detail earlier in your course in the topic on **Atomic structure and the Periodic Table**. You also learnt that sodium and chlorine are very reactive elements.

Iron sulfide

Iron sulfide is a compound formed from the elements iron and sulfur.



▲**Figure 13** The difference between a) a mixture of the elements iron and sulfur, and b) the compound iron sulfide.

Iron is one of the most common building materials and one of the uses of iron sulfide is in the manufacture of ceramics and glass.

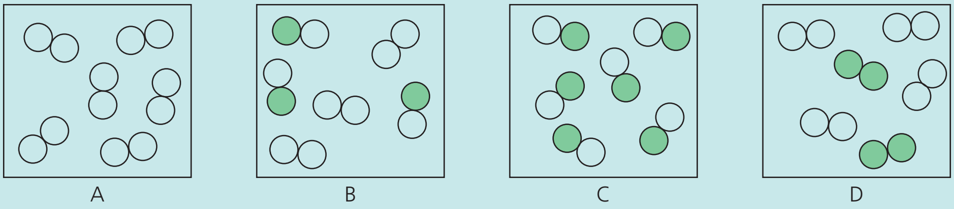
Check your understanding

Know

1 Is carbon dioxide an atom, element, compound or mixture? Explain your choice.

2 Name **three** diatomic elements.

Apply



▲Figure 14

3 Which of the diagrams in Figure 14 represent:

- a an element
- b a compound
- c a mixture?

4 In the diagrams in Figure 14, describe the difference between boxes B and D.

5 Identify the mistake in each statement and state the correct key term:

- Seawater is a compound – it is made when sodium chloride dissolves in water.
- Water is a mixture – it contains hydrogen and oxygen atoms joined together with chemical bonds.
- Oxygen is made up of two atoms joined together. It is a diatomic compound.

Extend

6 Compare and contrast the physical properties of the elements copper, sulfur and oxygen with those of the compound copper sulfate.

Learning summary

Now you have completed **Atoms, molecules, elements, compounds and mixtures** and **Comparing a compound to the elements it is formed from**, you should be able to:

- recognise atoms, molecules, compounds and mixtures from models and diagrams
- explain the difference between atoms, molecules, compounds and mixtures
- explain why a compound has different properties from the elements it is formed from
- carry out research to compare the properties and uses of a compound and the elements it is made from
- present facts about different substances using clear language and visual images.

▶ Chemical formulae

It is essential for a chemist to understand what makes up a chemical compound. A chemical formula shows which atoms are combined in the compound and the ratio of the numbers of each type of atom. This allows chemists to predict both the physical and chemical properties of a substance.

Every element has a chemical symbol. Scientists use these symbols as a shorthand version of an element's name. The symbol for many elements is derived from either the first letter (e.g. H for hydrogen) or the first two letters (e.g. He for helium) of their names. A few elements have symbols derived from their Latin names, for example, *ferrum* for iron, which gives the symbol Fe.

When you use a chemical symbol, it is important to write it correctly. If the symbol is just one letter, that letter must be a capital. If the symbol is two letters, then the first must be a capital and the second must be lowercase:

- symbol for iodine = I ✓ i ✗
- symbol for silver = Ag ✓ AG ✗ ag ✗

Look at the Periodic Table for the symbols of all the known elements. If a substance is shown there, you can be sure it is an element.

metals non-metals

H																	He
Li	Be											B	C	N	O	F	Ne
Na	Mg											Al	Si	P	S	Cl	Ar
K	Ca	Sc	Ti	V	Cr	Mn	Fe	Co	Ni	Cu	Zn	Ga	Ge	As	Se	Br	Kr
Rb	Sr	Y	Zr	Nb	Mo	Tc	Ru	Rh	Pd	Ag	Cd	In	Sn	Sb	Te	I	Xe
Cs	Ba		Hf	Ta	W	Re	Os	Ir	Pt	Au	Hg	Tl	Pb	Bi	Po	At	Rn
Fr	Ra		Rf	Db	Sg	Bh	Hs	Mt	Ds	Rg	Cn	Nh	Fl	Mc	Lv	Ts	Og

▲**Figure 15** The Periodic Table of the elements shows all the chemical symbols and can help you identify the metals and the non-metals.

Key terms

Ion – a charged particle that forms when an atom gains or loses electrons.

Ionic compounds – substances that form when oppositely charged ions are strongly attracted.

Naming compounds

You should remember from your earlier work on atomic structure that charged **ions** are formed when metal atoms lose electrons or when non-metal atoms gain electrons.

These ions, having opposite charges, then attract strongly to form **ionic compounds**.

You can name an ionic compound using this rule:

> When a non-metal element forms a compound, the ending of the name changes to –ide.

▲**Figure 16** Crystals of table salt, sodium chloride, an ionic compound (top). An ionic crystal structure (bottom).

For example, these non-metals join with other atoms to form compounds with the following names:

- oxygen → oxide
- chlorine → chloride
- bromine → bromide.

Worked example

You need to be able to name a compound from the elements that react together.

Name the compound formed from the reaction of sodium and chlorine.

▶ **STEP 1** Use the Periodic Table to identify the elements as metal or non-metal:

sodium is a metal

chlorine is a non-metal

▶ **STEP 2** For the non-metal ion, change the name ending to –ide:

chlorine → chloride

▶ **STEP 3** Name the compound using the name of the metal first, then the non-metal:

sodium chloride

Name the compound formed from the reaction of magnesium and oxygen.

▶ **STEP 1** Identify the elements as metal or non-metal:

magnesium is a metal

oxygen is a non-metal

▶ **STEP 2** For the non-metal ion, change the name ending to –ide:

oxygen → oxide

▶ **STEP 3** Name the compound using the metal first, then the non-metal:

magnesium oxide

1. Name the compound formed from the reaction of sodium and bromine.
2. Name the compound formed from the reaction of calcium and oxygen.
3. Name the compound formed from the reaction of lithium and chlorine.

Writing formulae

You will remember from the first part of this chapter that some elements do not exist as single atoms; in these elements, two atoms of the same element combine to form elemental molecules.

These elements are called diatomic (*di* means 'two', so *diatomic* means 'made of two atoms'). We represent them using a small 2 after the chemical symbol for that element. For example, the formula of an oxygen molecule is O_2. To show the number of atoms in any formula, a small number is placed immediately after the symbol for the atom and is written below the line of the text (this is called a subscript). For example, we have hydrogen (H_2), nitrogen (N_2), oxygen (O_2) and the halogens (F_2, Cl_2, Br_2, I_2).

Compounds can be formed between different non-metal atoms, making new molecules as the non-metal atoms are bonded together. The name of the compound can show the types of atoms and their numbers. Every compound has a chemical formula. Using the symbols for each atom as shown on the Periodic Table (page 8), the chemical formula tells you the atoms a compound is made of and the numbers of each atom in it, for example:

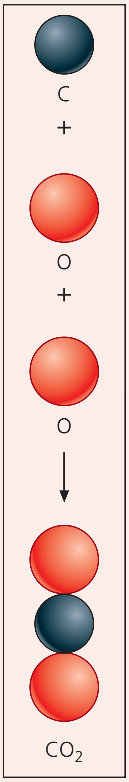
- carbon dioxide, CO_2
- carbon monoxide, CO.

Though both carbon dioxide and carbon monoxide are made from carbon and oxygen only, they are different compounds because their molecules contain different proportions of oxygen. We can see this in their names as well as in their chemical formulae (mono = 1, di = 2, tri = 3).

There are some compounds which do not have names that relate to their atoms, for example ammonia and methane (Table 1). The names and formulae of these compounds need to be learnt so that we can recognise them.

Table 1 You need to know the names and formulae of these compounds.

Name	Formula
water	H_2O
ammonia	NH_3
methane	CH_4



▲**Figure 17** A carbon dioxide molecule is made up of one carbon atom and two oxygen atoms bonded together.

You will have noticed the use of subscript numbers in these formulae. If we take another look at carbon dioxide in Figure 17, you will see there is one carbon atom joined to two oxygen atoms. The subscript number 2 is written after the symbol for oxygen to show this ratio: CO_2.

Worked example

Identify how many of each type of atom are in the compound, $C_6H_{12}O_6$.

▶ **STEP 1** Identify the different elements in the compound:

C = carbon

H = hydrogen

O = oxygen

▶ **STEP 2** The subscript number that follows each element's symbol tells you how many atoms there are:

number of atoms of carbon = 6

number of atoms of hydrogen = 12

number of atoms of oxygen = 6

Octane has eight carbon atoms and 18 hydrogen atoms. What is its formula?

▶ **STEP 1** Identify the symbols for the elements in the compound:

carbon = C

hydrogen = H

▶ **STEP 2** Write the given number of each element as a subscript number following the element's symbol:

number of atoms of carbon = 8

number of atoms of hydrogen = 18

So, we have C_8H_{18}

1 How many of each type of atom are in the compound H_3PO_4?

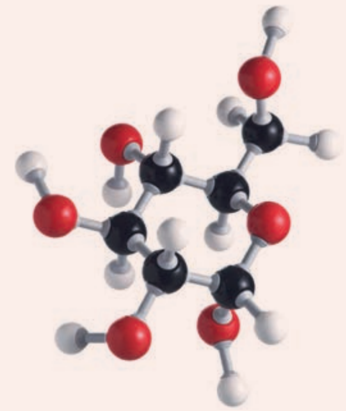
2 How many of each type of atom are in the compound C_2H_5OH?

3 The substance hydrogen peroxide has two hydrogen atoms and two oxygen atoms. What is its formula?

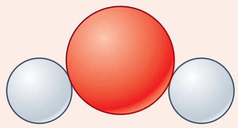
4 The substance ozone only contains oxygen atoms – it has three oxygen atoms. What is its formula?

Another way to work out a formula is from a molecular model or diagram of the substance. For example, Figure 18 is a molecular model of glucose. Using the key of red for oxygen, black for carbon and white for hydrogen, you can count six carbon atoms, 12 hydrogen atoms and six oxygen atoms, giving the formula $C_6H_{12}O_6$.

Figure 19 is a diagram of a molecule of water. Using the same key, you can work out that the formula of the water molecule is H_2O.



▲**Figure 18** A molecular model of glucose.



▲**Figure 19** A diagram of a water molecule.

▶ Formulae of ionic compounds

The chemical formula of an ionic compound shows the simplest ratio of ions in the compound. In order to write chemical formulae of ionic compounds, you need to be able to identify the ions that form from a particular element. For most elements, we can work these out based on the position of the element in the Periodic Table.

Metal atoms lose electrons and form positive ions. They lose all of the outer shell electrons and so the group number gives the size of the charge. For example, magnesium loses two electrons so the charge on the ion is 2+. The charge is written to the right of the element's symbol, as a superscript, Mg^{2+}.

Non-metal atoms gain electrons and form negative ions. They gain as many electrons as needed to fill the outer shell, up to eight electrons. The size of the charge is 8 minus the group number. For example, chlorine (in Group 7) gains one electron so the charge on the ion is 1–. The charge is written to the right of the element's symbol, as a superscript. In the case of a single charge the number 1 is not written, for example Cl^-.

Table 2 shows the charges of some common metal and non-metal ions.

Table 2 The charges of some common metal and non-metal ions.

Group 1 metal ions	Group 2 metal ions	Group 3 metal ions	Group 5 non-metal ions	Group 6 non-metal ions	Group 7 non-metal ions
Li^+ Na^+ K^+	Mg^{2+} Ca^{2+}	Al^{3+}	N^{3-} P^{3-}	O^{2-} S^{2-}	F^- Cl^- Br^- I^-

Making links

You should remember from your work on **Atomic structure and the Periodic Table** that the group number of an element shows how many electrons are in the outer shell. You also learnt that if the outer shell is full, the atom is stable.

Hydrogen is an unusual element as it is in the first period and is not placed in a group. It has one outer shell electron but is not a metal. You need to learn that it forms a positive ion, the hydrogen ion H^+.

If there are more than two elements in an ionic compound, the formula of the ions is more complex. These compounds contain a **compound ion** of two non-metals.

You need to learn the names and formulae for the compound ions in Table 3. You should know any subscript numbers (and which symbols they are placed after) and the charge on the ion.

Table 3 The names and formulae for some common compound ions.

Name of ion	Formula of ion
sulfate	SO_4^{2-}
nitrate	NO_3^-
carbonate	CO_3^{2-}
hydroxide	OH^-
ammonium	NH_4^+

Making links

You met this important ion, H^+, earlier in your course in the topic on **Acids and alkalis**. The hydrogen ion is responsible for making a solution acidic.

Key term

Compound ion – two non-metal atoms bonded together and with an overall charge.

One final set of formulae you need to be familiar with are for the acids, as shown in Table 4. These compounds are formed when hydrogen ions bond with particular non-metal ions, which give the name of the acid.

Table 4 The names and formulae of some common acids.

Acid	Ions in formula		Formula
hydrochloric acid	H^+	Cl^-	HCl
sulfuric acid	H^+	SO_4^{2-}	H_2SO_4
nitric acid	H^+	NO_3^-	HNO_3

Once you have identified the ions in the formula of a compound, you can work out the subscript numbers after the element symbols for each ion. These subscript numbers indicate the ratio of ions. A compound always has a neutral charge; to work out the ratio of ions you need to show the numbers of each ion needed for the total positive charge to be cancelled out by the total negative charge.

For example, potassium oxide contains potassium and oxide ions, K^+ and O^{2-}. In order to cancel out the 2– charge on the oxide ion, two potassium ions are needed. The formula of the compound is written with a subscript number 2 after the symbol for potassium.

$$\left.\begin{array}{ll} K^+ & \\ & O^{2-} \\ K^+ & \end{array}\right\} K_2O$$

Magnesium chloride contains magnesium and chloride ions, Mg^{2+} and Cl^-. To cancel the 2+ charge on the magnesium ion, two chloride ions are needed so the formula has subscript number 2 after the symbol for chlorine.

$$\left.\begin{array}{ll} & Cl^- \\ Mg^{2+} & \\ & t \end{array}\right\} MgCl_2$$

For compound ions, we need to use brackets if more than one of the compound ions is required. The brackets mean that everything inside the brackets is affected by the subscript number that follows.

For example, calcium nitrate contains Ca^{2+} and NO_3^- ions. To cancel the 2+ charge on the calcium, two nitrate ions are needed, so the formula of the compound is written with brackets around the nitrate group and a subscript number 2 outside the brackets.

$$\left.\begin{array}{ll} & NO_3^- \\ Ca^{2+} & \\ & NO_3^- \end{array}\right\} Ca(NO_3)_2$$

Worked example

Work out the formula of aluminium oxide.

▶ **STEP 1** Identify the symbols of the elements in the compound:

aluminium, Al

oxide (oxygen), O

▶ **STEP 2** Determine the charges on the ions that form from these elements:

Al^{3+} O^{2-}

▶ **STEP 3** Look at the total positive and total negative charge and write out the correct number of each ion in order to cancel these charges to zero:

Al^{3+} O^{2-}

Al^{3+} O^{2-}

O^{2-}

▶ **STEP 4** From the numbers of each ion, write the formula of the compound using the ratio of the atoms. The number of atoms of an element is shown by the subscript *after* the symbol for that element.

Al^{3+}	O^{2-}	
Al^{3+}	O^{2-}	Al_2O_3
	O^{2-}	

1 Work out the formula of magnesium bromide.

2 Work out the formula of lithium sulfide.

3 Work out the formula of potassium sulfate.

4 Work out the formula of calcium hydroxide.

Check your understanding

Know

1 Write the formulae for the following:

a oxygen b methane

c ammonium ion d hydrogen ion.

Apply

2 Draw a diagram and key to show the structure of the following:

a ammonia b nitrogen c nitrogen dioxide.

3 Write the formulae for the following compounds:

a potassium fluoride b aluminium bromide

c calcium nitride d ammonium sulfate.

4 Name the following compounds:

a $CaCO_3$ b $LiNO_3$ c $MgSO_4$.

5 Sulfuric acid contains hydrogen and sulfate ions. State and explain the formula of sulfuric acid.

Extend

6 Draw a particle diagram with a key for the following molecules:

a PCl_3 b CCl_4

Chemical equations

Not only do chemists write symbols for elements and compounds, but they can also use them to build up chemical equations. These show what happens when atoms rearrange during a chemical reaction. Chemical equations are a universal code that all chemists, wherever they work in the world, can understand.

Reactions can be represented using chemical names in a word equation or as equations with chemical symbols. Both types of equations are useful because they tell you what is happening in a reaction.

Here is an example of word and chemical symbol equations for the reaction between zinc and copper sulfate solution to form zinc sulfate and copper:

zinc + copper sulfate → zinc sulfate + copper

$Zn + CuSO_4 \rightarrow ZnSO_4 + Cu$

Worked example

When it comes to writing a chemical equation, you need to look for clues in the description or observation of the chemical reaction. Once you can identify the reactants and products, you can build up your word equation. Then, using your skills in writing chemical formulae, you can write the matching symbol equation.

When sulfur burns in air, it reacts with the gas oxygen. A single product forms called sulfur dioxide. Write a symbol equation for this reaction.

- **STEP 1** Highlight the **reactants** and **products**:

  When **sulfur** burns in air, it reacts with the gas **oxygen**. A single product forms called **sulfur dioxide**.

- **STEP 2** Write these out as a word equation:

  sulfur + **oxygen** → **sulfur dioxide**

- **STEP 3** Work out the chemical formulae:

  Sulfur is an element, shown by its chemical symbol, S. Oxygen is a diatomic element, shown as O_2. For sulfur dioxide, the 'di' means two oxygen atoms for every sulfur so the formula is SO_2.

- **STEP 4** Write the symbol equation:

  $S + O_2 \rightarrow SO_2$

When magnesium reacts with bromine, a single product called magnesium bromide forms. Write a symbol equation for this reaction.

- **STEP 1** Highlight the **reactants** and **products**:

  When **magnesium** reacts with **bromine**, a single product called **magnesium bromide** forms.

- **STEP 2** Write these out as a word equation:

  magnesium + **bromine** → **magnesium bromide**

- **STEP 3** Work out the chemical formulae:

  Magnesium is an element, shown by its chemical symbol, Mg. Bromine is a diatomic element, shown as Br_2. For magnesium bromide, we need to work out the formula of this ionic compound.

$$Mg^{2+} \quad \left.\begin{matrix} Br^- \\ Br^- \end{matrix}\right\} \quad MgBr_2$$

▶ **STEP 4** Write the symbol equation:

$Mg + Br_2 \rightarrow MgBr_2$

1 Write the word and symbol equations for the following descriptions:

a A small piece of the metal calcium is added to a gas cylinder filled with chlorine. White salt crystals of calcium chloride form.

b Magnesium sulfide forms when the metal magnesium reacts with the non-metal sulfur.

Balancing equations

All of the examples so far have the same number of each type of atom on both sides of the equation. We say the equations are balanced. However, most equations will not have equal numbers of the different types of atoms if you just write the formulae of the reactants and products under the word equation. Balancing an equation means making sure you have the same number of each type of atom before and after the reaction has taken place. When making an equation balance, you cannot change the chemical formulae of any of the substances. Instead, numbers can be added in front of one or more of the substances. The number applies to all the atoms in the formula of the compound that follows, as shown in Figure 20.

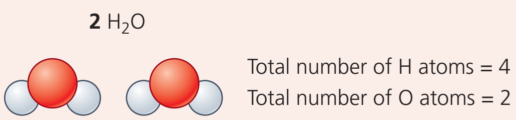


Figure 20

The following equation for a reaction is not balanced:

$$CH_4 + O_2 \rightarrow CO_2 + H_2O$$

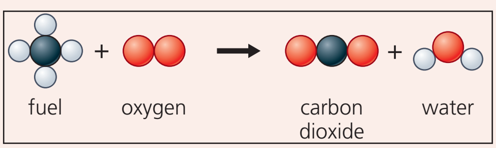


Figure 21

In Figure 21 there are four hydrogen atoms on the left-hand side, but only two hydrogen atoms on the right-hand side. This means we need to change the relative numbers of each particle involved and write in another molecule of water.

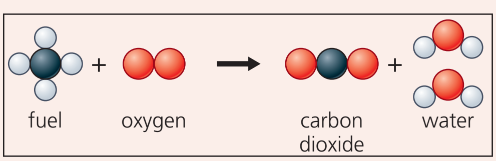


Figure 22

In Figure 22 the number of hydrogen atoms is balanced. However the total number of oxygen atoms on the right-hand side is four but there are only two on the left. Adding a second molecule of oxygen to the diagram finishes the balancing (Figure 23).

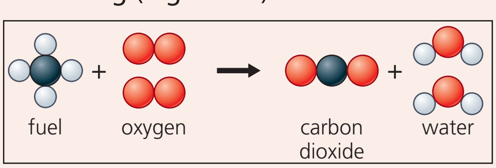


Figure 23

Science in context

Modern chemical formulae and equations capture a great deal of information about chemical reactions based on the chemical elements involved. They began with simple diagrams, such as in the text *Tyrocinium Chymicum* (1610) by the French medical chemist Jean Beguin (1550–1620), but took centuries to evolve as experimental understanding of materials and reactions grew.

Science in context

Antoine-Laurent de Lavoisier (1743–1794) made many important contributions to early chemistry before becoming a victim of the French Revolution. In 1774, he showed that although substances in a chemical reaction changed considerably the mass of the system did not change. Thus, he established the conservation of mass for chemical reactions which is the principle we apply when balancing chemical equations.

The symbol equation is balanced by adding a 2 in front of the O_2 in the reactants and a 2 in front of the H_2O in the products:

$$CH_4 + \mathbf{2}O_2 \rightarrow CO_2 + \mathbf{2}H_2O$$

A more efficient way to work this out is to add up the total number of each type of atom on each side of the symbol equation. Each time you spot a number that is not equal, you will need to add a number in front of the correct substance and then re-check the totals.

Your working out can fit under the equation, using 'No. of C' to represent 'number of carbon atoms', as shown here.

$CH_4 + \mathbf{2}O_2$	$\rightarrow$	$CO_2 + \mathbf{2}H_2O$	
No. of C = 1		No. of C = 1	✓
No. of H = 4		No. of H = 4	✓
No. of O = 4		No. of O = 4	✓

Worked example

Write a balanced symbol equation for the reaction of calcium with hydrochloric acid to make calcium chloride and hydrogen.

▶ **STEP 1** Write the formulae of the reactants and the products on each side of the equation, and count the total number of each type of atom on each side:

$Ca + HCl$	$\rightarrow$	$CaCl_2 + H_2$	
No. of Ca = 1		No. of Ca = 1	✓
No. of H = 1		No. of H = 2	✗
No. of Cl = 1		No. of Cl = 2	✗

The numbers of hydrogen and chlorine atoms are not balanced.

▶ **STEP 2** To have two hydrogen atoms and two chlorine atoms available on the right-hand side, we need to add a 2 in front of the HCl in the reactants:

$Ca + \mathbf{2}HCl$	$\rightarrow$	$CaCl_2 + H_2$	
No. of Ca = 1		No. of Ca = 1	✓
No. of H = **2**		No. of H = 2	✓
No. of Cl = **2**		No. of Cl = 2	✓

Balance the following equations:

1 $Mg + O_2 \rightarrow MgO$

2 $Fe + Br_2 \rightarrow FeBr_3$

3 $H_2 + N_2 \rightarrow NH_3$

4 $C_2H_4 + O_2 \rightarrow CO_2 + H_2O$

State symbols

The final part of writing a chemical equation is to include state symbols. These are simple letter codes to indicate the state of matter of each substance in the reaction:

- (s) for a solid
- (l) for a liquid
- (g) for a gas
- (aq) for **aqueous solution**.

Key term

Aqueous solution – the substance has been dissolved in water.

The fourth symbol is used to show if the substance is in solution (dissolved in a liquid), which is true for all acids and many other substances. In most solutions the solvent is water, and the Latin term for water is *aqua*, so we use the symbol (aq).

The state symbols are written in brackets as subscripts next to each chemical formula. When the gas methane combusts with oxygen gas in the air, the gas carbon dioxide and the liquid water are formed:

$$CH_{4(g)} + \mathbf{2}O_{2(g)} \rightarrow CO_{2(g)} + \mathbf{2}H_2O_{(l)}$$

Worked example

Now you can put all your learning about equations together.

Write a word and symbol equation for this reaction. When a piece of sodium burns in air, it reacts with the gas oxygen. A single solid product forms called sodium oxide.

▶ **STEP 1** Highlight the **reactants** and **products**:

When a piece of **sodium** burns in air, it reacts with the gas **oxygen**. A single solid product forms called **sodium oxide**.

▶ **STEP 2** Write out the word equation:

sodium + **oxygen** → **sodium oxide**

▶ **STEP 3** Work out the chemical formulae of the reactants and products.

Sodium is a metal, shown by its symbol Na. Oxygen is a diatomic molecule, shown as O_2. Sodium oxide is an ionic compound formed between sodium ions and oxide ions. Sodium is a Group 1 metal so loses one electron to form ions with the symbol Na^+. The oxide ion is formed from the non-metal oxygen which is in Group 6, so it gains two electrons to form the ion O^{2-}.

$$\left.\begin{matrix} Na^+ & \\ & O^{2-} \\ Na^+ & \end{matrix}\right\} Na_2O$$

▶ **STEP 4** Now use these chemical formulae to start writing the symbol equation:

$$Na + O_2 \rightarrow Na_2O$$

▶ **STEP 5** Count the total number of each type of atom on each side:

$Na + O_2$	→	Na_2O	
No. of Na = 1		No. of Na = 2	×
No. of O = 2		No. of O = 1	×

To balance the number of oxygen atoms, we need to add a 2 in front of the Na_2O in the products:

$Na + O_2$	→	**2**Na_2O	
No. of Na = 1		No. of Na = 4	×
No. of O = 2		No. of O = 2	✓

The equation is still not balanced so we need to add a 4 in front of the Na in the reactants:

4$Na + O_2$	→	$2Na_2O$	
No. of Na = 4		No. of Na = 4	✓
No. of O = 2		No. of O = 2	✓

▶ **STEP 6** Finally, add the state symbols using clues in the description to work out the state of the materials.

When a **piece** of sodium burns in air, it reacts with the **gas** oxygen. A single **solid** product forms called sodium oxide.

$$4Na_{(s)} + O_{2(g)} \rightarrow 2Na_2O_{(s)}$$

1 Write a balanced symbol equation with state symbols for the following descriptions:

a A small piece of lithium metal is placed in a gas cylinder filled with the yellow-green gas chlorine. A single white solid product forms, lithium chloride.

b A piece of aluminium foil is placed into a solution of hydrochloric acid. The reaction bubbles as hydrogen is produced and a salt, aluminium chloride, forms.

Check your understanding

Know

1 On which side of the arrow are reactants written?

Apply

2 Copy and complete the table under this symbol equation to show that it is balanced.

$4Fe + 3O_2$		→	$2Fe_2O_3$
No. of Fe =		No. of Fe =	
No. of O =		No. of O =	

3 When a piece of magnesium is heated, it reacts with oxygen in the air. A bright light is seen and a single solid product, magnesium oxide, forms. Write a balanced symbol equation with state symbols for this reaction.

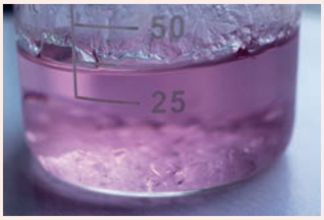
Learning summary

Now you have completed **Chemical formulae**, **Formulae of ionic compounds** and **Chemical equations**, you should be able to:

- name a substance when given its formula
- write chemical formulae for some common compounds
- work out formulae when given the number of each type of atom or from diagrams with keys
- use ion charges to work out simple and complex formulae of compounds containing ions
- write word equations from a description of the reactants and products
- balance a symbol equation
- write a full, balanced symbol equation, including state symbols, from a word equation for a reaction.

Solubility

Solubility is a physical property. It is a measure of how soluble a substance is, because it measures how much of a solute can dissolve in a fixed volume of solvent to make a **saturated solution**.

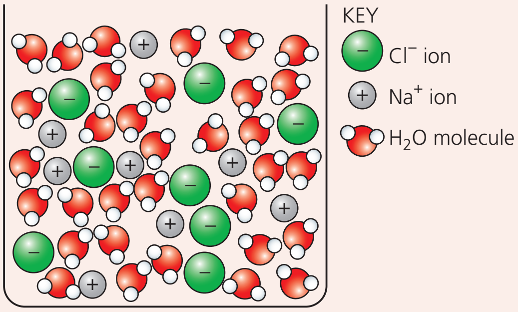


▲**Figure 24** Once a solution is saturated, no more solid can dissolve.

Solubility of solids

Water is an excellent solvent that dissolves many different things. Some substances dissolve in water better than others, and some do not dissolve at all, such as sand.

If a substance is soluble, the particles on the surface of the solid separate as they make contact with the solvent. The solute particles mix completely with the solvent particles forming a clear solution. No solid particles are visible.



◀**Figure 25** When an ionic compound such as sodium chloride (NaCl) dissolves in water, the ions separate and mix in with the water molecules.

Key terms

Solubility – a measure of the maximum amount of solute that can be dissolved in a fixed volume of solvent.

Saturated solution – one that has dissolved the maximum mass of solute possible.

Science in context

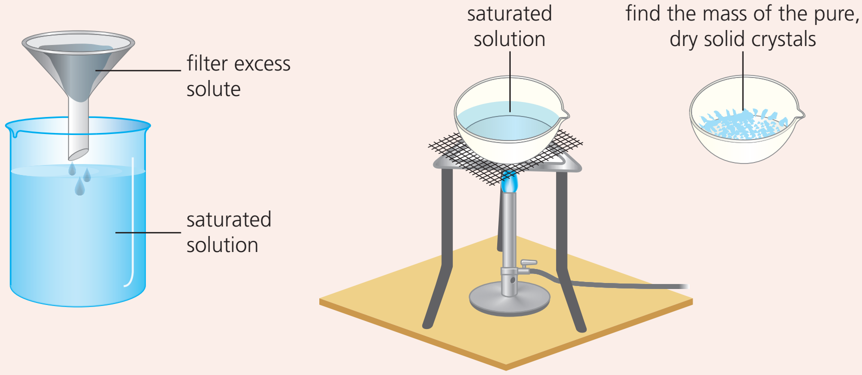
A solution can look exactly the same as the pure solvent, but there are ways to find out if something has dissolved. If the solute is coloured, the solution will take on the colour or if the substance changes the acidity of the solution, you can test its pH. Not to be tried in the laboratory, but if salt or sugar is dissolved in water, our taste buds can detect not only which has been added but also how much.

Solubility is determined by measuring a fixed volume of solvent and adding an **excess** of the solute. This is more solute than the solvent can dissolve. This makes a saturated solution and there will be some undissolved solid visible in the beaker.

Next, filter the undissolved solid, so that only the saturated solution remains. Then evaporate the water from the saturated solution, by heating in an evaporating dish over a Bunsen burner. Then the mass of the pure, dry solid crystals can be found.

Key term

Excess – more than is needed.



▲**Figure 26** Determination of solubility by extracting pure, dry, solid crystals from a saturated solution.

Making links

You met these techniques for separating solids from solutions earlier in your course in the topic on **Acids and alkalis**. The difference here is that you have added the solid directly, rather than making it in a chemical reaction.

The unit for solubility is g/100 g. This is a measure of the mass (in g) that can dissolve in 100 g of the solvent. It is calculated by:

$$\text{solubility (g/100 g)} = \frac{\text{mass of solute (g)}}{\text{mass of solvent (g)}} \times 100$$

If the solvent is water, then the mass of the liquid in g is the same as the volume in cm^3 because water has a density of 1 g/cm^3. If you use a different solvent, you would need to look up the density before calculating solubility.

Worked example

Once you have determined the mass of the solute in a saturated solution, you need to be able to calculate the solubility value in g/100 g.

By experiment it was found that the maximum mass of sodium chloride that dissolved in 50 cm^3 of water was 18 g. Calculate the solubility in g/100 g.

▶ **STEP 1** Convert the volume of solvent into mass. For water, density = 1 g/cm^3, so the mass = 50 g.

▶ **STEP 2** Input values into the calculation:

$$\text{solubility} = \frac{18\text{ g}}{50\text{ g}} \times 100$$

▶ **STEP 3** Calculate the solubility:

solubility = 36 g/100 g

1 By experiment it was found that the maximum mass of copper sulfate that dissolved in 20 cm³ of water was 7 g. Calculate the solubility in g/100 g.

2 Ruben measured out 30 cm³ of water. He made a saturated solution of calcium chloride. After evaporating the water from the saturated solution, he was left with 24.3 g of pure, dry calcium chloride crystals. Determine the solubility of calcium chloride in g/100 g.

3 Jayu investigated two different solids. For solid A, she found that 19 g dissolved in 50 cm³. For solid B, she found that 19.5 g dissolved in 150 cm³. Calculate the solubility of each solid and identify which solid was the most soluble.

Practical skills — Presenting data and drawing graphs

Nia and Ieuan wanted to investigate the solubility of different metal chlorides in water. They wrote the following method:

- Measure 100 cm³ of water in a measuring cylinder and pour into a beaker.
- Taking the first solid, calcium chloride, add to the water and stir. Add until some undissolved solid is visible in the bottom of the beaker.
- Filter the undissolved solid.
- Evaporate the water and dry the crystals.
- Find the mass of the pure dry crystals of calcium chloride.
- Repeat steps 1 to 5 for each of the other salt samples.

The data they collected is shown below:

salt 1: 81 g

magnesium chloride = 54 g

KCl = 32 g

NaCl = 36 g

aluminium chloride: 46 g

1 Put this data into a results table. Remember to include relevant units in the table headings. You should be consistent and either use the names *or* the chemical formulae of the different solids. Look in the method to identify Salt 1.

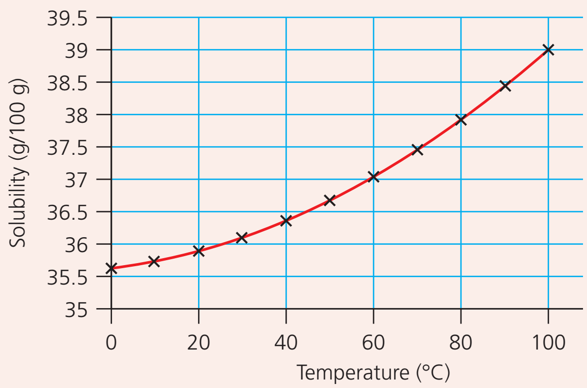
2 Which type of graph would be drawn for this data? Give a reason for your answer.

3 Draw a graph of the data.

Solubility and temperature

An important factor that affects solubility is temperature. Generally, the higher the temperature of the solvent, the more solute will dissolve. As the solvent is heated the molecules move more quickly, and with greater energy, meaning they can separate the solute particles more easily.

This explains why as saturated liquids cool, the solute comes out of solution and crystallises to form solid particles. For example, 100 cm³ of a saturated solution of sodium chloride at 80 °C contains 38 g of salt. As the solution cools to 30 °C, only 36 g of salt can dissolve. The difference of 2 g will come out of solution and will be seen as solid salt crystals at the bottom of the solution.



▲**Figure 27** The solubility of the salt sodium chloride varies with temperature.

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ISBN 978-1-3983-4677-2

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