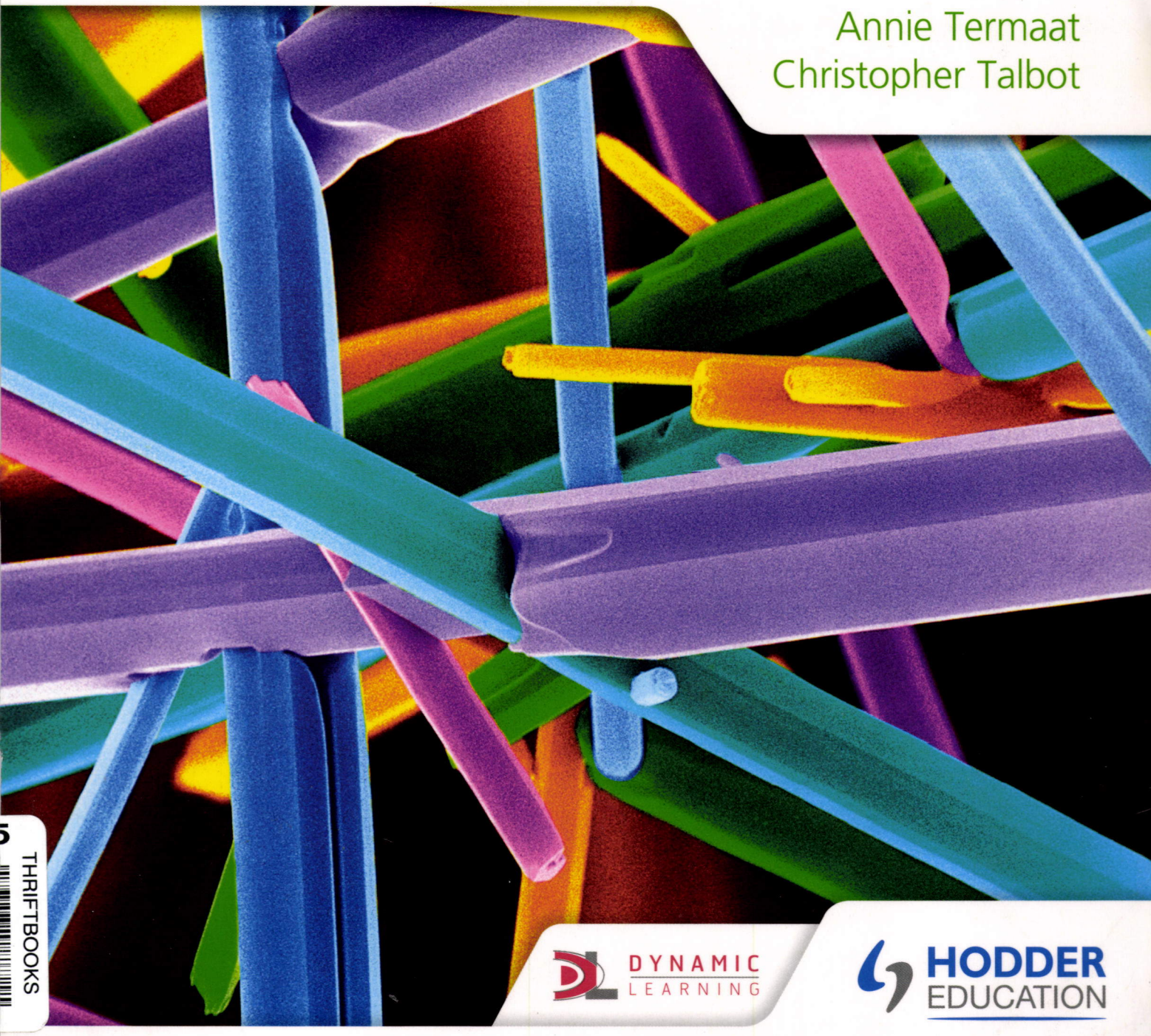
MYP by Concept

4&5

# Chemistry

Annie Termaat
Christopher Talbot



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Annie Termaat
Christopher Talbot

Series editor: Paul Morris

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# Contents


1 What is matter? 2

2 How do we use matter? 24

3 How do we map matter? 48

4 How do atoms bond? 72

5 What are the impacts of chemical industry? 96

6 What determines chemical change? 122

7 What's inside the nucleus? 146

8 Why do electrons matter? 168

9 How are environmental systems sustained by their chemistry? 200

10 How can our energy resources be accessed fairly? 226

11 How can we shift the balance of a reaction? 254

12 Does organic chemistry mean we can make any substance we want? 274

Glossary 305

Acknowledgements 313

Index 314

# How to use this book

Welcome to Hodder Education's *MYP by Concept* series! Each chapter is designed to lead you through an *inquiry* into the concepts of Chemistry, and how they interact in real-life global contexts.

Each chapter is framed with a *Key concept*, *Related concept* and set in a *Global context*.




The *Statement of Inquiry* provides the framework for this inquiry, and the *Inquiry questions* then lead us through the exploration as they are developed through each chapter.

**KEY WORDS**

*Key words* are included to give you access to vocabulary for the topic. **Glossary** terms are highlighted and, where applicable, **search terms** are given to encourage independent learning and research skills.

## Assessment opportunities in this chapter:

- Some activities are *formative* as they allow you to practise certain of the MYP Chemistry *Assessment Objectives*. Other activities can be used by you or your teachers to assess your achievement against all parts of an assessment objective.

Key *Approaches to Learning* skills for MYP Chemistry are highlighted whenever we encounter them.

Definition boxes are included for important terms.

## ATL

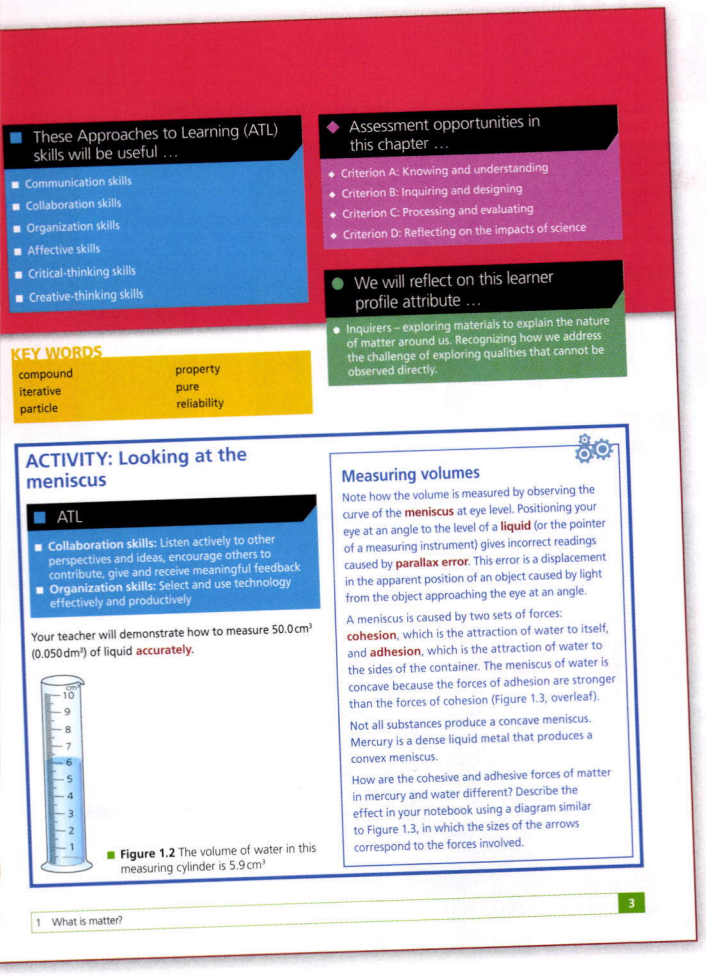
- Activities are designed to develop your *Approaches to Learning* (ATL) skills.

*Hint*

*In some of the activities, we provide hints to help you work on the assignment. This also introduces you to the new Hint feature in the on-screen assessment.*

## EXTENSION

Extension activities allow you to explore a topic further.



■ These Approaches to Learning (ATL) skills will be useful …

- Communication skills
- Collaboration skills
- Organization skills
- Affective skills
- Critical-thinking skills
- Creative-thinking skills

◆ Assessment opportunities in this chapter …

- Criterion A: Knowing and understanding
- Criterion B: Inquiring and designing
- Criterion C: Processing and evaluating
- Criterion D: Reflecting on the impacts of science

● We will reflect on this learner profile attribute …

- Inquirers – exploring materials to explain the nature of matter around us. Recognizing how we address the challenge of exploring qualities that cannot be observed directly.

KEY WORDS

compound, iterative, particle, property, pure, reliability

ACTIVITY: Looking at the meniscus

■ ATL

- **Collaboration skills:** Listen actively to other perspectives and ideas, encourage others to contribute, give and receive meaningful feedback
- **Organization skills:** Select and use technology effectively and productively

Your teacher will demonstrate how to measure 50.0 $cm^3$ (0.050 $dm^3$) of liquid accurately.

■ **Figure 1.2** The volume of water in this measuring cylinder is 5.9 $cm^3$

Measuring volumes

Note how the volume is measured by observing the curve of the **meniscus** at eye level. Positioning your eye at an angle to the level of a **liquid** (or the pointer of a measuring instrument) gives incorrect readings caused by **parallax error**. This error is a displacement in the apparent position of an object caused by light from the object approaching the eye at an angle.

A meniscus is caused by two sets of forces: **cohesion**, which is the attraction of water to itself, and **adhesion**, which is the attraction of water to the sides of the container. The meniscus of water is concave because the forces of adhesion are stronger than the forces of cohesion (Figure 1.3, overleaf).

Not all substances produce a concave meniscus. Mercury is a dense liquid metal that produces a convex meniscus.

How are the cohesive and adhesive forces of matter in mercury and water different? Describe the effect in your notebook using a diagram similar to Figure 1.3, in which the sizes of the arrows correspond to the forces involved.

1 What is matter? 3

As you explore, activities suggest ways to learn through *action*.

## ! Take action

! While the book provides opportunities for action and plenty of content to enrich the conceptual relationships, you must be an active part of this process. Guidance is given to help you with your own research, including how to engage in scientific research, guidance on forming a research question, as well as linking and developing your study of Chemistry to events happening today. This should give you a better understanding of global issues in our twenty-first century world.

You are prompted to consider your conceptual understanding in a variety of activities throughout each chapter.

Finally, at the end of the chapter you are asked to reflect back on what you have learned with our *Reflection table*, maybe to think of new questions brought to light by your learning.

**Use this table to reflect on your own learning in this chapter.**

| Questions we asked | Answers we found | Any further questions now? | | | |
|---|---|---|---|---|---|
| Factual | | | | | |
| Conceptual | | | | | |
| Debatable | | | | | |
| Approaches to learning you used in this chapter: | Description – what new skills did you learn? | How well did you master the skills? | | | |
| | | Novice | Learner | Practitioner | Expert |
| | | | | | |
| | | | | | |
| | | | | | |
| Learner profile attribute(s) | *Reflect on the importance of the attribute for your learning in this chapter.* | | | | |
| | | | | | |

We have incorporated Visible Thinking – ideas, framework, protocol and thinking routines – from Project Zero at the Harvard Graduate School of Education into many of our activities.

## ▼ Links to:

Like any other subject, Chemistry is just one part of our bigger picture of the world. Links to other subjects are discussed.

## ● We will reflect on this learner profile attribute …

- Each chapter has a *IB learner profile* attribute as its theme, and you are encouraged to reflect on these too.

# 1 What is matter?

When matter **changes** we observe **similarities and differences** that help us build **models** to explain underlying **relationships**.



**Figure 1.1** What really makes up the materials our lives depend on? How do they change? How can we find out?

## CONSIDER AND ANSWER THESE QUESTIONS:

**Factual:** What is matter? How can we measure properties of matter? What are some examples of physical and chemical properties of matter?

**Conceptual:** How can we determine the nature of substances?

**Debatable:** Has our ability to measure things more precisely changed our ideas about the material world?

Now **share and compare** your thoughts and ideas with your partner, or with the whole class.

## DISCUSS

Look at Figure 1.1. In pairs, discuss how you might respond to the questions in the caption. What do you think you will learn in this chapter? List your responses so that you can review them when reflecting on your learning throughout this chapter.

## IN THIS CHAPTER, WE WILL ...

- **Find out** how the form of matter depends on (or derives from) its underlying properties.
- **Explore**
  - physical, conceptual or virtual models to help develop our understandings of change in matter;
  - how we develop our understanding of information.
- **Take action** by raising awareness of non-renewable resources.

## These Approaches to Learning (ATL) skills will be useful …

- Communication skills
- Collaboration skills
- Organization skills
- Affective skills
- Critical-thinking skills
- Creative-thinking skills

## Assessment opportunities in this chapter …

- Criterion A: Knowing and understanding
- Criterion B: Inquiring and designing
- Criterion C: Processing and evaluating
- Criterion D: Reflecting on the impacts of science

## We will reflect on this learner profile attribute …

- Inquirers – exploring materials to explain the nature of matter around us. Recognizing how we address the challenge of exploring qualities that cannot be observed directly.

**KEY WORDS**

| | |
|---|---|
| compound | property |
| iterative | pure |
| particle | reliability |

# ACTIVITY: Looking at the meniscus

## ATL

- **Collaboration skills:** Listen actively to other perspectives and ideas, encourage others to contribute, give and receive meaningful feedback
- **Organization skills:** Select and use technology effectively and productively

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**Figure 1.2** The volume of water in this measuring cylinder is 5.9 $cm^3$

## Measuring volumes

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Not all substances produce a concave meniscus. Mercury is a dense liquid metal that produces a convex meniscus.

How are the cohesive and adhesive forces of matter in mercury and water different? Describe the effect in your notebook using a diagram similar to Figure 1.3, in which the sizes of the arrows correspond to the forces involved.

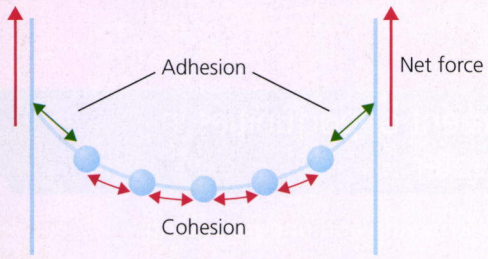



**Figure 1.3** The relative sizes of the arrows indicate the difference in the strength of cohesive and adhesive forces. The forces attracting the water to the glass are greater than the forces attracting the water to itself, and this causes the meniscus of water to have a concave shape

# ACTIVITY: Testing matter

## ATL

- Critical-thinking skills – Practise observing carefully in order to recognize problems; interpret data

## How does matter mix?

### Materials and equipment

- water
- ethanol
- vegetable oil
- 2 × 100 $cm^3$ measuring cylinders

**Safety:** Take care when using glassware! You should always wear covered shoes in a laboratory, and never taste chemicals. Ethanol is an alcohol. Wear eye protection.

### Method

1 **Predict** the total volumes of the pairs of liquids when they are combined in the volumes shown in the table.

| Combination | Predicted total volume/$cm^3$ | Measured total volume/$cm^3$ |
|---|---|---|
| 50 $cm^3$ of vegetable oil<br>50 $cm^3$ of water | | |
| 50 $cm^3$ of ethanol<br>50 $cm^3$ of water | | |

2 **Observe** the total volume when you combine the two liquids in each pair.

### Analysing results

**Explain** these observations.

## Assessment opportunities

- In this activity you have practised skills that are assessed using Criterion C: Processing and evaluating.

## How does matter add up?

### Materials and equipment

- electronic balance (e.g. kitchen scales ±1 g precision)
- 100 $cm^3$ measuring cylinders
- 100 $cm^3$ beaker
- stirring rod
- water
- 'kitchen chemical', for example, crystallized sugar or salt
- spatula (for moving dry ingredients)

### Method

1 **Predict** the total mass of the substances when they are combined as shown in the table.

| Prediction | Measurement (show appropriate units) |
|---|---|
| The total mass of the combined materials (g) | (using electronic balance) |
| The total volume of the combined materials ($cm^3$) | (using measuring cylinder) |

2 Tare the balance with the empty measuring cylinder on it. The next reading will only record the mass of the substance you are adding.

3 **Measure** the mass of 10 $cm^3$ of solid sugar or salt.
**Measure** the mass of 60 $cm^3$ of water.
Now combine the two materials in the beaker, and stir until all the solid has dissolved.
Complete the table.

### Analysing results

1 **Suggest** what happened to the sugar/salt.

2 **Suggest** how you might test whether the solid substance is still in the container.

3 How do you **explain** your observations?

4 **Sketch** a model of your ideas in your notebook, **labelling** how the particles of the mixed materials might look.

5 What have the two activities **suggested** about the nature of matter?

# EXPLORING MATTER: A BRIEF HISTORY OF IDEAS

Early ideas about **matter** were probably closely linked with its use, for example, whether it was edible or could be worn. Many cultures and belief systems include the concept of four, five or eight 'elements'. Examples include ancient Babylonian, Arab, Chinese, Hindu, Japanese and Tibetan traditions. Many of these preceded the ancient Greeks, who took the ideas further.

## Ancient Greeks

Empedocles (492–432 BCE), who lived in Sicily, suggested all substances were made of different combinations from a small number of **elements**: fire, air, water and earth which, combined in different ratios, resulted in properties like 'softness' or 'warmth'.

Some philosophers, most notably Democritus (460–370 BCE), argued that there was a limit to the size a substance could be divided into. These tiny units, which they called 'atomos' contained precisely all the properties of the matter they originally came from, and were indestructible.

Aristotle (384–322 BCE) came from a slightly later school of philosophy (Platonism) based in Athens. He sided with Empedocles' views, claiming the four elements were capable of change. At this time the need to test ideas practically had not yet been recognized. No one was able to distinguish which of the philosophers' claims was accurate, but Aristotle's rhetoric influenced thinking for nearly 2000 years.

These very early ideas were the origin of Alchemy, a tradition of beliefs that sought to 'transmute' matter, to change lead and other 'base metals' to gold, and discover the 'elixir of life'. The Alchemists' practical approach became the basis for modern laboratory techniques, and their name is also the origin of the word 'Chemistry'.

### Links to: Individuals and societies: History

Why do you think so many new ideas were created in ancient Greece, and then in the European Enlightenment? Do certain times and places lend themselves to new ideas better than others? Or is this just the way history has been recorded?

## The European Enlightenment

How do we learn and how do we know? During 17th century Europe, approaches to these questions began to change. After centuries of immense social, political and religious upheaval, plagues and famines that may have killed up to half the population, global exploration introduced awareness of different societies and ways of living. In this special environment, individual responsibility and direct experiences began to be highly valued, and created the intellectual conditions for a science based on experimental observation.

**Gas** was shown to be a form of matter when the Italian, Evangelista Torricelli (1608–1647), invented an air barometer. Changes to the height of a mercury column caused by air pressure demonstrated that invisible matter was real. Further experiments by Swiss Daniel Bernoulli (1700–1782) led him to develop a model of gas as consisting of tiny, constantly moving particles separated by relatively large distances. His **kinetic theory** explained air pressure as a result of millions of tiny collisions with ball-like particles.

Englishman Joseph Priestley (1733–1804), and French scientists Antoine Lavoisier (1743–1794) with his wife and collaborator Marie-Anne Paulze (1758–1836), investigated the composition of matter, identifying components with unique chemical properties, including 'elements' that could not be broken down further. Priestley famously isolated oxygen by heating a **mineral** of mercury, and distinguished oxygen from air. The Lavoisiers produced hydrogen when they **reacted acids** with **metals**. Careful measurements of hydrogen, oxygen and the liquid product that formed when they combined, water, led Antoine Lavoisier to develop the **law of conservation of mass**. It states that the total mass of matter does not change during a **chemical reaction**.

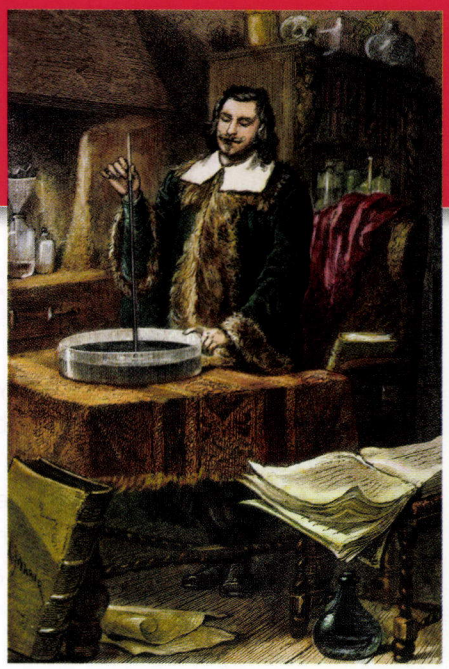


**Figure 1.4** Torricelli's air barometer provided the first evidence air is present, even in calm, windless rooms. Would this device work if you used water instead of mercury?

## A 19th century synthesis

Another Englishman, John Dalton (1766–1844), used his own observations of weather patterns to infer that matter could exist in different **states**. He synthesized his ideas about solids, liquids and gases with those of others to develop an atomic **theory** of matter. In summary, his theory stated:

1. All matter consists of small ball-like particles called **atoms**. The state of matter, as a solid, liquid or gas, can be explained by differences in degrees of separation and amount of motion of these different particles.
2. All of the atoms of an element are identical, and the atoms of different elements have different properties.
3. **Compounds** are formed when atoms combine. Compounds also have unique properties.
4. When elements react, the atoms are combined, separated or are rearranged in defined, whole-number ratios.

Theories become established when they explain new, unexpected observations. By 1860, Dalton's atomic theory and new technologies had helped identify more than 60 elements. Chemists were beginning to suspect that patterns based on chemical reactions might be used to develop 'a **taxonomy** of **elements**'. A three-day meeting held in Karlsruhe, Germany, provided a forum for open, collaborative discussion between leading scientists of the day.

In the decade following this first example of an international scientific conference, at least six different classifications of elements emerged. The best known today was developed by a Russian, Dmitri Mendeleev (1834–1907). He approached the problem by summarizing the properties of all the known elements on a set of cards, which he shuffled in search of recurring patterns. One day he had a crucial insight: the set was incomplete! Based on the trends revealed by his organization, he even predicted the properties of missing elements, later shown to be largely correct.

This was the origin of the construct now called the **periodic table**, an organizer you will refer to many times during your course of Chemistry.

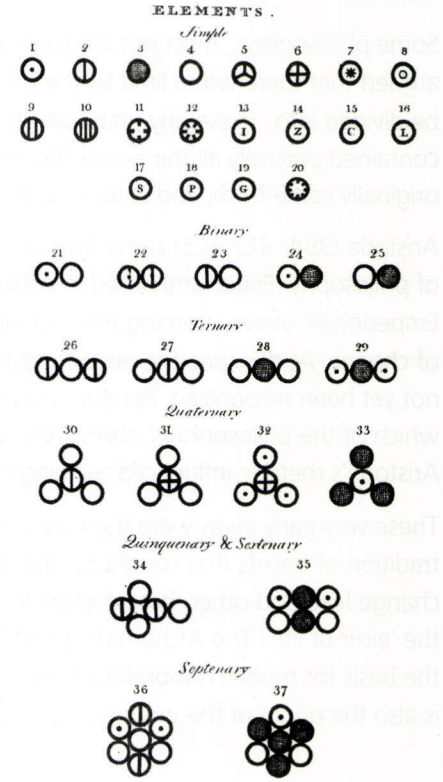



**Figure 1.5** A diagram from John Dalton's text, *A New System of Chemical Philosophy* (1808) modelling aspects of his atomic theory

## Critical thinking about language

In science, argumentation helps make thinking visible. Every **claim** or opinion should be **justified** by referring to observable **evidence**. If there is more than one possible, logical interpretation, further experimentation may resolve the argument.

# ACTIVITY: Three-Level Guide

### ATL

- Communication skills: Read critically and for comprehension; make inferences and draw conclusions
- Critical-thinking skills: Gather and organize relevant information to formulate an argument; test generalizations and conclusions

A Three-Level Guide is a strategy to help you learn how to interpret challenging text. The claims are grouped according to whether the text supports them literally, whether they can be inferred from it, or whether it is debatable. With practice, this activity helps you understand how texts can be read in different ways.

Read pages 5–6 about scientific ideas and discoveries of matter in history. Decide whether you agree with each of the statements that follow. Prepare to discuss and justify your answers with your partner. As you do this, reflect which responses are easiest to resolve.

### Claims made in the text

Level 1: Literal statements. Tick the box if you think the text actually says this.

- ☐ **Empedocles died aged 40.**
- ☐ **Empedocles and Democritus never met.**
- ☐ **Lavoisier isolated oxygen by heating a mineral of mercury.**
- ☐ **Elements are a form of matter that consists of identical atoms.**
- ☐ **Pressure is caused by atoms bouncing on a surface.**
- ☐ **Alchemists were the first chemists.**

Level 2: Interpretative statements. Tick the relevant box if you think the text supports these opinions.

- ☐ **Sicily was part of ancient Greece.**
- ☐ **Platonism is named after the Greek philosopher Plato (approximately 423–347 BCE).**
- ☐ **Scientific knowledge can only progress when it is tested experimentally.**
- ☐ **The ancient Greeks' four elements were developed from Babylonian traditions.**
- ☐ **Any matter can exist as solid, liquid or gas states, depending on its temperature.**
- ☐ **Science is a collaborative endeavour.**

Level 3: Applied statements. Tick the box if you think this is a 'take-home' message from the text. Be prepared to justify your opinion.

- ☐ **Everything – planets, chemicals and light – consists of particles.**
- ☐ **Ideas from ancient Greece endure to this day.**
- ☐ **The ability to do science is not limited to a particular nation or gender.**
- ☐ **Ideas are more powerful than action.**
- ☐ **Amazing breakthroughs do not always require sophisticated technologies.**
- ☐ **Science is 'ideologically neutral'.**

### Assessment opportunities

- In this activity you have practised skills that are assessed using Criterion A: Knowing and understanding and Criterion D: Reflecting on the impacts of science.

# How can we measure properties of matter?

## *STATING* THE OBVIOUS?

You may often have noticed evidence of matter expanding and contracting in response to the surrounding temperature. Examples include the sizes of the 'expansion joints' in solid railway lines or bridges, the amount that overhead power cables sag during different seasons, or how the liquid inside a thermometer rises and falls in response to different temperatures.

### DISCUSS

1. **Outline** how three-level guides can develop your literacy skills.
2. **Apply** Lavoisier's law of conservation of matter to **explain** your observations in the Activity: How does matter add up? (page 4).
3. **Describe** how Dalton's atomic theory models
   a. the organization of matter in gases, liquids and solids
   b. elements and compounds.
4. Reflect on what the following incident **suggests** about how science works.
   Mendeleev's approach of using cards to finding patterns. Can you think of other problems that might be solved in a similar way?

## MATTER AND TEMPERATURE

Let's consider alternative explanations for hypotheses that relate observations about how matter (the independent variable) responds to temperature. If expansion and contraction (the dependent variable) in solids, liquids and gases are caused by changes in the:

- numbers of atoms objects contain, then hot objects (which are larger) will have more particles, and therefore more mass
- sizes of the particles objects contain, then hot objects (which are larger) will have larger particles, and therefore more mass
- spaces between the particles objects contain, then hot objects (which are larger) have the same number of particles as cold objects and, therefore, the same mass.

A simple investigation should be able to identify the correct scientific reasoning. **Occam's razor** assumes that space does not have mass and rules out more complicated explanations.

### Hypothesizing: making scientific predictions

A **hypothesis** is a prediction, explained by scientific reasoning. If two competing hypotheses explain evidence equally well, a recommended strategy is to select the one that uses the fewest assumptions.

### THINK–PAIR–SHARE

How might you test whether mass is affected by temperature?

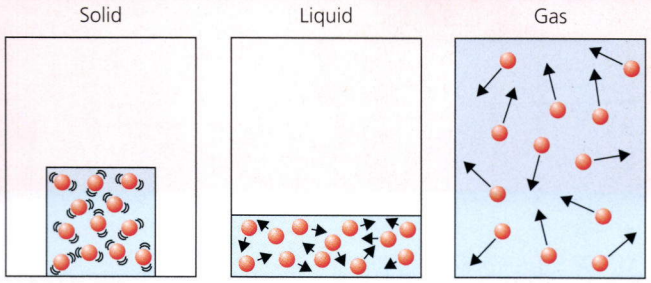



**Figure 1.6** A schematic representation of particles in a solid, liquid and gas. The relative sizes of the arrows represent the average kinetic energies of the particles in these three states of matter

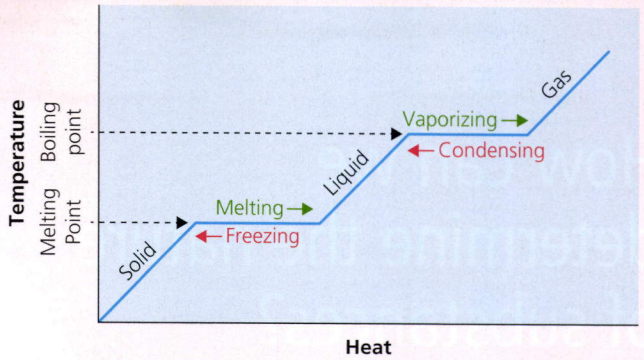



**Figure 1.8** State-change temperature plateaux as matter is heated and cooled

## A model for matter in different states

Any observations you are likely to have made would have involved matter in the same state. The atomic theory, or **kinetic molecular theory**, describes **changes of state** (Figure 1.6) in terms of the movement energy and spaces between particles.

Objects we can see as solid have a fixed volume and shape. From this we can infer that particles in a solid are strongly bonded and have order. The forces of attraction between particles are higher than other forces, if these are present.

The matter we see as liquid has volume, but no shape. From this we can infer that particles in a liquid are bonded but are disordered because they can move around each other, for example when we stir tea. The forces of attraction between particles in a liquid are stronger than other forces, but much less than in a solid.

The evidence from ease of mixing, high compressibility and very low density compared to solids and liquids suggests that matter of a gas is not in contact. As a consequence of weaker attractive forces compared to particles in solids and liquids, gas particles do not have boundaries, instead quickly filling the volume of any container they are in. They also tend to have particles with higher kinetic energy (move rapidly). Whenever a gas particle collides with a surface, it exerts a tiny amount of pressure.

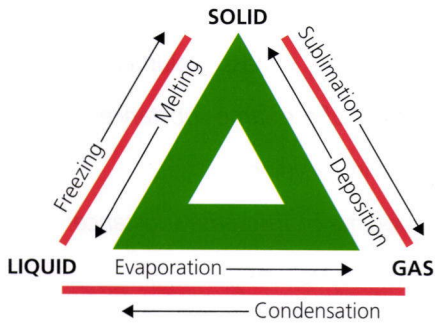



**Figure 1.7** Processes that link the states of matter

### THINK–PAIR–SHARE

**Suggest** how this model comparing the relative kinetic energies and order of particles in solids and liquids might explain how a solid substance like sugar or salt might dissolve in a liquid.

## STATE CHANGES

What happens at the transitions between the states of matter: freezing and melting between solid and liquid states, or **condensing** and **evaporating** between gas and liquid states (Figure 1.7)?

State changes involve matter absorbing or losing thermal energy and are completely reversible. Temperature measurements of matter that is changing state, for example as it is being heated to melt from solid to liquid, or to boil from liquid to gas, are constant. Similarly, as gases cool to liquids and liquids freeze to solids, each state change involves the release of the equivalent amount of thermal energy (Figure 1.8). This constant temperature indicates that there is no increase in the average kinetic energy of the particles (see Chapter 6).

How, then, does matter incorporate thermal energy internally? During the transition process, the forces of attraction between particles are changing (strengthening or weakening), which is evident in the average separation distance between particles. This we can measure as thermal expansion or contraction.

A liquid boils at the temperature at which its **vapour** (evaporating particles) has the same pressure as the surrounding pressure. At higher altitudes air is rarefied (thinner), so pressures are lower, which makes it easier for some of the particles of a liquid to gain enough kinetic energy to escape as gas.

# How can we determine the nature of substances?

## STANDARDIZING MATTER

When particles are too small to be seen (even with a good light microscope), our knowledge relies on interpretations of hidden events. So far, our inquiries suggest:

- The only constant is mass. The total mass did not change when
  - alcohol was mixed with water, even though the total volume of the combined liquids was less than the volumes of the liquids measured apart
  - matter is heated or cooled, changing the average separation distance (space) between particles.
- Local physical conditions, including air pressure and temperature at different altitudes can affect physical properties like state changes.

For scientists to be confident their descriptions were consistent, they needed to agree on a global standard. An International System of Units for science first emerged during the French Revolution. The abbreviated name, 'SI', comes from the French: *Le Système International d'Unités*.

Another international body, the International Union of Pure and Applied Chemistry (IUPAC), uses SI units to define reference conditions for describing pure matter. Standard conditions for temperature and pressure (usually abbreviated, '**STP**') are 0 °C (or 273.15 K) and 100 kPa (or the 'ideal' atmospheric pressure at sea level).

## ACTIVITY: Standardizing matter

### ATL

- **Critical-thinking skills:** Interpret data; draw reasonable conclusions and generalizations

1. **State** what the following abbreviations mean:
   a. SI
   b. IUPAC
   c. STP.
2. **Outline** why your drink stays 'icy cold' when you add ice cubes.
3. **Explain** why a globally consistent approach to describing matter is important.
4. There is a fourth state of matter called *plasma*, found in extremely hot environments like the Sun. **Suggest** why Dalton did not include this form in his atomic theory.

### Assessment opportunities

- In this activity you have practised skills that are assessed using Criterion A: Knowing and understanding.

## Density

**Density** is a relationship of mass to unit volume:

density (rho, $\rho$) = mass/volume

Therefore, the SI unit for density is $kg\,m^{-3}$.

For example, if: $mass_1/volume_1 = mass_2/volume_2$

*To find an unknown mass of the same substance:*

$mass_1 = (mass_2/volume_2) \times volume_1$

*To find an unknown volume of the same substance:*

$volume_1 = (mass_1)/(mass_2/volume_2)$

$= mass_1 \times (volume_2/mass_2)$

## ! Take action: What is the fairest use of our resources?

! In this activity we will apply understanding of density to compare resource use.

! To whom do you feel the greatest responsibility to share resources?

**1 Rank these suggestions of communities in order of importance to you:**

- **a Earth's human population**
- **b My immediate family**
- **c Future global populations**
- **d My local community**
- **e My future family**
- **f All other living organisms, e.g. plants and animals**

**2 Is there a pattern in the relationships you have chosen to rank more highly? Although people usually feel the greatest commitment to individuals they are close to personally, a little reflection reveals we are linked to all living organisms, and to future generations.**

**Your action uses your knowledge of chemistry to provoke awareness in the school community about resources all of us use, all the time.**

**3 a Use the Internet to identify two examples of non-renewable resources (for example, a particular fuel or a metal used to package consumables). Use the table below.**

| Non-renewable resource | Estimated mass used in time periods shown (kg) | | | | |
|---|---|---|---|---|---|
| | Day | Week | Month | Year | Generation |
| A | | | | | |
| B | | | | | |

**b Also record the density (mass/volume at STP) of these two types of matter.**

**c In the first column, estimate the mass (in kg) of the matter you are responsible for using each day. (If the resource is shared, estimate the fraction used to support you.)**

**d Extend your estimates to calculate your use over a month, a year or a generation (assume 25 years) by multiplying your daily estimate by 7, 30, 365 and so on.**

**e Use the density information from part b to estimate the volume occupied by the resource in any two of the time periods of your table.**

A sample calculation is shown below. Note that this is an example of a **renewable** resource. Water (liquid) is a renewable resource because it is recycled by natural processes.

Estimated daily use (i.e. drinking, cooking, bathroom): 120 litres (or 0.120 $m^3$)

Density: 1000 $kg\,m^{-3}$

Using density to calculate mass:

Mass = density (mass/volume) × volume used

= 120 kg

**4 Applying your knowledge! Collectively, build an exhibit to show the volumes of the non-renewable resources we use in our lives. Use recycled cardboard to create boxes of the same volume.**

### DISCUSS

- **Learning to learn: evaluate how effective displays are for modelling concepts.**
- **Do you personally now feel more motivated to use fewer non-renewable resources?**
  - **How might you achieve that (i.e. use fewer non-renewable resources)?**
  - **How can estimation help you develop your confidence in approaching calculations?**

## ◆ Assessment opportunities

◆ In this activity you have practised skills that are assessed using Criterion A: Knowledge and understanding.

## Presenting data: using standard notation and SI units

### Significant figures

**Significant figures** refer to the number of digits known with certainty, and the next (uncertain) digit. All these digits are carried through the working of a problem and appear in the solution, which should be rounded to the same level of significance.

For example, using **scientific notation** a 4000 metre length could be expressed as $4 \times 10^3$ m, $4.0 \times 10^3$ m, $4.00 \times 10^3$ m and $4.000 \times 10^3$ m, to 1, 2, 3 and 4 significant figures respectively.

### Operations using exponents

#### *Addition and subtraction*

The exponents need to be the same, e.g.:

1 $1.2 \times 10^3\,\text{m} + 10.6 \times 10^2\,\text{m}$

$= 12 \times 10^2\,\text{m} + 10.6 \times 10^2\,\text{m}$

$= (12 + 10.6) \times 10^2\,\text{m}$

$= 23 \times 10^2\,\text{m} = 2.3 \times 10^3\,\text{m}$

(note that we can only quote to the significant figures of the least accurate value in the calculation, i.e. $1.2 \times 10^3$).

2 $2.04 \times 10^6 - 4.70 \times 10^5$

$= 2.04 \times 10^6 - 0.470 \times 10^6$

$= (2.04 - 0.470) \times 10^6$

$= 1.57 \times 10^6$ (three significant figures, or 3 sf).

#### *Multiplication and division*

Add or subtract the exponents, e.g.:

1 **find** the volume of a rectangular brick building with dimensions 3.25 × 10 m, $1.305 \times 10^2$ m and 5.2 m.

$= (3.25 \times 1.305 \times 5.2) \times 10^{(1+2+0)}\,\text{m}$

$= 22 \times 10^3\,\text{m} = 2.2 \times 10^4\,\text{m}$ (2sf)

(two significant figures, because we can only quote to the significant figures of the least accurate value in the calculation, i.e. 5.2).

2 **find** $(3.2/1.6) \times 10^{(-3+-6)}$

$= 2.0 \times 10^{-9}$ (2 sf)

### Links to: Mathematics (Numeracy)

When describing values in science the use of exponents (powers) avoids uncertainty around the **significance** of the numbers. If you know how to add, subtract, multiply and divide numbers that are expressed in **scientific notation**, you have the numeracy tools to be a successful scientist.

There is on the common a large pond which I observed one day to be very rough with the wind. I fetched out a cruet of oil and dropped a little of it on the water. I saw it spread itself with surprising swiftness upon the surface… I then went to the windward side where [the waves] began to form; and there the oil, though not more than a teaspoonful, produced an instant calm over a space several yards square which spread amazingly and extended itself gradually till it reached the lee side, making all that quarter of the pond, perhaps half an acre, as smooth as a looking glass.

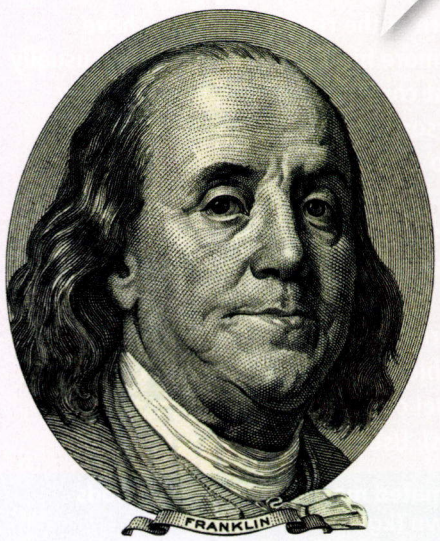



**Figure 1.9** Benjamin Franklin

How thin can an oil spill spread? The first **quantitative** recorded measurement was by the American inventor Benjamin Franklin in 1762, when he repeated an experiment first performed by the Roman thinker, Pliny the elder (23–79 AD). Read what he has to say in Figure 1.9.

### EXPLANATION Game

Use the Explanation Game to **suggest** how invisible particles in Franklin's 'teaspoon' of oil might have covered 'half an acre' (2023.4 m²) of the 'pond matter'.

# ACTIVITY: Using scientific notation and SI units to estimate the size of a particle of matter

## ATL

- **Collaboration skills**: Delegate and share responsibility for decision-making; encourage others to contribute
- **Critical-thinking skills**: Practise observing carefully in order to recognize problems

The English scientist Lord Rayleigh (1842–1919) hypothesized that the thinnest layer would be just one molecule thick. You are going to repeat Rayleigh's experiment.

Work with a team in a calm area outdoors, to avoid water damage to indoor flooring. Alternatively, protect the floor of an indoor area with painter's plastic sheeting.

### Materials and equipment

- a very precise electronic balance
- a fine pipette
- a large tub filled with water (e.g. a child's paddling pool)
- a measuring tape
- vegetable oil (e.g. olive oil)
- (optional) a fine powder to help detect the edge of the oil film. Moss spores called *Lycopodium* powder is recommended, but very fine, dry talc may also work.

**Safety:** Take care when using glassware! You should always wear covered shoes in a laboratory, and never taste chemicals. If using *Lycopodium* powder, take care not to inhale it as it can be an allergen for some people.

### Method

1. Fill the paddling pool with 3–5 cm of water to provide a calm, even surface.
2. (Optional) Sprinkle *Lycopodium* powder on the surface, or clap your hands with some talc between them just above the surface.
3. Using the balance, **measure** the mass of 'practice droplets' of oil until your pipetting technique produces a consistent amount. Record this mass. (Less than 0.5 g is ideal.)
4. Pipette a droplet of oil close to the middle of the paddling pool.
5. Be ready to measure the diameter of the film at its widest point (it should not touch the edges of the paddling pool).

### Processing and evaluating your data

#### Presenting and organizing data

1. **Convert your recorded values for the mass of the droplet and the radius of the oil film to scientific notation, using SI units.**
2. **Most vegetable oils, including coconut oil, have a density of 0.92 kg $m^{-3}$.**
   **Assuming the droplet was cubic ($m^3$), calculate the mass of your droplet.**
3. **The formula for the area of a circle is: $A = \pi r^2$.**
   **Calculate the area of the oil film ($m^2$).**
4. **Estimate the size of an oil molecule, assuming the units for the volume of oil used ($V = A \times h$) are $m^3 = m^2 \times$ the length of the molecule.**
5. **If you had opportunities to repeat the experiment, or access to results obtained by other teams, calculate the mean and range for the set of results. Refer to the section, 'Why do scientists use replicates', overleaf.**

#### Reflecting on the validity of Rayleigh's hypothesis

1. **Suggest how confident you can be that the oil film was just one oil molecule thick. (Hint: Figure 1.9).**

#### Reflecting on the validity of the method

1. **Estimate how large the range of the data was.**
2. **If all the teams used the same paddling pool, suggest whether there were any patterns in the results, and what might have caused this.**
3. **You made two measurements during your experiment. Identify which of these had greater uncertainty.**

#### How might your method have been improved?

1. **Rayleigh's results, and other methods, suggest that the length of the oil molecules was about $2 \times 10^{-9}$ m (2 nanometres). The method you have used is extremely crude, and it may be chance if the spread of results obtained were similar to this value. However, the size of the error may enable you to suggest where changes in your approach may make the greatest difference.**

## Assessment opportunities

- This activity can be assessed using Criterion C: Processing and evaluating.

# What are some examples of physical and chemical properties of matter?

## HOW CAN I BE CONFIDENT OF THE RESULTS OF MY INVESTIGATION?

### Why do scientists use replicates?

**Replicate tests** (also called **repeats** or **duplicates**) in an experiment give you greater confidence that your results are correct.

All experimental data have variability. This can be caused by variation in the sample (particularly in, but not limited to, biological populations), or by variations in the process, for example unintended differences when using standard procedures (e.g. measurement error) or systematic variations caused by incorrectly calibrated equipment, contamination or uncontrolled environments. Every data point is an important indicator of the **reliability** of the investigation process. Discarding data points will introduce bias and damage the integrity of the experiment. Repeat trials provide 'data sets' which improve confidence in whether differences between treatments are real.

### Statistical treatment of replicates

The most common statistical treatments are *mean, median, mode, range* and (in MYP extended mathematics) *standard deviation*. The use of spreadsheets simplifies these calculations.

In your science reports, you should use only the processes with which you are familiar and which you understand.

### Brainstorming

A brainstorm is a collaborative tool for open-minded sharing of ideas. During a brainstorm, all suggestions from participants will be accepted and recorded visually. Brainstorming supports creative thinking because:

- quantity will generate quality
- acceptance without criticism will encourage divergent problem solving
- unusual ideas may provide novel solutions and perspectives
- ideas are improved when combined or associated with others.

## ACTIVITY: Clarifying properties

**ATL**

- Communication skills: Give and receive meaningful feedback; use appropriate forms of writing for different purposes and audiences
- Creative-thinking skills: Use brainstorming and visual diagrams to generate new ideas and inquiries; consider multiple alternatives, including those that might be unlikely or impossible; practise flexible thinking – develop multiple opposing, contradictory and complementary arguments

By 'property' we mean how an object looks, feels, or behaves. Brainstorm examples of properties of matter.

### Conversation triads

In this learning strategy, each member of your group takes each role in turn. The Speaker responds to the situation, uninterrupted for up to two minutes. The Listener paraphrases the speaker's information. The Observer takes notes, and provides constructive feedback, including making comments of an affective nature (e.g. the confidence of members of the group in managing material).

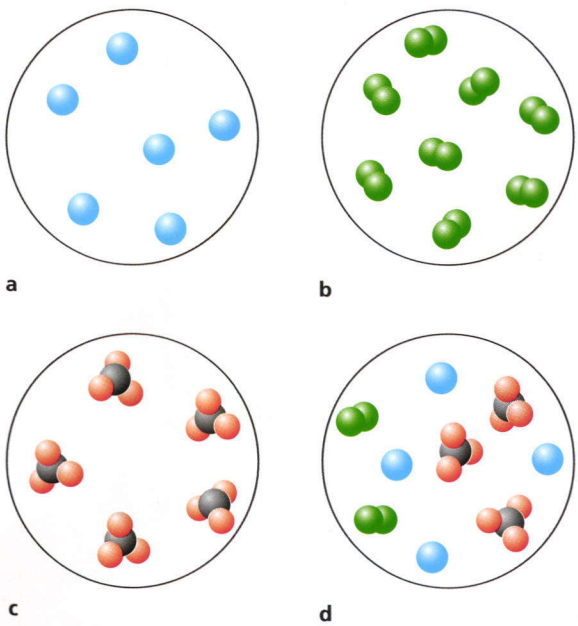
1 **Which of these properties:**
   - **a are physical (how it looks or feels)?**
   - **b are chemical (how it reacts with other substances)?**
   - **c never changes?**
   - **d are measurable?**

## REFLECTING on matter

1 **The diagrams in Figure 1.10 use different coloured spheres to represent the atoms of different elements. Use these terms to describe what each of the diagrams represent: *pure substance, mixture, atom, molecule, element, compound.***

2 **Sketch a similar diagram to show a mixture consisting of a combination of**
   - **a two elements**
   - **b a compound and an element.**

3 **Predict whether the matter of the familiar materials in the table is likely to be pure, and which are likely to be mixtures.**




■ **Figure 1.10**

| | Material | Pure matter? | Mixed matter? |
|---|---|---|---|
| a | PVC drink bottle | | |
| b | Soup | | |
| c | Ice cream | | |
| d | Yoghurt | | |
| e | Coffee | | |
| f | Table salt | | |
| g | Cake | | |

4 **The matter in these common household materials is usually nearly pure. List some properties you associate with these materials. The first example is completed for you.**

| | Material | Properties |
|---|---|---|
| a | Iron nail | *solid, metallic, grey* |
| b | Water | |
| c | Sugar | |
| d | Ghee (clarified butter) | |
| e | 'Methylated spirits' (cleaning alcohol) | |

### ◆ Assessment opportunities

◆ In this activity you have practised skills that are assessed using Criterion A: Knowing and understanding.

# RE-IMAGINING MATTER

## Defining chemical 'purity'

When matter consists of particles of the same type, it is considered 'pure', whether it consists of single atoms or molecules (atoms joined chemically). All elements are pure, because they consist of identical atoms. Compounds are pure because their molecules are identical, consisting of ions or atoms from more than one element combined in particular ratios. For example, water is a compound of hydrogen and oxygen, and pure water consists only of water molecules.

A mixture is any combination of elements and compounds. Mixtures differ from compounds in that the elements in them are not necessarily chemically bonded, and can therefore be separated using purely physical processes (Chapter 2). Unlike compounds, the components in mixtures do not have to be in particular ratios. Soft drinks and sea water are examples, because you can have 'concentrated' and 'dilute' versions, depending on how much of the solid or gas has been added to the liquid.

# ACTIVITY: Investigating the effect of impurities on the properties of matter

## ATL

- Organization skills: Plan short- and long-term assignments, meet deadlines; set goals that are challenging and realistic; select and use technology effectively and productively

**Individually or in pairs:** In this activity you will design an investigation to **identify** the differences in properties between pure and impure substances.

Start by brainstorming some examples of materials you think may be pure, and mixtures you may know about. Look at this list for some ideas:

- **ice cube made from laboratory distilled water**
- **sea-water ice from the Arctic**
- **unsweetened black tea**
- **a gold wedding ring**
- **a glass window pane**
- **an iron cooking pot**
- **ice cream**
- **a plastic bag.**

**Safety:** Make sure your teacher checks your investigation design before you begin. Remember that in the laboratory even familiar substances should be treated with care, in accordance with your laboratory safety rules. Consider also the environmental impact of your experiment – especially when disposing of materials.

### Your task

In this task you will be working in the laboratory using standard laboratory apparatus. You are required to identify a property of a 'pure' substance, and compare how this property changes as a result of adding an impurity. It is recommended you consider familiar, inexpensive materials for this first investigation.

The inquiry cycle (Figure 1.11) summarizes the design and reporting process used to carry out an experimental investigation. By representing the development of scientific understanding through a cycle beginning with reflection, planned action and then returning to critical evaluation and further reflection, this inquiry cycle captures how our scientific knowledge has grown through time. All inquiry cycles are **iterative**: they offer repeated opportunities to develop and master the skills they emphasize. You will also find that many of the skills they include are transferable to other subjects.

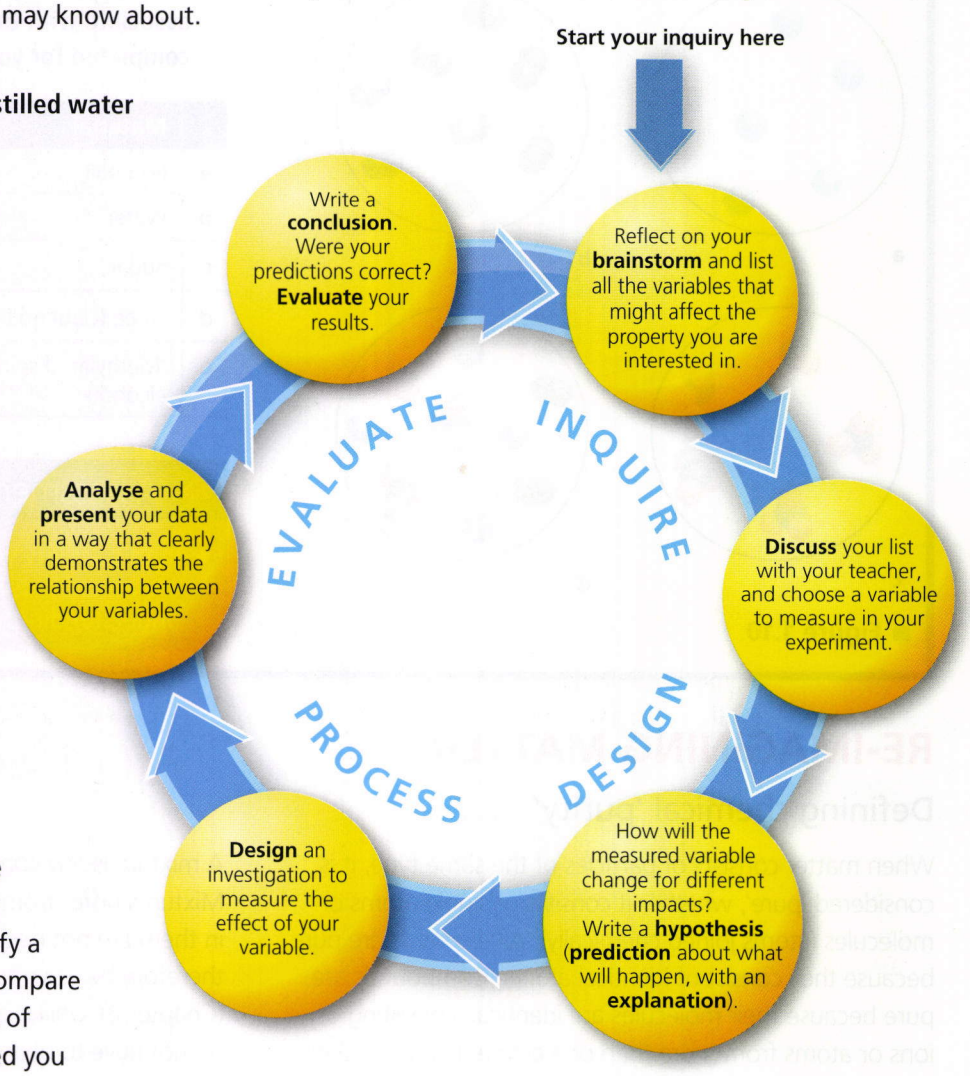



**Figure 1.11** The scientific experiment cycle is broadly divided between inquiring and designing, and processing and evaluating

## An application of inquiry

1 **For this investigation, it may be helpful to identify possible variables by completing the table below. As you master the skill of writing scientific investigation reports, you will be expected to identify and describe these variables using your own words.**

| Type of variable | Examples | Measurements needed (e.g. quantity or quality/units) |
|---|---|---|
| Independent (IV)<br><br>The variable that could be changed deliberately | Your impurity | |
| Controlled (CV)<br><br>The variables that are kept the same, to make your investigation scientifically valid<br><br>An experimental control provides a reference for comparison with the test conditions | Your pure substance | |
| Dependent (DV)<br><br>The variable that changes as a result of your manipulation of the independent variable | Changes in the physical property you will measure | |

2 **Ideally, your hypothesis should be worded so your prediction is followed by scientific reasoning based on your own understanding of this research using secondary sources.**

**If I change [the independent variable] ..... ..... then [the dependent variable] ..... will change by ....., because [scientific reasons] .....**

3 **When reporting your results, consider:**
   - a **tabulating only the 'average' of your replicate observations – additional columns may be used to record maximum and minimum results in this table**
   - b **graphing only the 'average' results of your replicate observations. The values for independent variables should be shown along the *x*-axis, and the dependent variables along the *y*-axis. Represent the range of your results in some way. For example, 'box-and-whisker' representations could indicate the maximum and minimum observations on the line graph. Showing the range of replicate results for each group of observations will help you analyse your results in the later stage of your report.**

4 **When reporting your results,**
   - a **state whether your results support or refute (disprove) your hypothesis**
   - b **comment on the reliability of your results; reflect on how closely results are clustered around the mean – very scattered results, or 'outliers', need to be explained**
   - c **comment on the validity of your results – reflect on whether your results could have any alternative explanation apart from the problem you planned.**

5 **Finally, evaluate the validity of the method. This means, that the measurements you made were relevant to the properties you investigated. The range of your data for repeated trials may give you an indication.**

### Assessment opportunities

- This activity can be assessed using Criterion B: Inquiring and designing, and Criterion C: Processing and evaluating.

# ACTIVITY: Comparing chemical with physical change

## ATL

- Critical-thinking skills: Practise observing carefully in order to recognize problems; revise understanding based on new information and evidence

Your inquiries into matter have all involved observing evidence caused by physical changes, for example changes caused by mixing matter or manipulating conditions like the temperature.

In this activity you will identify similarities and differences before and after combustion of a candle, and identify physical and chemical changes.

**In pairs or in groups, discuss:** what changes do we observe when something burns (undergoes **combustion**)?

**Classify** the changes you identified as **physical** or **chemical** changes.

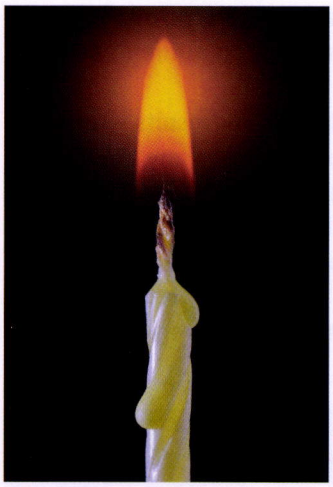


**Figure 1.12** What types of change can you see as a candle burns?

Collect the equipment.

*Before* lighting the candle, read the prompts for inquiry, to prepare for the class discussion. **Write** the **aim** of your experiment in the form of an **inquiry question**.

### Materials and equipment (per group)

- **birthday candle**
- **matches**
- **safety/heat mat**
- **electronic balance**

### Method

1. **Weigh the candle.**
2. **Light the candle and set it on the safety mat with a drop of melted wax.**
3. **Let the candle burn until it is extinguished.**
4. **Weigh any remaining mass.**

### Observations

While the candle burns, **observe** carefully and **record** all the changes you see taking place. **Organize** your observations so that they are clear and easy to interpret.

### Prompts for inquiry

- **What has happened to the wax body of the candle?**
- **What has happened to the wick?**
- **What was produced during the combustion process?**
- **What is the function of the wick?**
- **Where do the heat and light come from?**
- **How might the changes be stopped?**
- **Are any of the changes reversible?**

## Assessment opportunities

- In this activity you have practised skills that can be assessed using Criterion B: Inquiring and designing.

# DISCUSS

The 19th century French microbiologist Louis Pasteur is famous for stating: 'Chance favours only the prepared mind.' By this he meant his scientific insights were no simple accidents, but came about because he was alert to finding relationships in his observations.

1. **Did the prompts for inquiry help you observe? Could there be any disadvantages in providing a list of questions to guide you?**
2. **Which of the questions referred to physical changes?**
3. **Which questions referred to other types of change?**
4. **What has this activity taught you about chemical change? You may want to start a list.**
5. **Share suggestions how you can also develop a 'prepared mind'.**

# Has our ability to measure things more precisely changed our ideas about the material world?

## Links to: Design (Technology)

Uses for new materials are constantly being introduced through design technology. Examples include materials used for construction, communication, transport and in health. Each innovative change was enabled through our understanding of the nature of matter.



### The contexts of science

Science does not develop in isolation: it develops in the social contexts where it is used or needed. Depending on their moral, ethical, social, economic, political, cultural or environmental perspectives and interests, different societies can develop different technological solutions. For example, to avoid the common problem of diseases caused by contaminated water, some cultures developed traditions that used fermented alcohol and others invented tea drinking. Each solution used different physical and chemical properties of matter.

## Take action: Mimicking matter

Models are never perfect but can clarify concepts by simplifying them by making the invisible visible. How might a model help someone understand these phenomena?

- two blended liquids occupy less volume than each does separately
- while matter is changing state, its temperature does not change
- pure matter can have different properties from impure matter

1 **Make a dramatic classroom display of one of these concepts, or a virtual model that is scientifically more accurate than many found online (search state changes).**
2 **Estimate the amount the particles have been enlarged in your replica. Assume that an atom has a diameter of $10^{-10}$ m.**
3 **Evaluate the limitations of your model.**

### Assessment opportunities

- In this activity you have practised skills that are assessed using Criterion C: Processing and evaluating.

## ACTIVITY: Gallery walk

### ATL

- Communication skills: Give and receive meaningful feedback; share ideas with multiple audiences using a variety of digital environments and media
- Collaboration skills: Practise empathy; help others succeed; encourage others to contribute; give and receive meaningful feedback
- Affective skills: Practise strategies to develop mental focus; practise managing self-talk; practise positive thinking

Hold a student-led conference on: 'Reflecting on how matter really matters'.

This activity models a poster session at a 'scientific' conference. All the presentation material will be on display simultaneously. The class will be divided into two groups that will rotate roles within the allocated time. While one group of students 'gallery walks' around the display, asking questions on areas of interest, students in the other group stand next to their own presentation and briefly explain their research, entering into discussion.

At the end of the conference, each student selects one of the presentations for praise, and shares with the class what it was that impressed them.

In this activity, begin by choosing one 'mixed' substance from medication, agriculture, or 21st century technology.

- **Analyse** it to identify the 'pure' substances within it.
- **Then describe** how this material was isolated, discovered, made using its properties.
- **Then evaluate** the use of that material in terms of its social, political, economic, ethical, moral, environmental or political impacts.

Present your substance (matter) visually, for example as a poster, or a brief electronic slideshow, for example using Prezi™ or a PowerPoint ® presentation. Whatever the format, you should also be able to communicate your message orally in five minutes or less, referring to the visuals that support your presentation.

### How to reflect on the impact of the matter you selected

- **What problem or issue does your matter address? Describe the matter you selected, for example its chemical structure (state at STP) and other standardized properties. Explain how this matter is used and made available to us.**
- **Scientific knowledge always interacts with moral, ethical, social, economic, political, cultural or environmental factors in our world. Explain how your selected substance does this. For example, who needs to know this? Why should we care? How can we balance impacts which are advantageous and disadvantageous?**
- **Fluent, confident oral presentations are the result of practice. Learn to pronounce unfamiliar terms correctly. Complex ideas are best broken down using short sentences. Time yourself, so the entire summary including time for questions does not take longer than five minutes.**
- **Sources should be clearly documented using the school's standard referencing format. These, and notes for your script or a recording of a practice presentation, should be submitted after the poster conference together with your poster.**

### Assessment opportunities

- This activity can be assessed using Criterion D: Reflecting on the impacts of science.

## SUMMARY REFLECTION

1. **How did praise for a quality in your poster make you feel? Would you look forward to participating in a similar activity?**
2. **How important is collaboration for making this activity enjoyable?**
3. **In the past, scientists have sometimes been accused of being poor communicators of their message. What skills are you developing through cooperative learning activities such as 'Gallery walk'?**

# SOME SUMMATIVE PROBLEMS TO TRY

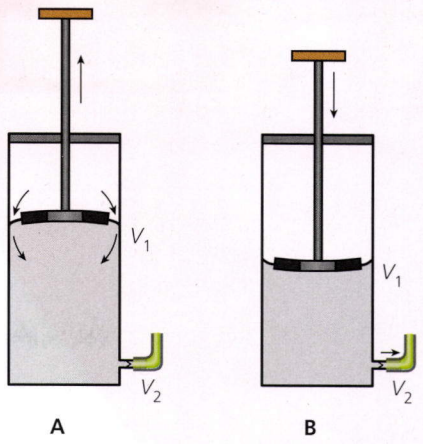
Use these problems to apply and extend your learning in this chapter. The problems are designed so that you can evaluate your learning at different levels of achievement in Criterion A: Knowing and understanding.

## THESE PROBLEMS CAN BE USED TO EVALUATE YOUR LEARNING IN CRITERION A TO LEVEL 1–2

1 **State** one physical property that allows you to distinguish between the following paired examples of matter:
   - **a** soda water and tap water
   - **b** sand and salt
   - **c** gold and iron
   - **d** ethanol and water.

2 **Apply** your knowledge about the attraction and kinetic energy of particles in a solid, liquid or gas to **suggest** the form of matter these groups of people could be modelling:
   - **a** students sitting at desks in the hall taking an external exam
   - **b** a crowd leaving a movie theatre through a single door
   - **c** all the students pushing up against the window of the canteen
   - **d** recess, small children rushing around the play area
   - **e** drama class, everyone walking randomly around, keeping a similar distance apart.

3 Your friend is staying overnight and you are pumping up an air mattress for her to sleep on. Figure 1.13 shows the pump at different positions. After the handle is pulled up (image A), no more air can enter.
   **Interpret** this information and judge:
   - **a** whether the mass of gas inside the pump has changed between position A and B
   - **b** the position of the pump at which the gas it contains is at its most dense.

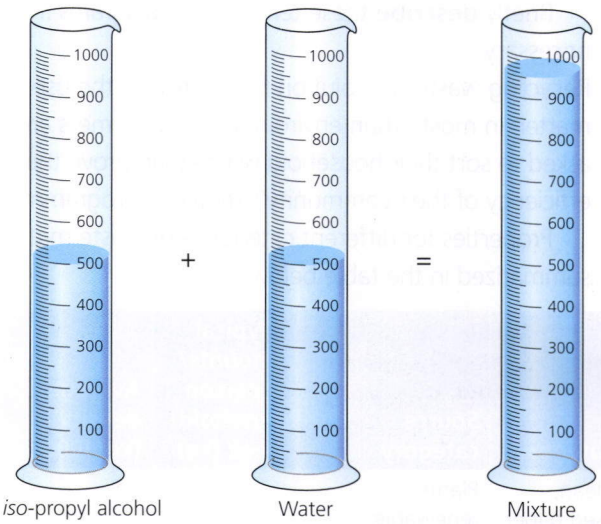



■ **Figure 1.13** A diagram showing how an air pumps between 'strokes'

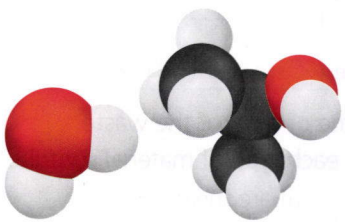
## THESE PROBLEMS CAN BE USED TO EVALUATE YOUR LEARNING IN CRITERION A TO LEVEL 3–4

4 **Outline** reasons for standardizing conditions in which chemists describe matter.

5 In an experiment similar to the Activity: How does matter mix?, a student mixed 500 $cm^3$ each of two pure liquids, *iso*-propyl alcohol (propan-2-ol) and water.
   **Apply** your knowledge and understanding about matter to explain why the total volume of the mixed liquids is less than 1000 $cm^3$.




■ **Figure 1.14** Apparatus for experiment



■ **Figure 1.15** Particle models of *iso*-propyl alcohol and water

6 Your little sister left her balloon in the back seat of a hot car. You return to the car with her after visiting a shopping mall for a few hours and notice the balloon seems a lot bigger. **Interpret** this observation with a scientifically supported judgment about how this may have been caused.

## THESE PROBLEMS CAN BE USED TO EVALUATE YOUR LEARNING IN CRITERION A TO LEVEL 5–6

7 Dalton's atomic theory included (a) elements, (b) atoms, (c) compounds and ideas about (d) states of matter: solids, liquids and gases.

Briefly **describe** these terms, using diagrams if necessary.

8 Recycling waste is a solution for improving the use of matter. In most urban environments, consumers are asked to sort their household waste to improve the efficiency of their community's recycling programmes.

Properties for different categories of waste matter are summarized in the table below.

| Category | Source category | Typical amounts/ 4 person household/ week (kg) | Average density (kg/1000 cm³) |
|---|---|---|---|
| Clean, used paper | Plants, renewable | 5 | 0.5 |
| Metals | Minerals, non-renewable | 1.0 | 2.70 (aluminium)<br>7.87 (steel) |
| Plastics | Fossil fuels, non-renewable | 0.5 | 1.1 (PVC)<br>0.9 (polystyrene) |

a **Calculate** the volume of each of the waste categories. Assume each type of material contributes equally, in categories that are mixtures.

Express your answers using scientific notation.

b In the event of limited transport being available, **suggest** the waste category likely to deliver the best economic returns to the city, if recycled, and why.

9 A grain of sand can be assumed to be a sphere of diameter $10^{-4}$ m. It can be assumed that the particles making the sand grain are $10^{-10}$ m in diameter.

**Estimate** the number of atoms in the grain of sand. Express your answer using scientific notation.

10 The table below shows some physical properties of familiar, everyday substances.

| | Material | Boiling point/°C | Melting point/°C | Density/ kg/1000 cm³ |
|---|---|---|---|---|
| a | PVC drink bottle) | – | 100–260 | 1.3–1.45 |
| b | Table salt | 1465 | 801 | 2.17 |
| c | Gasoline (petrol) | 23.5–190.2 | – | 0.71–0.77 |
| d | Cane sugar (sucrose) | – | 186 | 1.59 |

**Analyse** the information to make scientifically supported judgments about which of these materials is likely to be chemically pure.

## THESE PROBLEMS CAN BE USED TO EVALUATE YOUR LEARNING IN CRITERION A TO LEVEL 7–8

11 **Explain**, using examples about the nature of matter, the limitations of developing scientific knowledge by argument and discussion alone.

12 Consider the following two situations involving the storage of gases:

- Cooking gas is often stored and delivered in steel bottles. Over a period of time, the pressure of the gas in the steel bottle does not change.
- Air and helium are gases that are often used to fill rubber balloons. Over a period of time, the balloons gradually shrink.

a **Explain** these observations, using your scientific understanding about the nature of matter.

b **Suggest** how your ideas might be tested.

**13** **Analyse** and **evaluate** the observations below, to determine whether the changes described are likely to involve the formation of new combinations of matter, or are physical changes.

| | Observation | Chemical or physical? | Scientifically supported judgment |
|---|---|---|---|
| **a** | The edge of a towel hanging in a wet bath draws up water, wetting the entire towel | | |
| **b** | A firecracker explodes, producing noise, smells and smoke | | |
| **c** | Copper is a pink-coloured metal that is often used as cladding (covering) on roofs and domes of important buildings. After a few years, it goes bright green | | |
| **d** | When a clean, dry, very cold glass is placed on a table at room temperature, it quickly becomes covered with small droplets of water | | |

# Reflection

In this chapter we have investigated properties of matter and identified the need to standardize conditions in which it is measured, by using scientific notation, international systems of units, and controlling variables when designing practical investigations. We began to recognize some of the evidence for physical and chemical changes of matter. We shared examples of how matter makes a difference to our communities, and clarified our ideas using models.

| Use this table to reflect on your own learning in this chapter. | | | | | | |
|---|---|---|---|---|---|---|
| Questions we asked | Answers we found | Any further questions now? | | | | |
| **Factual:** What is matter? How can we measure properties of matter? What are some examples of physical and chemical properties of matter? | | | | | | |
| **Conceptual:** How can we determine the nature of substances? | | | | | | |
| **Debatable:** Has our ability to measure things more precisely changed our ideas about the material world? | | | | | | |
| Approaches to learning you used in this chapter: | Description – what new skills did you learn? | How well did you master the skills? | | | | |
| | | Novice | Learner | Practitioner | Expert | |
| **Communication skills** | | | | | | |
| **Collaboration skills** | | | | | | |
| **Organization skills** | | | | | | |
| **Affective skills** | | | | | | |
| **Critical-thinking skills** | | | | | | |
| **Creative-thinking skills** | | | | | | |
| Learner profile attribute(s) | How did you demonstrate your skills as an inquirer in this chapter? | | | | | |
| **Inquirer** | | | | | | |

# 2 How do we use matter?

**Changing conditions** for matter has allowed us to make attractive products that express **who we are and where we are from**.

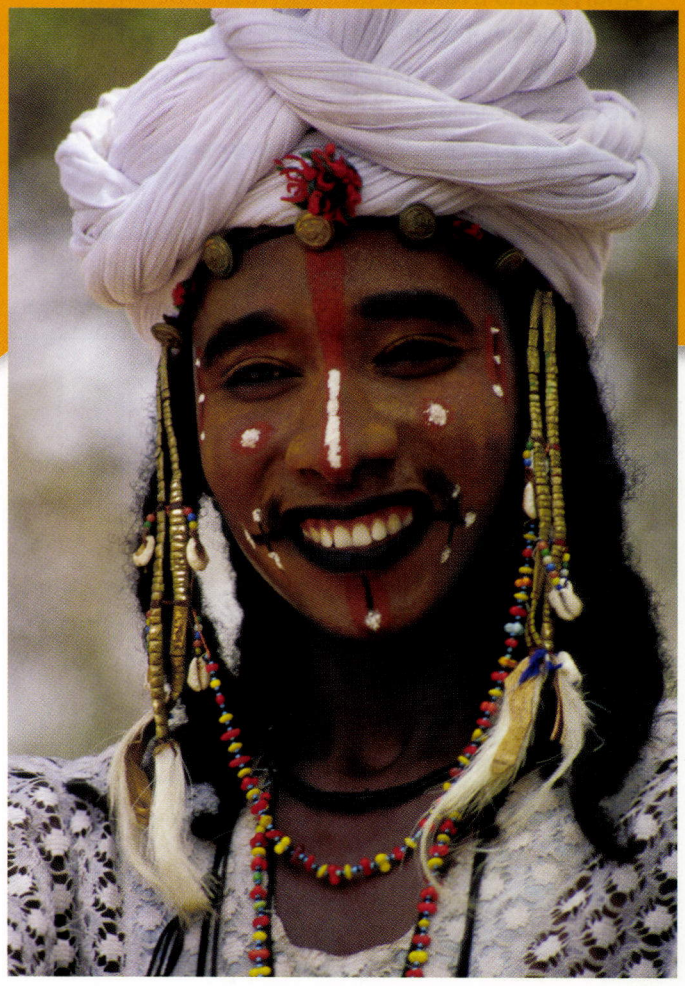


**Figure 2.1** Our endlessly creative approach to body art. How does the chemistry of this man's jewellery, cosmetics and tattoos make matter fit for purpose?

## CONSIDER AND ANSWER THESE QUESTIONS:

**Factual:** What are the differences between pure substances and mixtures? Can mixtures consist of matter in more than one state? Can all mixtures be separated?

**Conceptual:** How do separation techniques rely on physical properties? Which conditions result in the most effective separation process?

**Debatable:** How have our ways of expressing ourselves developed along with our understanding of materials? Does understanding of the nature of mixtures improve our ability to express ourselves?

Now **share and compare** your thoughts and ideas with your partner, or with the whole class.

## IN THIS CHAPTER, WE WILL ...

- **Find out** how pure substances and mixtures serve our cultural needs and creative expression.
- **Explore:**
  - the chemistry of mixtures in domestic and decorative arts;
  - how stable and unstable mixtures behave, and the advantages and disadvantages of this stability;
  - how the differences in physical properties of pure matter are used to separate mixtures;
  - tools and techniques of an analytical chemist.
- **Take action** by creating a range of cosmetic products for use as personalized gifts.



**Figure 2.2** Decorative glass – a slumped glass bowl (moulded by heating) and a core formed glass fish

## These Approaches to Learning (ATL) skills will be useful …

- Organization skills
- Affective skills
- Critical-thinking skills
- Creative-thinking skills
- Transfer skills

## We will reflect on this learner profile attribute …

- **Open mindedness** – How you respond to ideas that differ from yours, whether from other cultures or the scientific community, and your approach to investigation results that contradict your expectations and preconceptions about how matter works and interacts.

## Assessment opportunities in this chapter …

- Criterion A: Knowing and understanding
- Criterion D: Reflecting on the impacts of science

## KEY WORDS

| | |
|---|---|
| filter | gel |
| fuse | solution |

## ACTIVITY: Glass works

Watch some videos of glass objects similar to those in Figure 2.2 being made. What do you think is happening to make these objects? What do you think is happening to the particles when each of the objects is heated? And when the glass solidifies?

You could start with these videos:

Fused and slumped glass: making a bowl **https://youtu.be/Asrlv4t0Yjk**

Core formed glass: a 16th century technique **https://youtu.be/Nocv4qLpxa8**

This chapter will explore how some culturally desirable materials are valued for their mixed physical properties and others for their purity.

# Can mixtures consist of matter in more than one state?

## WHAT ARE THE DIFFERENCES BETWEEN PURE SUBSTANCES AND MIXTURES?

In Chapter 1 we were introduced to a model that described particles in solids, liquids and gases. However, each of these categories can be more complex. For example, in solids, the particles may be closely packed and ordered like stacked oranges, which is called a **'crystalline'** arrangement. If the pattern is made of many crystals, the solid, e.g. metal, is 'polycrystalline'. If the particles seem randomly organized, the solid is described as **'amorphous'** (Figure 2.3).

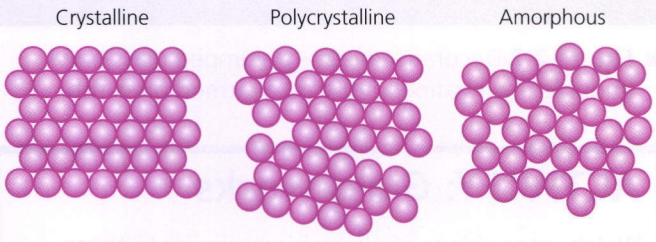



**Figure 2.3** Which of these models for solids best describes the physical properties of glass?

## MATTER IN OUR COMMUNITIES

Figure 2.4 is a flowchart of matter. To 'read' this flowchart, start with the box at the top ('Matter') and follow the arrows to other boxes. A major point of difference in the chemistry of matter is deciding whether a substance is pure or a mixture. You are familiar with the idea that matter may be 'pure' or a 'mixture', represented by 'elements' or 'compounds' (see Chapter 1). Figure 2.4 also introduces new terms, explaining that mixtures can be **homogeneous** or **heterogeneous**. Words by the arrows connecting the boxes describe the relationships between them.

## ACTIVITY: Reflecting on the nature of glass

### ATL

- Critical-thinking skills: Evaluate evidence and arguments

Glass is an example of a material for which appearances can be deceptive. For centuries, people have added chemical substances to the silicates that are the basis of glass in order to produce different and attractive varieties. But what is glass? Research using glass properties to find out.

1. **Describe** the physical properties of glass. **Outline** why pure glass can be considered a 'super-viscous liquid'.
2. **If kinetic molecular theory (Chapter 1) explains the movement and arrangement of particles from solid to liquid to gas as they heat or cool, suggest how it explains:**
   - a **the ductility (ability to be stretched) of molten glass**
   - b **how materials fuse together**
   - c **why a slowly cooled material might be stronger than one cooled quickly**
3. **Identify the model for the arrangement of particles in Figure 2.3 that best explains the behaviour of glass.**
4. **Research glass blowing and decorative glass to find out how artists can manipulate conditions to produce glass of different kinds. Use your research to outline how one special kind of glass is made.**

### Assessment opportunities

- In this activity you have practised skills that are assessed using Criterion A: Knowing and understanding.

### Links to: Visual Arts

Personal and cultural expression in the visual arts uses many types of mixtures, for example: pigments and dyes (painting and textiles), glazes and minerals (ceramics and sculpture). A knowledge and understanding of the chemical and physical properties of the substances involved is likely to enhance the success and durability of the artistic product.

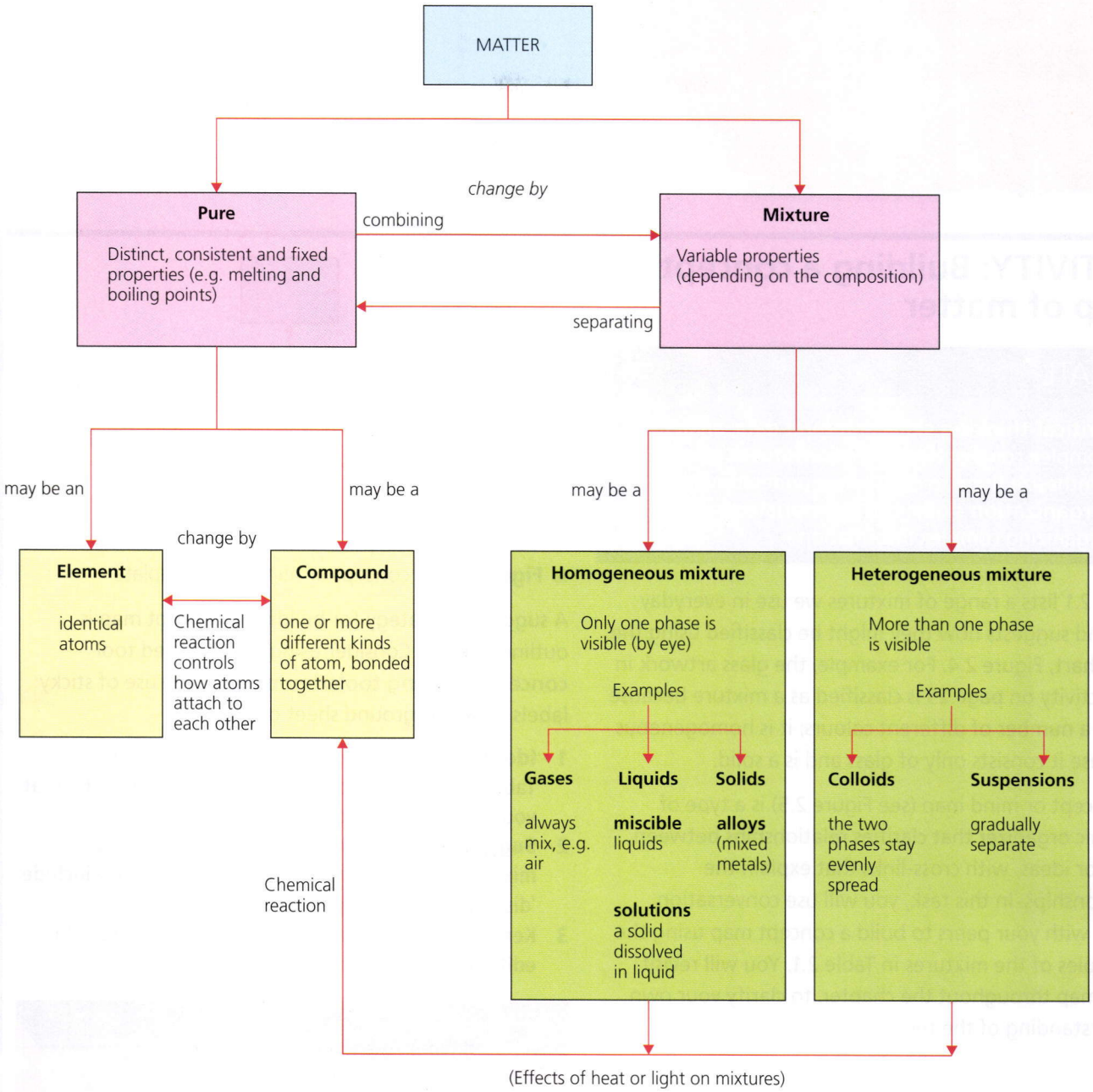



**Figure 2.4** A flowchart describing relationships between arrangements of matter

## ACTIVITY: Building a concept map of matter

### ATL

- **Critical-thinking skills:** Interpret data; analyse complex concepts into their constituent parts and synthesize them to create new understanding
- **Organization skills:** Use appropriate strategies for organizing complex information

Table 2.1 lists a range of mixtures we use in everyday life and suggests how they might be classified using the flowchart, Figure 2.4. For example, the glass artwork in the activity on page 25 is classified as a mixture because it has a number of different colours; it is homogeneous because it consists only of glass and is a solid.

A concept or mind map (see Figure 2.5) is a type of graphic organizer that clarifies relationships between facts or ideas, with cross-links that explain the relationships. In this task, you will use conversation triads with your peers to build a concept map using the examples of the mixtures in Table 2.1. You will revisit your map throughout the chapter, to clarify your own understanding of the terms.

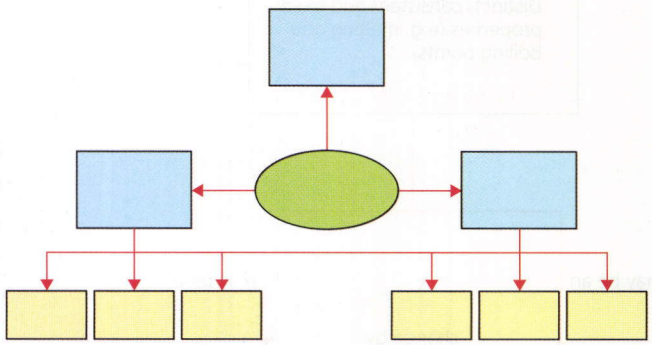


**Figure 2.5** A concept or mind map template

A suggested strategy for building a concept map is outlined below. Consider using a web-based tool **concept mapping tools/template** or the use of sticky labels on a background sheet of paper.

1. **Identify common features in the examples in Table 2.1. These features will form the 'concepts' that you will place in boxes.**
2. **Suggest the relationship between the types of mixtures. Examples you may want to consider include 'dissolved in' or 'suspended in'.**
3. **Keep your concept map where you can access it for editing and for reference.**

### Assessment opportunities

- In this activity you have practised skills that are assessed using Criterion A: Knowing and understanding.

| Cultural category | Example | Suggested explanation referring to Figure 2.5 |
|---|---|---|
| **Decorative arts** | | |
| | Glass used by artists | Mixture – homogeneous – solid<br>Reason: Silica glass ($SiO_2$) can be pure, but additives are added for blown and fused glass to lower the melting point. The clue is the gradual change of state as the glass is heated; a second clue is the examples are coloured. |
| | Ceramics | Mixture – heterogeneous – suspension<br>The solids are mixed in water, followed by chemical reaction |
| | Water-colour paint | Mixture – heterogeneous – suspension<br>The solids are suspended in water |
| | Oil paint | Mixture – heterogeneous – suspension<br>The solids are suspended in oil |
| | Bronze | Mixture – homogeneous – solid<br>Mixed solids – copper and tin |
| **Cuisine** | | |
| | Diet cola | Mixture – homogeneous<br>Gas and other substances are dissolved in liquid |
| | Chocolate chip cookie | Mixture – heterogeneous – solid<br>Solids: sugar, flour, cocoa solids and liquid oils are mixed in cocoa butter |
| | French dressing (salad ingredient) | Mixture – heterogeneous – suspension<br>Solids: seasoning, suspended in a mixture of liquids: water, oil |
| | Homogenized milk | Mixture – homogeneous – colloid<br>A mixture of water, fats, proteins |
| | Non-homogenized milk | Mixture – heterogeneous – suspension<br>The mixture of water, fats and proteins will separate over time |
| **Hygiene practices** | | |
| | Toothpaste | Mixture – heterogeneous – colloid<br>Liquid through solid |
| | Facial cream | Mixture – heterogeneous – colloid<br>Liquid through solid |
| | Aerosols | Mixture – heterogeneous – colloid<br>Colloid is of a solid in a gas |
| | Soap | Mixture – heterogeneous<br>Soap is a suspension followed by chemical reaction |
| | Shampoo | Mixture – homogeneous – liquid<br>The liquids are water and detergents |
| **Communication signals** | | |
| | Smoke | Mixture – heterogeneous – colloid<br>The mixture is of a solid and a gas |
| | Tattoos | Mixture – heterogeneous – suspension<br>The solids:<br>Traditionally: ground minerals or charcoal<br>Modern: metal salts or even plastics suspended<br>Liquid (carrier) can be pure or a mixture and may be ethanol, water, glycerol |

■ **Table 2.1** Cultural uses of matter

# Does understanding of the nature of mixtures improve our ability to express ourselves?

## PHASES

When one substance (called the **solute**) dissolves in another (called the **solvent**), only one **phase** is present in the solution. A phase differs from a state of matter in that it can refer to a homogeneous mixture, such as a solution.

If the particles of the material do not dissolve, and the solute is less dense than the solvent, the mixture is called a **suspension**. If the solute is too dense to be suspended by the solvent, it will settle out (precipitate), forming two separate phases.

Colloidal systems lie between true solutions and suspensions. The dispersed or internal phase consists of particles between 1 and 1000 × $10^{-9}$ m (1–1000 nanometres) and the surrounding, continuous or external phase can be compared with a solvent. The materials making up the bulk of a colloid are **immiscible**, in other words they do not mix. They are stabilized by adding **emulsifiers**, which arrange themselves in a thin layer at the interface between the two liquids. Emulsifiers are molecules with different chemical properties at opposite ends.

Colloids, **emulsions** and **gels** are all examples of colloidal systems. The size of the dispersed particles can be inferred from the colloidal system's appearance (Table 2.2).

| Size of dispersed particles | Appearance of the system |
|---|---|
| Macroglobules > 1 × $10^{-6}$ m (1 micron) | Two phases are visible Milky white |
| 100–1000 × $10^{-9}$ m | Blue-white |
| 50–100 × $10^{-9}$ m | Grey to semi-transparent |
| <50 × $10^{-9}$ m | Transparent |

**Table 2.2** Inferring the size of dispersed particles in a colloidal system from its appearance

Traditional cultures are often renowned for their use of renewable materials. In construction, clothing and produce, these communities have a very direct relationship to their natural resources. Simple technologies like drying (used for grain, pulses or nuts), smoking or salting (fish) preserve food by removing the availability of water from microbes. Fresh food is often shared immediately with all members of the community.

In the developed world, the relationship of people to their natural environment is often very different. Our homes are heated or cooled to comfortable temperatures, and moist products are ideal environments for the growth of bacteria and fungi.

## DISCUSS

Do you think the technology that allows people in developed societies to store perishable materials influences how they interact with their communities?

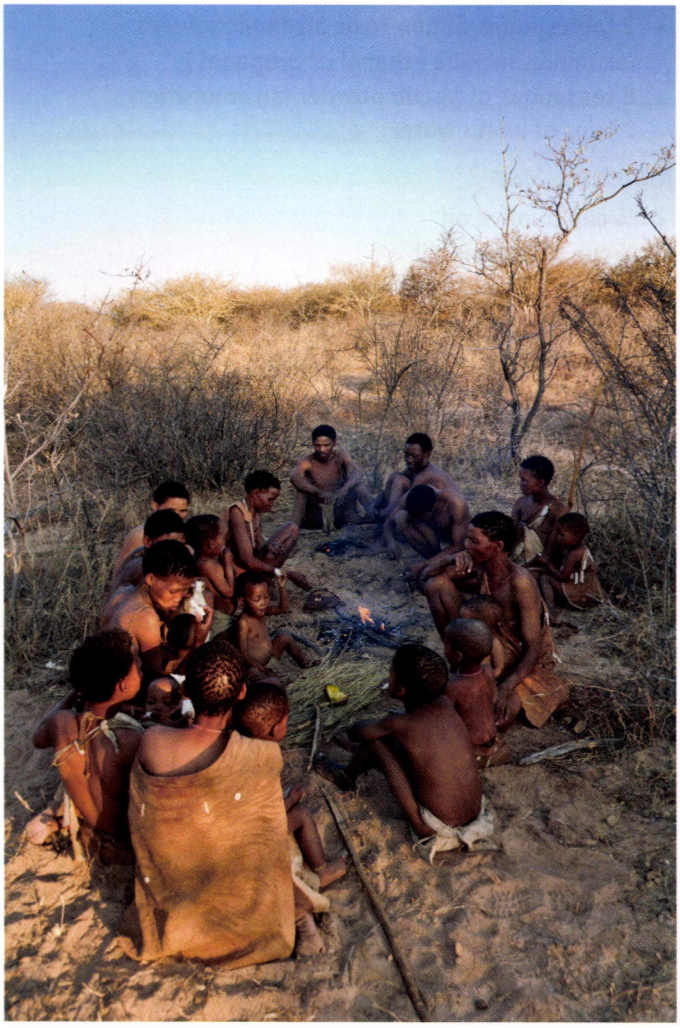


**Figure 2.6** Feasts benefit all members of their community without waste

## PREDICT–OBSERVE–EXPLAIN

What sorts of preservatives are used in your kitchen ingredients, cleaning products or cosmetics or toiletries? The following weblinks may be useful:

- Food products **www.hc-sc.gc.ca/fn-an/securit/addit/list/11-preserv-conserv-eng.php**.
- Cosmetics **www.rsc.org/education/teachers/Resources/aflchem/resources/39/39%20resources/39-2%20database.pdf and www.essentialingredients.com/pdf/ClariantPreservatives.pdf**
- Cleaning agents (bathroom and laundry) **www.cps.ca/documents/position/antimicrobial-products-in-the-home**

- **Predict** which ones might be listed on the labels in your pantry, bathroom and medicine cabinets.
- **Observe** some product labels. Can you see any of the preservatives you have identified?
- **Explain** why different types of preservatives are used in different categories of products.

## EXTENSION: READING THE LABEL!

Why do homemade cosmetics and condiments have short 'shelf lives'?

# ACTIVITY: Making cosmetic materials

## ATL

- Affective skills: Practise strategies to prevent and eliminate bullying; practise strategies to reduce stress and anxiety; practise positive thinking
- Organization skills: Use appropriate strategies for organizing complex information; select and use technology effectively and productively

The three recipes below have been selected because their ingredients are widely available (often in 'health food' stores) and because they are personal products that are used outside the body. Alternative, edible examples of gels and emulsions include salad dressings or mayonnaise.

Make one or more and present them with care; they will be thoughtful gifts.

**Safety:** Never use laboratory equipment to make products for personal use. Your school should have access to these ingredients, and may have a kitchen in which they can be combined using cooking utensils.

Do not ingest any of the 'ingredients'.

Avoid skin contact – some ingredients are in concentrated form.

Wear eye protection.

Consider allergies (nuts, bees) if you have them.

### Colloid – Dispersible bath oil

Add ½–¼ cup of this colloid to the bath as the water is running. This recipe is for a 'spicy' scent. Other types of essential oils can be substituted for a different effect, for example lavender and rose oils.

Materials, Step 1

- **2 tablespoons of non-toxic alcoholic solvent (examples include ethanol or propanol )**
- **8 teaspoons of pectin powder (an emulsifier)**
- **2 cups of warm water**

Materials, Step 2

- **⅛ cup of olive oil**
- **⅛ cup of almond oil**
- **1 teaspoon of vanilla essence**
- **30 drops of essential oil, e.g. 20 drops cinnamon oil, 10 drops clove oil**
- **'pinch' (use a tooth pick) of sodium benzoate (This is a preservative. If you don't have it, store the gel in a refrigerator.)**

Method

1. **Mix alcohol and pectin powder together, and then slowly add the mixture to warm water, beating to avoid lumps. Stand aside for a few hours, to allow the mixture to thicken.**
2. **Mix together and then slowly add to the pectin mixture. Present in a bottle.**

### Emulsion – Cleansing skin cream

Materials, Step 1

- **12 g of beeswax**
- **1 tablespoon of coconut oil**
- **100 ml of olive oil**
- **15 g of cetomacrogal wax (also sold as cetostearyl alcohol, it is an emulsifier)**

Materials, Step 2

- 2 tablespoons of water
- 1 teaspoon of rosewater
- 5 drops of essential oil
- ¼ teaspoon of borax (sodium tetraborate, often sold as 'ant bait')

Method

1. Mix by melting together in a double boiler. When mixed, remove from heat.
2. Heat together slightly in a pan until all the borax is dissolved. The borax will make chemical 'cross-linkages' between the oily components, which stabilizes the mixture.
3. Add the watery liquid slowly to the oil mixture above, stirring constantly as the mixture cools. It can then be poured into jars, ready for presentation.

### Gel – Mild abrasive gel (used to smooth feet)

In this variation, a mild abrasive is added to exfoliate dead skin cells. Notice the effect of adding more borax to the stiffness of the gel.

Materials, Step 1

- 1 teaspoon of Fuller's earth or kaolin (fine dry clay)
- 1 teaspoon of rolled oats
- ¼ teaspoon of cinnamon

Materials, Step 2

- 90 ml of olive oil
- 25 g of beeswax

Materials, Step 3

- 30 ml of rosewater
- 5 g of borax

Method

1. Mix the dry, abrasive ingredients (Step 1) thoroughly and set aside.
2. Mix by melting together in a double boiler materials for Step 2. When mixed, remove from heat.
3. Dissolve materials in Step 3 together, heating slowly in a small pan. Then add slowly to the wax mixture, stirring constantly as the mixture cools.
4. Stir in the abrasive mix. Present in a jar.

### Interpreting and concluding

1. a **Suggest** why in these recipes, the 'oily' and non-oily materials were mixed together separately, before combining.
   b **Identify** other situations (in the home or at school) that use the same approach.
2. Emulsifier molecules have two chemically different ends: one end is water soluble; the other end is oily, and insoluble in water. You can look at an interactive model here: www.indiana.edu/~oso/animations/water&oil.html
   **Predict** the effect of leaving out cetostearyl alcohol, the emulsifier in the cleansing cream recipe.
3. **State** the role of borax.

### Assessment opportunities

- In this activity you have practised skills that are assessed using Criterion B: Inquiring and designing.

## DISCUSS

1. **Comment** on what this activity has taught you about matter in domestic use. How did making cosmetic products as gifts make you feel?
2. **Evaluate** whether your concept map requires editing, based on your experiences.

# ACTIVITY: Using emulsions

## ATL

- Critical-thinking skills: Practise observing carefully in order to recognize problems; interpret data.

Expensive make-up products are sometimes advertised as being 'non-greasy', but are you just paying for water? Emulsions are often described as W/O or O/W, depending on the ratio of oil to water (Figure 2.7).

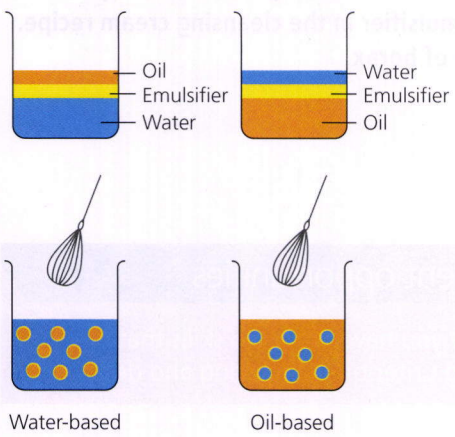



**Figure 2.7** Schematic diagrams of the relationships between oil and water in different emulsions

### Materials and equipment

- small samples of moisturizing creams, cosmetics or foods, provided by the school or by you
- spotting tiles
- toothpicks
- test solutions, in dropper bottles:
  - oil and an oil-soluble red stain (Sudan III)
  - water and water-soluble methylene blue stain

### Method

1. Place two small samples (0.5 $cm^3$) of moisturizer on the spotting tile.
2. Add a droplet of test solution to each, stirring a little with a toothpick.
3. Observe what happens.

### Analysing results

1. **State** what the colour of the test reveals about the type of emulsion being used in your samples.
2. **Suggest** what you can infer about the ratio of W/O or O/W, from the intensity of the colour.
3. **Investigate** further by testing some of the following:

| Foods | Cosmetics |
|---|---|
| Milk | Sun-screen lotion |
| (warmed) Margarine | Hand lotion |
| Mayonnaise | Hair cream |
| Custard | Hair gel |

4. Most people use cosmetics for health or beauty. **Comment** on whether any of the groups listed above were difficult to classify.
5. How would you **justify** 'paying for water'?

## Assessment opportunities

- In this activity you have practised skills that are assessed using Criterion C: Processing and evaluating.

## ACTIVITY: Inverting an emulsion

### ATL

- **Transfer skills:** Apply skills and knowledge in unfamiliar situations; change the context of an inquiry to gain different perspectives

Can you overdo things? 'Moderation' is often recommended as the key to a happy, balanced life. In this activity, you will explore whether some types of mixtures also require moderate treatment.

### Materials and equipment

- **150 ml (0.15 $dm^3$) of thick cream**
- **beater**
- **spotting tile**
- **test solutions in dropper bottles:**
  - **oil with Sudan III**
  - **water with methylene blue**

### Method

1. **Set a little cream aside.**
2. **Beat the cream, until it looks fluffy and white, just right for spreading on a cake.**
3. **Set a little of this cream aside.**
4. **Beat the remainder of the cream until it 'separates'.**
5. **Now test each example on the spotting tile with a drop of each test solution.**

### Analysing results

1. **State the effect extra 'beating' had on the colour of the cream.**
2. **Apply your understanding of emulsions to explain what happened.**
3. **Suggest how butter is made from cream.**

### Assessment opportunities

- In this activity you have practised skills that are assessed using Criterion C: Processing and evaluating.

## ACTIVITY: A close look at two emulsions

### ATL

- **Transfer skills:** Make connections between subject groups and disciplines

Microscopy is generally associated with biology. In this activity, you will use this skill to improve your understanding of mixtures.

### Materials and equipment

- **a high-powered microscope**
- **slides and cover slips**
- **butter, unhomogenized milk, cream**

### Method

Under a microscope, observe very thin smears of

- **softened butter**
- **unhomogenized milk**
- **cream**

### Recording results

1. **Sketch what you see, identifying the oil and water phases.**
2. **Suggest reasons why homogenized milk is not recommended for this activity.**

### Assessment opportunities

- In this activity you have practised skills that are assessed using Criterion C: Processing and evaluating.

## DISCUSS

1. **Suggest how hands-on experiences contribute to understanding.**
2. **Comment on why recording results and reflecting on what they mean are important skills.**
3. **Identify where emulsions and gels fit on the continuum of solid to liquid. Sketch your concepts.**
4. **Identify advantages of colloidal mixtures in consumer products.**
5. **Evaluate whether your mixtures concept map requires editing, based on your experiences.**

# How have our ways of expressing ourselves developed along with our understanding of materials?

## MOLECULAR GASTRONOMY

All cooking is applied chemistry, involving mixing, destroying and creating new flavour chemicals. A new movement of cooking called '**molecular gastronomy**' claims to extend the range of techniques used in food preparation by applying a scientific approach. It aims to transform familiar ingredients into new dishes, to create original 'taste and texture sensations', and asserts that cooking is more than a technical skill, because social and artistic elements are inherent in organizing meals.

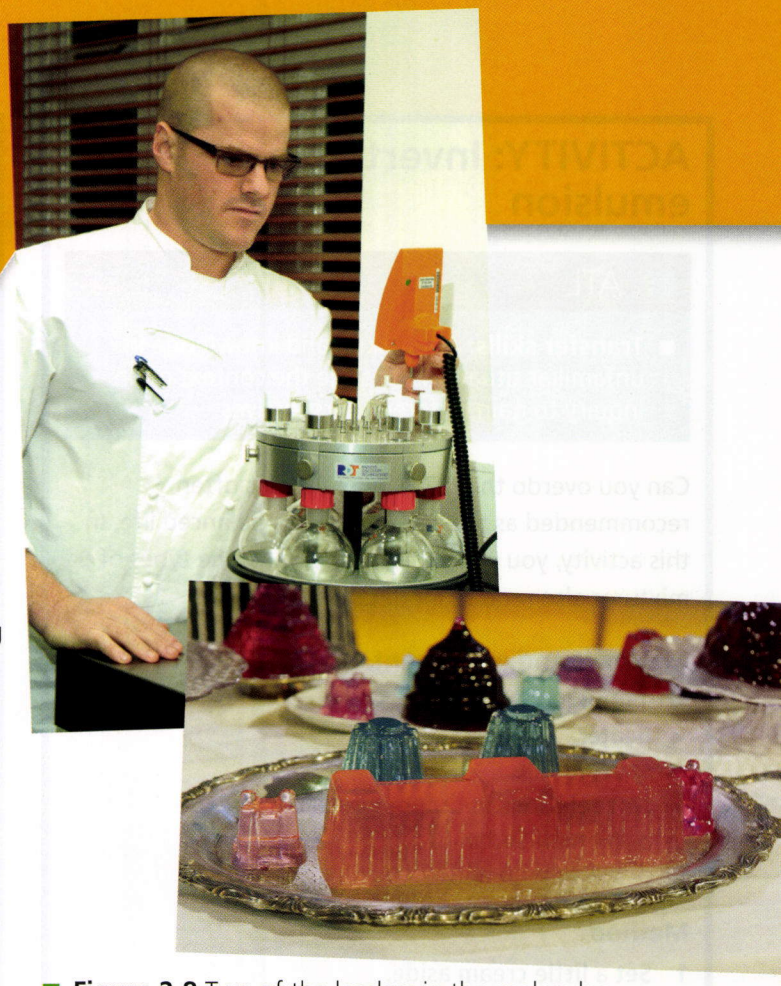


**Figure 2.8** Two of the leaders in the molecular gastronomy field: chef Heston Blumenthal and the weird world of Bompas & Parr – jelly sculptures of London

## ACTIVITY: Molecular gastronomy – scientifically purposeful or showy pretence?

### ATL

- Organization skills: Plan short- and long-term assignments; meet deadlines. plan strategies and take action to achieve personal and academic goals; use appropriate strategies for organizing complex information

Imagine yourself in the role of a feature journalist for a magazine, writing an article in which you are required to describe and report the claims about molecular gastronomy. What do you think?

Your feature article should be no more than 1200 words and should include the following features:

- **A human interest story about a meal created using molecular gastronomy, explaining how science was used for effect.**
- **A discussion and evaluation about how the development of the molecular gastronomy movement might interact with moral, ethical, social, economic, political, cultural or environmental considerations.**
- **Language appropriate for your audience: high quality science journalism describes complex ideas concisely and accurately.**
- **Submit a separate, complete reference list for file to support the magazine's legal team should your article prove controversial. Internal references should be identified and may be presented in a 'For further reading' section.**

### Assessment opportunities

- This activity can be assessed using Criterion D: Reflecting on the impacts of science.

# Can all mixtures be separated?

## SEPARATING SOLIDS

Your experiences will have shown you that most of the matter we use is in the form of mixtures. This includes concrete, ceramics, alloys and natural building materials such as wood. However, nearly all of these materials are not made using mixtures, but from matter that was refined or purified from its natural state.

All separation techniques differentiate matter using one or more physical properties (see Figures 2.9–2.12). In this section, we will compare examples familiar to a diversity of global cultural contexts with examples of techniques used in the laboratory.



**Figure 2.9** What might these people be sieving from the dust?



**Figure 2.10** Winnowing separates the chaff from grain in a light breeze



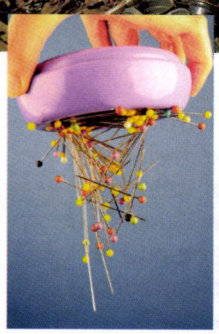


**Figure 2.11** Which elements will be present in high concentrations in the matter attracted to the magnets?



**Figure 2.12** Gold panning in a river in Sumatra, Indonesia. What does this technique have in common with winnowing?

## ACTIVITY: Evaluating the separation of solids

### ATL

- Critical-thinking skills: Draw reasonable conclusions and generalizations
- Transfer skills: Apply knowledge and skills in unfamiliar situations

**Analyse** Figures 2.9–2.12. What do these examples of separation reveal about the physical properties that may be used to separate solids from solids?

1 a **List** all the physical properties of solids used by the separating techniques shown.
   b **Suggest** other examples of separations that use the same physical properties.
   c **Outline** the role of **fluids** in some of these techniques.
2 **Outline** any common features of these techniques.
3 Could any of these techniques also be used to separate liquids, gases or other mixtures? If so, **suggest** example/s.

### Assessment opportunities

- In this activity you have practised skills that are assessed using Criterion A: Knowing and understanding.

## ACTIVITY: Evaluating the separation of liquids

### ATL

- Critical-thinking skills: Draw reasonable conclusions and generalizations
- Transfer skills: Apply knowledge and skills in unfamiliar situations

**Analyse** Figures 2.13–2.17. What do these examples of separation reveal about the physical properties that may be used to separate solids from liquids?

1 a **List all the physical properties of solids and liquids used by the separating techniques shown.**
   b **Suggest other examples of separations that use the same physical properties.**
2 **Identify the scientific terminology for the process used and the substances involved, in the examples listed below.**
   a **Pouring tea from a pot.**
   b **In parts of Asia and the Pacific, salt is extracted from sea water that has been left in upturned clam shells for several weeks.**
   c **The contents of a saucepan with cooked pasta are poured into a colander.**
   d **Sawmills sometimes dry out wood by placing it in an oven.**
3 **Suggest whether these techniques can also be used to separate solids, gases or other mixtures. If so, state (an) example(s).**
4 **Evaluate whether your concept map requires editing, based on your experiences.**

### Assessment opportunities

- In this activity you have practised skills that are assessed using Criterion A: Knowing and understanding.

## SEPARATING SOLIDS FROM LIQUIDS

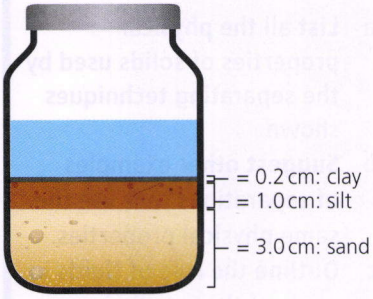



**Figure 2.13** Why have the sediments settled in layers? One way to recover the solid would be by decantation. The liquid can be carefully poured off without disturbing the soil



**Figure 2.14** **Filtration** is a familiar process in coffee-drinking



**Figure 2.15** In cooking, sauces are often thickened by boiling off excess water

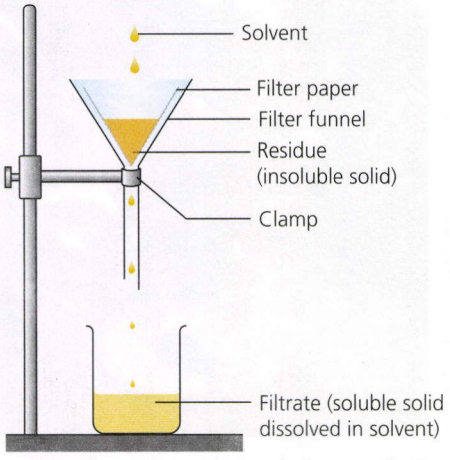



**Figure 2.16** Check your understanding of the terminology of filtration

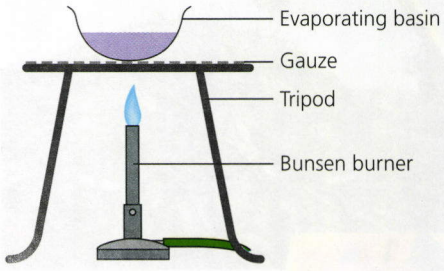



**Figure 2.17** Check your understanding of the terminology of this process. The expression '**evaporate** to dryness' refers to boiling off the water with heat; but '**vaporizing**' is sometimes used when the solvent evaporates more slowly at lower temperatures

## Links to: Biology, Physics

How can the concept of osmosis be applied to separation? You may be familiar with the concept from biology; it describes how the diffusion of water into and out of living cells depends on its ability to move unimpeded across a semi-permeable membrane. The water molecules will move from solutions with higher water potential (a pressure caused by low solute concentration) to solutions with lower water potential (caused by high solute concentration).

Physics students may recognize this as an example of the second law of thermodynamics, which states that the entropy of an isolated system always increases, as matter becomes more disordered.

### Osmosis and dialysis

The concepts of **diffusion** and thermodynamics apply to the movement of particles during **osmosis**, where a **semi-permeable** membrane only allows water molecules to pass through. Artificial kidney machines apply osmosis principles in their use of **dialysis** tubing made of cellulose, which has pores (small holes) that let only small molecules through. When the blood from a person with kidney failure passes through a dialysis machine, waste molecules (for example, urea) diffuse through but other, useful small molecules do not, because the concentration of substances of the **dialysate** balances their concentration in the blood (Figure 2.18). The pores in dialysis tubing are generally small enough to prevent colloid-sized particles escaping.

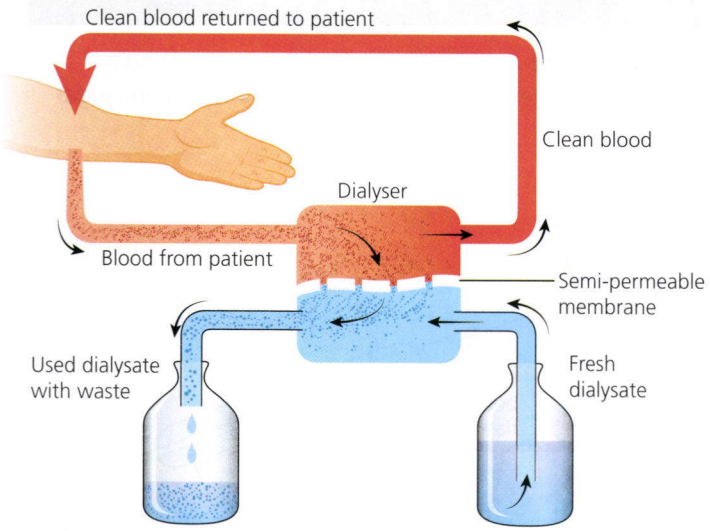



**Figure 2.18** The process of dialysis extracts urea and wastes from blood. Notice the **counter-current flow** of the two solutions, a design that maximizes the efficiency of exchange

## ACTIVITY: Dialysis uses a molecular sieve

### ATL

- Transfer skills: Inquire in different contexts to gain a different perspective

#### Materials and equipment

- skimmed (skim) milk
- 0.1 M copper(II) sulfate solution
- 15 cm length dialysis tubing
- 2 × large test tubes
- torch
- 2 × 250 $cm^3$ beakers

#### Method

1. Prepare two large test tubes with skim milk, and a skim milk and copper(II) sulfate mixture.
2. Wet two pieces of dialysis tubing, tie one end and fill each with one of the mixtures. Close the opposite end and rinse thoroughly, to remove external contamination of these solutions.
3. Place the sealed pieces of dialysis tubing in the 250 $cm^3$ beakers of water.
4. After 30 minutes (or overnight), use the torch to check the solutions surrounding the dialysis tubing for the Tyndall effect. This is a light-scattering effect is caused by a suspension of particles.

#### Analysis

1. **State** the evidence that cellulose pores are larger than the particles released into the solution from copper(II) sulfate.
2. **State** the evidence that the cellulose pores are generally smaller than particles of the milk colloids.
3. **Identify** any evidence that components of skim milk can be separated using dialysis tubing.
4. **Suggest** whether you expect these results to be different with homogenized milk.

### Assessment opportunities

- In this activity you have practised skills that are assessed using Criterion C: Processing and evaluating.

## SEPARATING LIQUIDS

When cooked food cools, dissolved spices separate into oil and water-soluble groups. In Figure 2.19, the red capsaicin has dissolved in the oils at the top of the curry. Sometimes recipes include an instruction to 'drain off excess oil' after cooling. What flavours might be lost from this meal, if this was done?

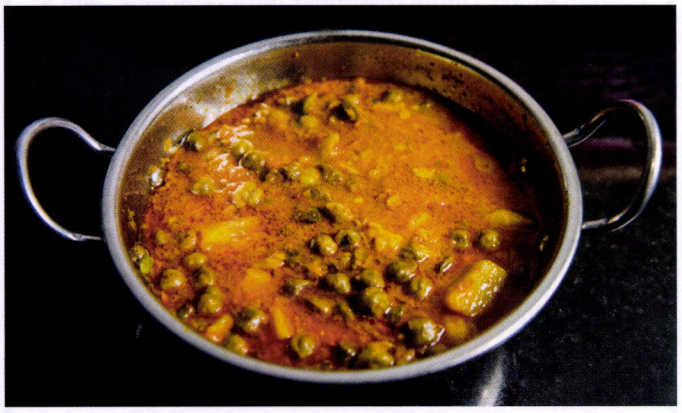


**Figure 2.19** Cooled curry sauce

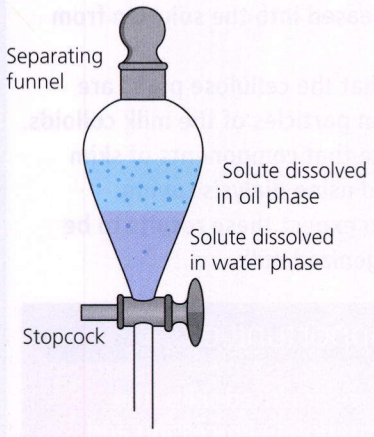



**Figure 2.21** In a laboratory, immiscible liquids can be separated using a separating funnel



**Figure 2.20** A still in South East Asia separating a traditional beverage made from fermented palm sugar

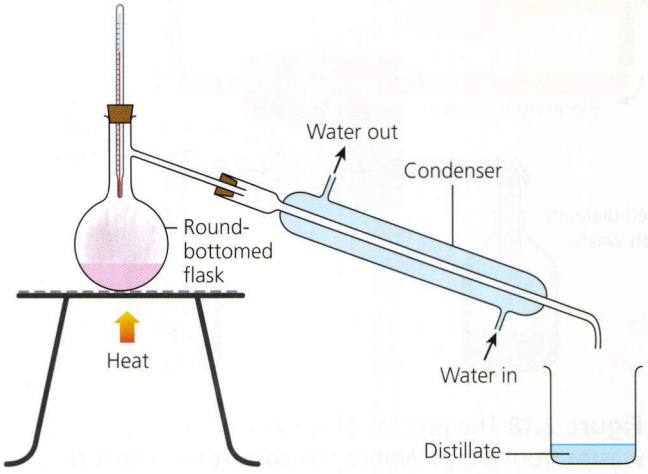



**Figure 2.22** In a laboratory, a condenser is commonly used for distillation

## ACTIVITY: Separating liquids

### ATL

- Critical-thinking skills: Draw reasonable conclusions and generalizations
- Transfer skills: Apply knowledge and skills in unfamiliar situations

**Analyse** Figures 2.19–2.22. What do these examples reveal about the physical properties that may be used to separate liquids?

1 a **List** all the physical properties of liquids used by the separating techniques shown.
  b **Suggest** other examples of separations that use the same physical properties.
2 If you added the mixtures you used to test colloids, oil with dissolved Sudan III and water with dissolved methylene blue, to a separating funnel:
  a **state** the colour of the top solution
  b **suggest** how could you could recover powdered methylene blue.
3 **Reflecting** on the condensation process:
  a in a laboratory condenser, **describe** the role of the cold water layer around the glass pipe
  b in the traditional still, **explain** why the bamboo pipe used is 8 m long.
4 You can smell orange peel because the oils it contains are **volatile**, in other words, they have low boiling points and evaporate. If orange peel and warm water are heated in a condenser, **predict** and **explain**
  a which would emerge first in the **distillate**, the oil or the water
  b whether liquids in the mix with similar boiling points could separate perfectly.

### Assessment opportunities

- In this activity you have practised skills that are assessed using Criterion A: Knowing and understanding.

## ACTIVITY: Purifying substances

### ATL

- Critical-thinking skills: Practise observing carefully in order to recognize problems; draw reasonable conclusions and generalizations

Strongly scented flowers are popular raw materials for aromas used in cosmetics. In this experiment, you will compare the effectiveness of different strategies for extracting scents.

### Materials and equipment

- three flasks
- fresh or dried petals from scented flowers
- water
- ethanol
- unscented vegetable oil (e.g. almond oil)
- filter paper, funnels

### Method

1 Place the petals from scented flowers in the flasks.
2 Cover them with one of the following:
  a water
  b alcohol mixture (70% ethanol, 30% water), or
  c vegetable oil.
3 Seal the flasks and store them in a cool dark place.
4 After a few days, **filter** the solid petals from the solutions.
5 Carefully smell each of the **filtrates**.

### Analysis

1 **State** how the scents of the filtrates differ.
2 **Identify** examples of solubility properties of scent in flowers.
3 **Predict** how your results might have differed if you had extracted the petals
  a for a shorter time
  b in a brightly-lit environment, such as a bench top
  c using strongly heated solutions.
4 **Outline** the evidence that different essences had been extracted by each solvent.
5 **Suggest** how using a separating funnel may have improved the efficiency of this experiment.

### Assessment opportunities

- In this activity you have practised skills that are assessed Criterion C: Processing and evaluating.

## CHROMATOGRAPHY

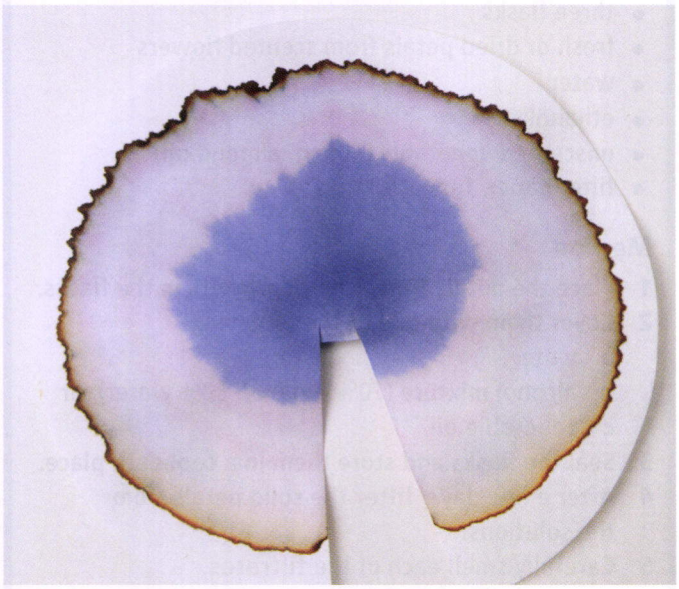


**Figure 2.23** This effect was created using water to separate the mixture of inks on the absorbent paper

**Chromatography** is a diverse separation technique that can be applied to a wide range of mixtures, including dissolved solids and mixtures of liquids or gases.

All forms of chromatography combine the movement of a fluid, called the mobile phase or medium, with a stationary phase or medium. The components within mixtures separate because each has a different solubility in the mobile fluid phase, and they have different affinities for the stationary phase. In principle, this is analogous to using air to separate chaff from grain (Figure 2.10), or water to separate alluvial gold from gravel (Figure 2.12) because air and water are both fluids. In Figure 2.23, the dark brown ink dye has a higher 'affinity' for water compared to the violet dye and it therefore appears to have moved to nearly the same extent as the solvent front of the water.

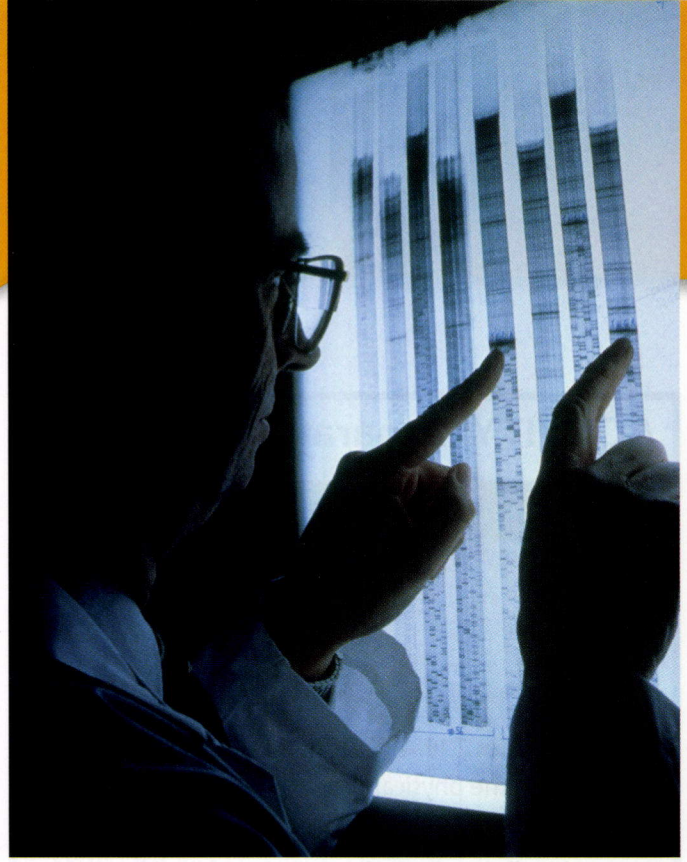


**Figure 2.24** A biochemist comparing DNA profiles, a chromatography process which separates pieces of DNA according to size and electrostatic charge, on a stationary gel. Is a DNA profile the ultimate example of personal expression?

The affinity of the mobile phase for the stationary phase affects the speed at which the mobile phase moves. However, the ratio of the distance moved by each of the components to the solvent front will be constant, for the same solvent and stationary phase (Figure 2.25). This ratio is the $R_f$ (**retardation factor**, or **retention factor**) and it provides a standard (Table 2.3). Even the most soluble solutes will have an $R_f$ of less than 1.

$$R_f = \frac{\text{distance moved by the compound}}{\text{distance moved by the solvent}}$$

| Pigment | Colour | $R_f$ value |
|---|---|---|
| β-Carotene | Orange–yellow | 0.96 |
| Phaeophytin | Yellow–grey | 0.81 |
| Chlorophyll *a* | Blue–green | 0.75 |
| Chlorophyll *b* | Green–yellow | 0.70 |
| Xanthophyll *a* | Yellow | 0.51 |
| Xanthophyll *b* | Yellow | 0.37 |
| Xanthophyll *c* | Yellow | 0.17 |

Solvent: 55% cyclohexane : 45% ethyl ethanoate; run on TLC (thin layer chromatography) plates

**Table 2.3** $R_f$ values (approximate) of plant pigments in spinach leaves

## The calculation of $R_f$

Simply divide the distance from the origin to the middle of each component by the distance from the origin to the **solvent front**. In standard conditions, the $R_f$ is constant for any specific combination of mobile and stationary media. In Figure 2.25, the $R_f = 4.0/5.5 = 0.72$.

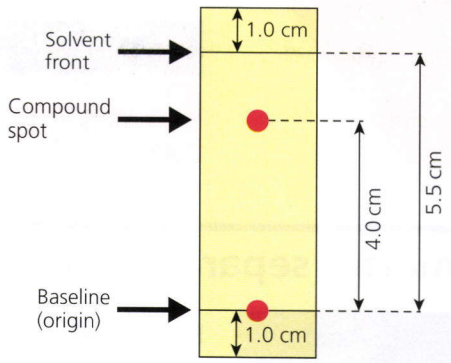



Figure 2.25

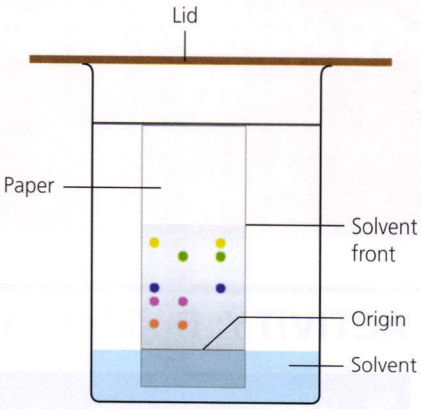



Figure 2.26

## ACTIVITY: Reflecting on chromatography

### ATL

- Critical thinking: Practise observing carefully in order to recognize problems; interpret data

1 **State** what is significant about the two bands in Figure 2.24.
2 **Sketch** a diagram of the colours and relative position of each of the plant leaf pigments listed in Table 2.3.
3 In Figure 2.26,
   a **suggest** what would happen to the solvent front eventually, if the solution was left for a long time
   b **explain** how running the separation too long would affect the $R_f$ of the yellow spots.
4 Sometimes a spot will remain on the baseline, where a sample was first applied.
   a **Suggest** what affinity this substance would have for the solvent.
   b **Suggest** a value for the $R_f$ of this substance.
   c **Outline** how you could determine whether these materials are pure, or a mixture.
5 **Suggest** how the shape of the spots might change over time.
6 Some students proposed measuring the position of each spot from the top, others from the centre. **Evaluate** and **explain** which method has greater validity.
7 Sometimes only one sample of a solution is separated near one side of a square-shaped stationary medium. Then the medium is rotated 90° and placed in a different solvent (Figure 2.27). **Suggest** what further information this method might reveal.

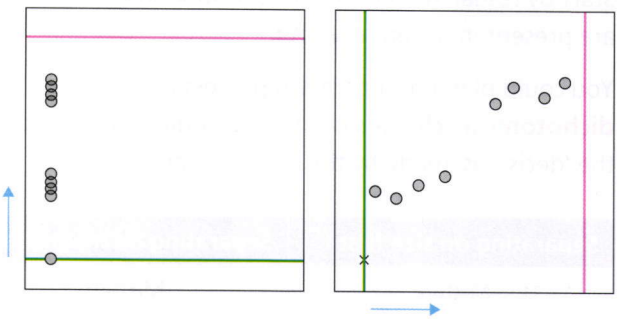


**Figure 2.27** Two-dimensional chromatography. The green lines represent the start position, the arrows the direction of the solvent movement and the pink lines, the solvent front. The first dimension separated the mixture into two groups of spots, which were then each resolved to four further components, after the second separation

### Assessment opportunities

- In this activity you have practised skills that are assessed using Criterion A: Knowing and understanding.

# Which conditions result in the most effective separation process?

**Links to: Technology**

What are the similarities and differences between the inquiry cycles of science and technology?

## ACTIVITY: Building a 'matter separating' device for recyclables

**ATL**

- Creative-thinking skills: Consider multiple alternatives, including those that might be unlikely or impossible; design improvements to existing machines and technologies

When materials arrive at a recycling station, all kinds of material will be mixed together. How can we go about separating plastics, metals, paper, card, wood and other materials so that they may be recycled separately?

Start by researching to find out what kinds of materials are present in mixed recycling.

You could plan the separation process using **dichotomous choices** or a similar organizer to describe the 'decisions' made by the device (Table 2.4).

| Separating on size first | Separating on magnetism |
|---|---|
| Mixture<br>↓ *filtration/sieving*<br>Beans / Iron filings, sand<br>↓ *expose to magnet*<br>Iron filings / Sand | Mixture<br>↓ *expose to magnet*<br>Iron filings / Beans, sand<br>↓ *filtration/sieving*<br>Beans / Sand |

**Table 2.4** Two dichotomous choices for separating a mixture of iron filings, sand and dry red kidney beans

For this task, you are required to build a 'matter separating' device and test its efficiency. There are two rules:

- **The device needs to be able separate three different materials.**
- **Once the mixture (which has been defined by you) enters the device, you should not need to touch the mixture directly.**

### DISCUSS

1. **Identify** how you could separate a mixture of solutions.
2. **List** components a device would need to separate physical properties like magnetism, size, solubility, viscosity, and density. **Suggest** whether the separations of a mixture based on any of these properties would be 'path dependent' or 'path independent'.
3. **Identify** measurements needed to test the efficiency of a separating device.
4. **Outline** information that will be required to report your results.
5. **Predict** what you will have at the end of your separation process.

**Assessment opportunities**

- In this activity you have practised skills that are assessed using Criterion B: Inquiring and designing.

## Take action: Reflecting on the impacts of toiletries

### ATL

- Organization skills: Plan short- and long-term assignments; meet deadlines; plan strategies and take action to achieve personal and academic goals; use appropriate strategies for organizing complex information

! Toiletries are consumer products developed for cosmetic or hygiene purposes. Examples include soaps and detergents, perfumes and substances that manipulate our image. All these products impact on moral, ethical, social, economic, political, cultural or environmental considerations. For example, consider the potential of the product to cause pollution, its pressure to manipulate personal presentation, and the impact of poor hygiene on a society.

! Use the Internet to research the way that 'scientific-sounding' claims are used in cosmetics advertisements. (Shampoo ads are a great start!) How convincing do you find the claims made in some advertisements? In this activity you will explore the real science behind cosmetics production, and its impact.

! Research a cosmetic product. Then write a script for your own 'true science' commercial, in which you

- **describe** the science involved in the production of a toiletry product, and how it works
- **discuss** and **evaluate** how the use of the selected product interacts with one of the factors listed.

! Make sure your advertisement captures the language and tone of a commercial. Acknowledge your sources by listing them on a separate page.

### Assessment opportunities

- This activity can be assessed using Criterion D: Reflecting on the impacts of science.

## SOME SUMMATIVE PROBLEMS TO TRY

Use these problems to apply and extend your learning in this chapter. The problems are designed so that you can evaluate your learning at different levels of achievement in Criterion A: Knowing and understanding.

### THESE PROBLEMS CAN BE USED TO EVALUATE YOUR LEARNING IN CRITERION A TO LEVEL 1–2

1 **State** the difference between an emulsion and a suspension.

2 Suppose you were given a solution of salt in water. **Suggest** how you would separate this mixture to obtain:
   - a pure salt
   - b pure water.

3 A student decided to investigate the composition of soil in her garden by shaking a small sample in a jar of water. After a few days, most of the material in the jar had settled at the bottom, but the water above the soil had a 'cloudy' appearance.

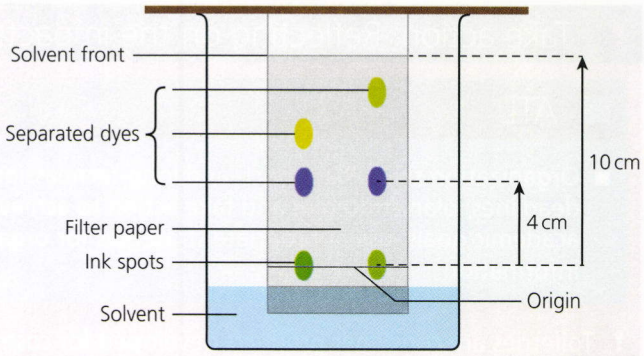
   **Interpret** this information to make judgments about the density of the particles in the liquid layer and the particles in the precipitate at the bottom.

### THESE PROBLEMS CAN BE USED TO EVALUATE YOUR LEARNING IN CRITERION A TO LEVEL 3–4

4 **Outline** using a flow diagram, how you might separate a mixture of copper bolts, iron nails, Styrofoam packaging balls and sugar.

5 Creamy mayonnaise is an emulsion of oil and water. **Identify** the role of adding a small amount of egg yolk or mustard powder in the recipe.

6 **Calculate** the $R_f$ values for each of the coloured spots in Figure 2.28:
   - a green
   - b yellow
   - c blue.




■ **Figure 2.28** Paper chromatography of water-soluble inks

7 Some creams are called 'vanishing' because they seem to disappear when rubbed on the skin. **Suggest** the type of oil and water combination that would give a vanishing-cream emulsion with this property.

8 During their use, perfumes often present a range of impressions. After a first fleeting scent, there can be a range of different, lingering impressions. Make a scientifically supported judgment to **explain** how this is possible.

9 At a party, in a bucket of iced water (i.e. containing both liquid and solid phases of water), you notice that cans of a regular soda sink, but cans of 'diet' sodas float. In the morning, when all the ice cubes have melted, the regular 'Coca-Cola' and regular 'Dr Pepper' drinks both float along with the diet sodas! **Interpret** this information and make scientifically supported judgments.

### THESE PROBLEMS CAN BE USED TO EVALUATE YOUR LEARNING IN CRITERION A TO LEVEL 5–6

10 **Describe** how a separating funnel can be used to differentiate between liquids of different densities.

11 When clothes are washed,
   - a **suggest** why it is difficult to remove grease spots from clothing using pure water
   - b if the clothing soiled with grease spots is treated with a spray-on stain remover, washing becomes more effective. **Suggest** the chemical a stain remover might be, and describe how it works.

12 Approximately 2000 rose petals produce 1 gram of pure essential rose oil. However, the smell is so powerful it cannot be used until it has been diluted 1000 times with a solvent that we can't smell. This 'fragrant oil' is then diluted further.

a Given the amount of fragrant oil in the product, **calculate** the dilution factor of the essential oil.

| Product | % of fragrant oil | Dilution factor |
|---|---|---|
| Parfum (strong perfume) | 25 | |
| Cologne | 6 | |
| Toilet water | 2 | |

b Why don't chemists simply add smaller quantities of the essential oils directly to the other ingredients?

**THESE PROBLEMS CAN BE USED TO EVALUATE YOUR LEARNING IN CRITERION A TO LEVEL 7–8**

13 **Explain** why the $R_f$ values for any set of specific conditions used in chromatography are constant. Illustrate your understanding with examples.

14 In the French perfumery industry, *pomade* is made by placing fresh lavender on highly purified blocks of animal fat in cool, dark rooms. After a few days, the fat is dissolved using cool alcohol, leaving the essential oils from the flowers behind. **Explain** how this separation process demonstrates an awareness of the physical properties of essential oils.

15 A plant physiologist investigating the structure of chloroplasts blended some leaves in a watery solution. **Explain** the equipment he would use to isolate the oil-soluble components from the mixture of blended leaves.

16 The table below classifies the phases of a colloid.

| Continuous phase | Dispersed phase: Gas | Dispersed phase: Liquid | Dispersed phase: Solid |
|---|---|---|---|
| Gas | none | liquid aerosol | solid aerosol |
| Liquid | foam | emulsion | suspension or sol |
| Solid | solid foam | gel | solid sol |

a **Suggest** how you would use this table to classify the following materials: glass, mist, Styrofoam, jelly, pumice stone, fog, whipped cream, salad dressing, paint, ink, smoke.

b **Explain** why there are no examples of purely gaseous colloids.

# Reflection

In this chapter you refined your understanding of how particles are arranged in solids and investigated mixtures called colloidal systems to understand how their immiscible liquid components result in a range of useful products, in art, cosmetics and cooking. You also learnt how mixtures can be purified and practised a range of separation techniques.

| Use this table to reflect on your own learning in this chapter | | | | | | |
|---|---|---|---|---|---|---|
| Questions we asked | Answers we found | Any further questions now? | | | | |
| **Factual:** What are the differences between pure substances and mixtures? Can mixtures consist of matter in more than one state? Can all mixtures be separated? | | | | | | |
| **Conceptual:** How do separation techniques rely on physical properties? Which conditions result in the most effective separation process? | | | | | | |
| **Debatable:** How have our ways of expressing ourselves developed along with our understanding of materials? Does understanding of the nature of mixtures improve our ability to express ourselves? | | | | | | |
| Approaches to learning you used in this chapter: | Description – what new skills did you learn? | How well did you master the skills? | | | | |
| | | | Novice | Learner | Practitioner | Expert |
| **Organization skills** | | | | | | |
| **Affective skills** | | | | | | |
| **Critical-thinking skills** | | | | | | |
| **Creative-thinking skills** | | | | | | |
| **Transfer skills** | | | | | | |
| Learner profile attribute(s) | How did you demonstrate your open-mindedness skills in this chapter? | | | | | |
| **Open-mindedness** | | | | | | |

# 3 How do we map matter?

**Scientific and technological innovation** has allowed us to identify **patterns** in the properties of chemical elements and so build **systems** to classify them.




**Figure 3.1** Edison's lab at the Thomas Edison Center, Menlo Park Museum, USA. When we break matter down to its elements, what can we learn?

## CONSIDER AND ANSWER THESE QUESTIONS:

**Factual:** What are some of the chemical characteristics of broad groups of elements?

**Conceptual:** How does recognizing patterns contribute to a deeper understanding of the nature of elements? How can the relationships between chemical elements be represented?

**Debatable:** How should names of newly discovered elements be determined?

Now **share and compare** your thoughts and ideas with your partner, or with the whole class.

## IN THIS CHAPTER, WE WILL ...

- **Find out** how elements may be classified, using common properties.
- **Explore**
  - patterns of properties of matter;
  - representations of the elements.
- **Take action** by creating a game for younger children, based on the periodic table.

## These Approaches to Learning (ATL) skills will be useful …

- Communication skills
- Collaboration skills
- Organization skills
- Reflection skills
- Creative-thinking skills

## We will reflect on this learner profile attribute …

- Communicators – How can your expression of scientific understanding contribute to the learning of others? How well do you listen when you work with others? How does the presentation of data contribute to understanding of relationships? How important were collaboration and communication for the development of a unified understanding of the elements?

## KEY WORDS

| | | | |
|---|---|---|---|
| alkaline | brine | metal | period |
| battery | group | neutral | |

## Assessment opportunities in this chapter …

- Criterion A: Knowing and understanding

# A GENERAL STRUCTURE OF ATOMS

A common way to manage complexity is to categorize components into groups, because remembering a small number of shared characteristics is easier than recalling all the details of each individual part.

The atoms of all elements are variations on a theme, because they consist of a positively charged nucleus surrounded by negatively charged **electrons**. Atoms are electrically neutral because the number of positive charges in the nucleus is balanced exactly by the number of negative charges outside the nucleus. Variations between elements are caused by differences in the patterns of attraction of the two types of charge, causing these atoms to gain or lose electrons. Atoms with unbalanced numbers of charges are called **ions** (Figure 3.2).

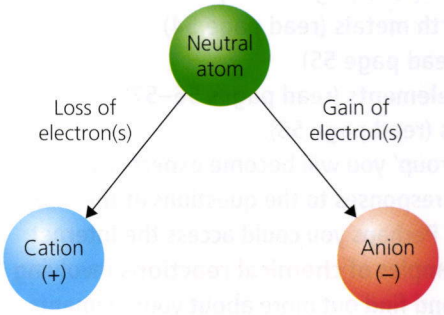



**Figure 3.2** The difference between an atom and an ion

# What are some of the chemical characteristics of broad groups of elements?

## ACTIVITY: Jigsawing groups of chemical elements

### ATL

- Communication skills: Read critically and for comprehension; give and receive meaningful feedback; use a variety of speaking techniques to communicate; interpret and use effectively modes of non-verbal communication
- Collaboration skills: Help others to succeed; listen actively to other perspectives and ideas; encourage others to contribute; exercise leadership and take on a variety of roles within groups; practise empathy

This activity introduces groups of chemical elements with common characteristics.

'Jigsaw' is a learning strategy that develops communication and listening. In this activity, you will work in two groups: an 'expert group' and a 'home group'.

1. First, get into groups of six. This is your 'home group'. Each member of the group is assigned to one of the groups of chemical elements from step 2. If your class is small, some individuals may need to become an 'expert' on more than one group of elements.
2. Now form 'expert groups'. For example, everyone that has been assigned Metals joins that 'expert group', and so on. Read the material for your group:
   a. Metals (read pages 51–52)
   b. Alkali metals (read page 52–53)
   c. Alkaline earth metals (read page 54)
   d. Halogens (read page 55)
   e. Rare earth elements (read pages 56–57)
   f. Noble gases (read page 58).
3. In the 'expert group' you will become experts by discussing your responses to the questions at the end of each section. Perhaps you could access the Internet and look up examples of chemical reactions involving your elements and find out more about your elements. Assume all the other groups in the class will be developing expertise in their own information category.
4. Each member of the team needs to practise how they will communicate the information about their assigned group of elements to their 'home group'. Support each other by listening to each other practise reports (perhaps do this in pairs) and provide feedback to help peers be brief and accurate – no individual report should be longer than 3 minutes. This part of the jigsaw may take 10–20 minutes, depending on your experience in oral communication, and the size of your group.
5. Return to your 'home group', where each 'expert' shares the specialized information. Active listening means you ask the 'experts' clarifying questions. This part of the jigsaw may take up to 20 minutes, because you will be hearing or presenting six short reports, and discussing the information.
6. The final part of the jigsaw is for the home group to reflect together on the shared information. Consider discussing responses to these questions:
   a. **Identify** the chemical group(s) that I could belong to:
      i. I am shiny, and you can use me as a container for cooking.
      ii. I am very unreactive, but my plasmas light up your night life!
      iii. Directly or indirectly, all of us were purified into metals using electrolysis.
      iv. I am coloured, and if you inhale me I am poisonous.
      v. I am reactive for a metal, and over time many of my compounds have dissolved in the sea.
      vi. Modern life, and particularly green technology, depends on me, even though my extraction causes dangerous environmental pollution.
   b. **Compare and contrast** physical and chemical properties of different groups of elements.
   c. **List** the technologies used to isolate different groups of elements, or create new elements.
   d. **Evaluate** whether any group does not have at least one element that touches our lives, every day.
   e. **Discuss** how 'jigsaw' as an approach to learning has changed your knowledge or enhanced your listening skills.

### Assessment opportunities

- In this activity you have practised skills that are assessed using Criterion A: Knowing and understanding.

## METALS

The majority of known elements are **metals**. Metals stand out by their **lustre** or shiny appearance when they are polished. A related physical property is their ability to **conduct** heat and electricity. Except for mercury (which melts at –39 °C), all metals are solid at room temperature (25 °C). Although the melting point, hardness and the way they react chemically is variable, solid metals are **malleable**, which means they can be rolled or hammered into shape, and **ductile**, which means they can be drawn into a wire.

The physical features of metals can be explained by their low or very low '**electronegativity**', meaning metal atoms lose one or more electrons quite easily to form positive ions (cations). Solid metals can be imagined as a **lattice** of positively charged nuclei surrounded by a 'sea' of these mobile electrons (Figure 3.5). 'Metallic bonding' involves the attraction of these **delocalized electrons** to the nearest nuclei, which helps to explain how molten metals can be mixed into alloys, as well their physical properties (Table 3.1).



**Figure 3.4** Examples of pure metals. *Top row, left to right:* aluminium, zinc, copper, nickel, cobalt. *Bottom row, left to right:* scandium, vanadium, chromium, manganese, titanium

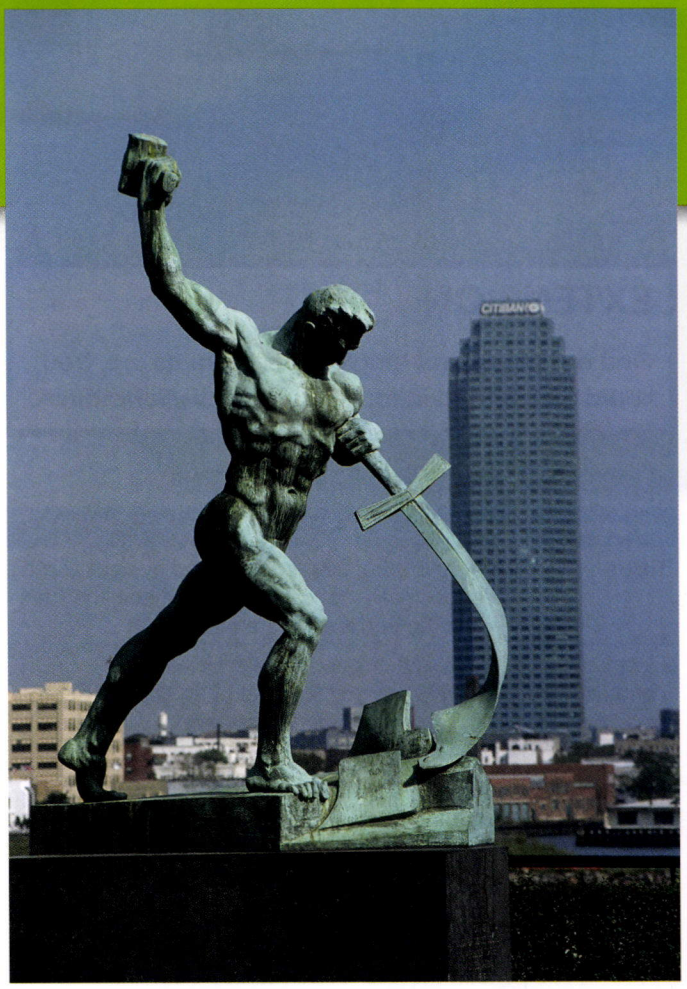


**Figure 3.3** Evgeny Vuchetich's bronze statue *Let Us Beat Our Swords into Ploughshares* symbolizes the global desire for a peaceful world, and was a gift from the Soviet Union to the United Nations in 1959. Modern bronze is an alloy similar in composition to those developed in Bronze Age cultures (87–88 per cent copper and 10–11 per cent tin) about 5000 years ago

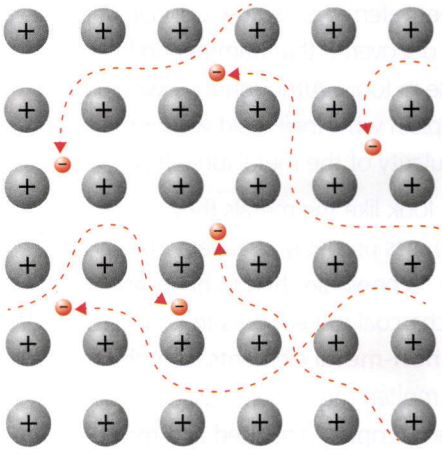


**Figure 3.5** A visual representation of a metal as a lattice of positively charged ions surrounded by a 'sea' of mobile, delocalized electrons. These are also the same electrons that are involved in chemical reactions

## EXTENSION

**Find out about smelting copper from its ore. You could watch this video: https://youtu.be/8uHc4Hirexc**

| Property | Explanation |
|---|---|
| Lustre | Light rays (photons) are absorbed by delocalized electrons near the surface of the metal and then re-emitted at the same frequency |
| Electrical conductivity | Delocalized electrons move towards the positively charged terminal of an applied electric field, creating an electric current |
| Thermal conductivity | This is mainly due to delocalized electrons increasing their kinetic energy in response to absorbing heat, and distributing this energy as they move through the lattice |
| Malleability and ductility | Metallic bonding between the atoms does not have a preferred direction, allowing positively charged nuclei of metal atoms to slip or slide within the 'sea' of delocalized electrons |

**Table 3.1** How delocalized, mobile electrons explain the properties of metals

When an element can be found naturally in its pure form, it is a sign that its atoms are chemically stable. Native gold, silver and copper were prized by many prehistoric civilizations, and often hammered into decorative and religious objects or used for trade. Between 5000 and 3000 years ago, a period now sometimes referred to as the 'Copper Age', these ancient metallurgists discovered that hammering helped harden copper for use in tools. Although they would not have been able to explain why, their 'cold working' physically reconfigured the regularity of the metal ion lattice!

Because **ores** do not look like the metals they contain, **smelting** (Chapter 8) was probably discovered by accident. A range of subsidiary technologies had to be invented, including the use of charcoal to heat ores to nearly 1000 °C or more, for separating **non-metal** elements from the minerals, and for handling the molten metal that was left behind. Smelting expanded how copper was used and made tin, lead and iron available. In all cultures that invented smelting, from China, the Middle East, Egypt and Europe, the Bronze and Iron Ages gradually followed the Copper Age. These remained the most important metals available until 1780.

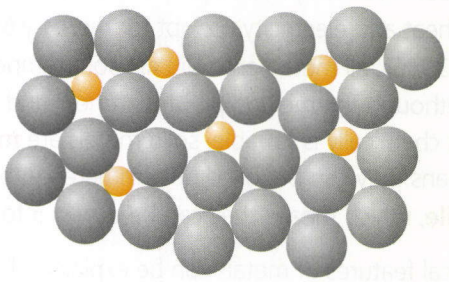


**Figure 3.6** A schematic representation of different metals mixed in an alloy. The different sizes of atoms of different elements combined in alloys distort the regular arrangement of the lattice, so different layers do not slip over each other easily

Bronze is an alloy of copper and tin, and much harder than either metal individually. The different sizes of atoms of different elements combined in alloys distort the regular arrangement of the lattice, preventing the layers from slipping over each other easily (Figure 3.6). Steel, developed during Roman times by adding carbon to iron, is stronger than pure iron for similar reasons.

## SUMMARY REFLECTION

1. **Suggest how 'metallic bonding' explains the properties of metals.**
2. **Describe how these properties are changed by (i) hammering and (ii) mixing metals into alloys.**
3. **Identify examples of metals known since prehistoric times still in use in your homes today.**

## ALKALI METALS

The **alkali metals** are never found as elements in nature. The word *alkali* comes from the Arabic *al-galy*, meaning 'roasted ashes', which are rich in compounds of alkali metals. The five naturally occurring elements in the group, caesium, lithium, potassium, rubidium and sodium, are soft enough to be cut with a steel knife, and react with water, releasing hydrogen gas and producing basic **oxides** (Chapter 5).




**Figure 3.7** Some alkali metals

Pure alkali metals are so reactive that they need to be stored under oil (Figure 3.7). Lithium, which has a density of $0.53\,g\,cm^{-3}$, is the least dense solid element.

They also react with oxygen, sulfur and halogens, forming hard, brittle compounds that in the solid state are gigantic networks of positive metal ions and negative non-metal ions, called ionic solids (Figure 3.8). Francium, discovered in 1939, is highly radioactive and unknown outside research laboratories and nuclear facilities.

How could such reactive elements be discovered and isolated? In 1800 an Italian physicist, Alessandro Volta, published a method for making a device that could produce an electric current, the 'voltaic pile', or what we would call a battery. Almost immediately the new technology was applied to decompose water to hydrogen and oxygen. A museum display of Volta's pile shows a stack of perhaps 30 silver and zinc discs, separated by blotting paper that had once been soaked with brine (very salty water).

The British chemist and inventor Sir Humphry Davy (1778–1829) increased the voltage of the pile by using 2000 paired metal discs, and applying the electrodes to molten salts. With this method, he identified both potassium and sodium as new elements in 1807, and worked with William Thomas Brande (1788–1866) in 1817 to isolate lithium, the same year as it had been discovered by Johan August Arfwedson (1792–1841) in Sweden.

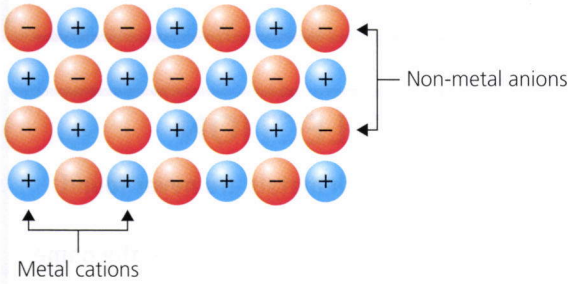



**Figure 3.8** The alkali metals readily give up an electron to non-metal atoms, creating solids that are networks of positive and negative ions

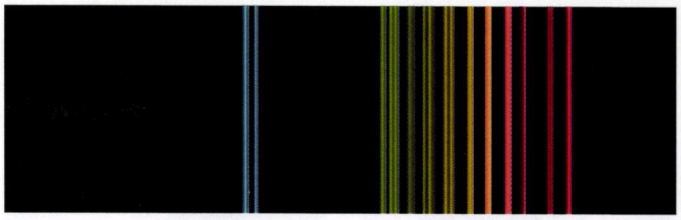


**Figure 3.9** The emission spectrum of caesium with its distinctive pair of two bright blue lines

A different innovation helped identify the remaining alkali metals. In Germany, Robert Wilhelm Bunsen (1811–1899) and Gustav Robert Kirchhoff (1824–1887) were observing the '**emission spectra**' of mixtures of gaseous atoms in the newly invented Bunsen burner. When an atom is heated, some of its electrons become 'excited' and jump to a new, higher energy level (a **quantum** transition). On cooling, the energy is emitted as a photon with energy equal to the energy difference between the two states.

Because there are many possible electron transitions for each atom, and every transition has a specific energy difference, and because each element has a different number of electrons, every element has its own emission spectrum.

In 1860 two unique bright blue lines (Figure 3.9) provided the first evidence for the element caesium ('*caesius*' means 'sky' or 'heavenly blue'). In 1861, rubidium ('*rubidius*' meaning 'dark (or deepest) red') was discovered using the same process.

## EXTENSION

Watch reactions of alkali metals with water:
https://youtu.be/uixxJtJPVXk

## SUMMARY REFLECTION

1. **State** why alkali metals are never found naturally as elements.
2. **Explain** why alkali metals were not purified until the early 19th century.
3. **Describe** an example of how a new technology may contribute to scientific knowledge.



**Figure 3.10** Some alkaline earth metals: calcium, beryllium and magnesium

## ALKALINE EARTH METALS

The **alkaline earth metals** (Figure 3.10) are never found as elements in nature. The word 'earth' refers to the idea that they are 'incombustible' or cannot burn, which is true for their oxides, compounds where the metal has already combined with oxygen. Many of the elements have a long history of use in construction as compounds, for example limestone and marble (calcium carbonate), and quicklime (calcium oxide). Our bones consist largely of calcium phosphate and magnesium is an essential component of chlorophyll. Beryllium compounds have been prized by civilizations the world over in the form of the minerals beryl and emerald. Recently it was found that many gemstones owned by Mughal rulers in 18th century India originated in Colombia, in South America, revealing a forgotten trade route between India and the Philippines, to which the precious stones had to be transported by Spanish vessels.

The alkaline earth metals – barium, calcium, magnesium and strontium – were all isolated by Sir Humphry Davy during 1808, sometimes within days of each other. Davy's method involved **electrolysing** their molten ionic compounds (Figure 3.11). Ionic compounds are bonded by the strong attraction of oppositely charged ions and melt at very high temperatures, because the attraction between the opposite charges is strong.

Melting mobilizes the ions, and molten ionic compounds are good **conductors**. Because the voltage (electromotive force) supplied by the battery is much greater than the electrostatic charges of the surrounding ions, the ions migrate to the oppositely charged electrode.

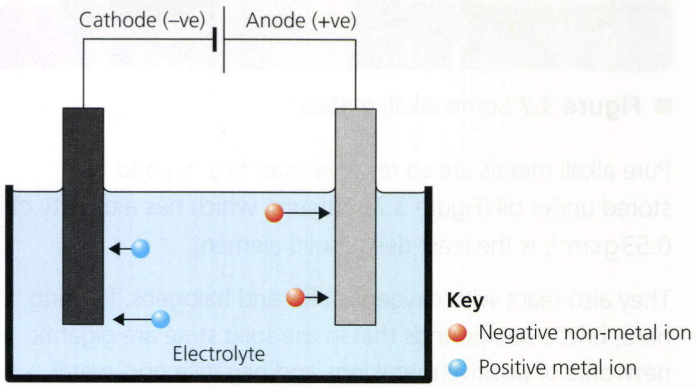



**Figure 3.11** A simple, generic representation of how **electrolysis** works. Reduction requires positive ions to gain electrons, and oxidation means negative ions lose electrons

Positively charged metal ions (**cations**) migrate to the negative electrode, called the **cathode**, where they gain the electrons they need to form **neutral** atoms, a process called **reduction**. Therefore, metals collect at the cathode. Negatively charged non-metal ions (**anions**) migrate to the **anode**, where they release their extra electrons in a process called **oxidation**, and also collect as molecules. Therefore, non-metals (which are often gases) collect at the anode.

Beryllium was isolated in 1828 by reacting the compound beryllium chloride with an even more highly reactive metal, potassium. Potassium, an alkali metal, had been isolated 11 years previously, also using the electrolysis process.

### EXTENSION

Watch reactions of alkaline earth metals in water:
**https://youtu.be/B2ZPrg9IVEo**

### SUMMARY REFLECTION

1. **State why alkaline earth metals are never found naturally as atoms.**
2. **Describe the origin of the term 'earth' in the name of this group.**
3. **Explain how one scientific discovery can lead to another.**

## HALOGENS

The **halogens** are a group of non-metal elements: bromine, chlorine, fluorine and iodine. All are coloured and have low boiling points, forming diatomic vapours at low temperatures (Figure 3.12). All were named by Sir Humphry Davy, who was also the first person to isolate chlorine.

The halogen elements are very reactive and toxic, affecting the lungs and eyes. In nature, halogens exist as negative **halide** ions found in sea water, or as ionic compounds found in salt deposits.

- Fluorine is the strongest known **oxidizing agent** (substance that accepts electrons), and reacts with almost all other elements, forming compounds that have a wide range of uses in industry and health care. For example, hydrofluoric acid is used to etch glass. Small quantities of sodium fluoride are added to drinking water to prevent tooth decay, the fluoride ions reacting with calcium phosphate to form a much harder material, apatite.
- Chlorine is also a powerful oxidizing agent. Industrial uses include hydrochloric acid, disinfectants and pool chemicals, and bleaching agents used to make wood pulp suitable for the manufacture of paper. Sodium and potassium chlorides are essential components of our body fluids, and each of us consumes approximately 4 kg of sodium chloride each year.
- Iodides have many applications, including cloud seeding with silver iodide to initiate rain. Without the ion in our diet, we would be unable to control our body's metabolic rate, because iodide is used to make the hormone thyroxine.
- Bromides have been used in sedatives, but their use in pharmacy is now limited to stages in the manufacture of medical drugs.

In 1928 CFC-12, a molecule consisting of two chlorine and two fluorine atoms attached to a single carbon atom, was the first of a range of synthetic **halogenated hydrocarbons** to be used as refrigerants, aerosol propellants and as fumigants. After a laboratory study in the 1960s revealed the potential for the chemicals to decompose ozone in the presence of high frequency UV



**Figure 3.12** In sealed containers at room temperature, chlorine is a gas, bromine is a liquid and iodine is a solid

radiation, calls to curb the use of the chemicals were met with limited, voluntary agreement. In the spring of 1984, ozone levels over Antarctica were found to have decreased by 35 per cent compared to values normal for the 1960s, confirming the laboratory predictions.

This time the response was unprecedented. An international treaty for phasing out the use of halogenated hydrocarbons was created within two years. The Montreal Protocol is the only international environmental treaty to have been signed by all 196 member countries of the United Nations and the European Union. Halogenated hydrocarbons are long-lived compounds, and the first evidence that the size of the 'hole' over Antarctica was no longer increasing came in 2014.

### EXTENSION

Watch this video on comparing the four halogens' properties and reactions (do not worry too much about the formulas at this stage) **https://youtu.be/u2ogMUDBaf4**

### SUMMARY REFLECTION

1. **Summarize the chemical properties of the halogen group.**
2. **Identify evidence in the passage, that atoms have different chemistry from ions, and that each ionic compound is unique.**
3. **Sketch a time line between introduction of a new compound to the global environment and its removal. Identify where the input of scientific knowledge occurred to make changes.**

## RARE EARTH ELEMENTS

The rare earth elements (REEs) are a group of 17 grey to silvery lustrous metals you would probably not recognize in your home, but they are crucial to the way people aspire to live in the 21st century. Chemically, the **reactivity** of the pure REEs is generally similar to magnesium, and they are soft and malleable (pliable). Small amounts are often alloyed with iron and nickel, or compounded in the luminous phosphors of electronic monitors. Examples of consumer goods in which REEs are used include televisions and computers, smart phones, high quality camera lenses, and the tiny permanent magnets in earphones and hard drives. Green technologies that use them include wind turbines, solar panels, catalytic converters and hybrid cars. A compound of one of the metals, europium, is embedded in the dyes of Euro banknotes to prevent forgery. High level applications include missile defence systems and medical scanners. The elements in this group are widely distributed.

The names of the REEs are also unlikely to be familiar: lanthanum, cerium, praseodymium, neodymium, promethium, samarium, europium, gadolinium, terbium, dysprosium, holmium, erbium, thulium, ytterbium and lutetium (collectively known as **lanthanides**), and scandium and yttrium. Because the metals are quite reactive and chemically similar to each other, they occur naturally as compounds and no natural ore is abundant in any particular element. Together, the metals are actually as common as tin, lead and zinc, but their mineral deposits are unevenly distributed over the Earth. More than a third (36 per cent) of the deposits are located in China, with large reserves in the USA (13 per cent) and Australia (5.5 per cent). Currently China has a market monopoly and produces 96 per cent of REEs used globally. However, several countries including Russia and the USA are currently investing in infrastructure to make them independent of China for these elements.



**Figure 3.13** The rare earth metal lanthanum is being poured into a mould for refinement



**Figure 3.14** A satellite image of an REE mine in northern China in 2006. This image covers an area of 48 $km^2$, the grey–green open-pit mines are 1 km deep. Vegetation is shown in red, and the tailings ponds are dark grey. A series of such images taken over several years reveals the growth of the industry

There is a very great contrast between the glossy presentation of modern consumer goods and the local environmental impact of mining and processing (Figures 3.13 and 3.14). The mines are open cast, and processing generates high levels of pollution, including carcinogens. REE ores are often naturally mixed with thorium, a radioactive element. Purifying one tonne of REEs typically generates 2000 tonnes of toxic waste, made up of sulfur dioxide, hydrofluoric and sulfuric acids, dust and radioactive residue, or tailings.

## SUMMARY REFLECTION

1. **Summarize** the chemical properties of the REE group.
2. **List** examples of goods you use that contain these elements. **Explain** why countries might want an independent supply of these elements.
3. **Comment** on whether global consumers have any responsibility for the pollution associated with REE mining in China. **Suggest** how much more we should be prepared to pay for our phones and other goods, to be assured that the industry is 'clean'.

## EXTENSION

Find out more about **China's rare earths mining**; **21st century gold rush**.

You could start by watching this presentation: www.bbc.com/news/world-asia-pacific-13777439

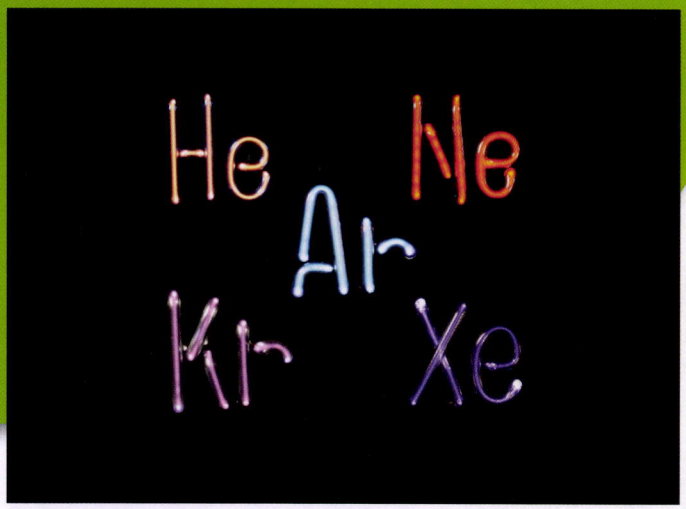



**Figure 3.15** Noble gas discharge tubes are popular for advertising signage, because the gases emit bright colours when an electric discharge passes through them. The colour emitted can also be varied by changing the pressure of the gas; at low pressures argon is pale red and at high pressures it is bluish

## NOBLE GASES

The **noble gases** (Figure 3.15) are the most recently discovered group of elements, and are so called because chemically they are almost unreactive, not bonding with most other elements or each other. They are monatomic, existing as single atoms. Helium and neon are completely **inert**, and argon, krypton, xenon and radon react with a very limited number of elements, forming unstable compounds.

If noble gases do not participate in chemical reactions, how did people learn they existed? In 1785, the wealthy entrepreneur scientist Henry Cavendish (1731–1810) found that about 1 per cent of the atmosphere consisted of a gas that would not combine chemically. In 1882, two other scientists, H. F. Newall (1857–1944) and W. N. Hartley (1845–1913), independently discovered evidence of a new element in emission spectra, but were unable to isolate the source. Emission spectra are the series of bright lines emitted by gaseous substances when they cool after being heated, indicating that electrons were returning to their usual location in the atom. They are unique for every element. In 1892, the physicist Lord Rayleigh measured a 5/1000th anomaly in the density of nitrogen found in air, compared with nitrogen he knew was pure, and sought the assistance of a chemist, William Ramsay (1852–1916), to resolve the mystery. Ramsay isolated first argon, then helium, neon, krypton and xenon.

## EXTENSION

Observe the noble gases in this video: https://youtu.be/QLrofyj6a2s

## SUMMARY REFLECTION

1. **Summarize the properties of the noble gases and examples of some of the uses of these elements.**
2. **Describe how careful measurements can determine knowledge.**
3. **Discuss whether a non-renewable resource (like helium) should be wasted on balloons, or whether we should first consider other strategies, like recycling and eliminating waste, when we capture the gas from its natural sources.**

Together, noble gases make up nearly 1 per cent of the volume of the atmosphere, and except for helium and radon, are purified using a distillation method applied to liquefied air. Argon is by far the most common, and has industrial uses in the steel industry, in electric light bulbs and sealed double glazing. The tyres of luxury cars may be filled with argon to prevent deterioration and limit noise. Krypton, neon and xenon also have roles in lighting, particularly in lasers when special wavelengths are required.

Helium is one of the most common elements in the universe, its existence first proposed in 1868 when a new line was detected in the Sun's absorption spectrum, indicating that an unknown element had absorbed energy of specific wavelengths. On Earth, helium is now collected from gases given off by mineral waters, and is a trace component in natural gas. It is also emitted when some radioactive elements decay. Approximately a third of the global supply currently comes from a stockpile in Texas, USA.

Helium is used in airships, medical **magnetic** resonance imaging (MRI) scanners and in deep-sea diving, where it does not have the narcotic effects of nitrogen. The most profitable commercial use is in party balloons, which accounts for about 8 per cent of global demand. However, it has been suggested this is a frivolous use of a non-renewable resource. The low density of helium makes it rare on Earth, where it continually escapes by diffusion from the atmosphere into space.

Radon is radioactive and does not have commercial uses. It is an occupational hazard in uranium mines. Granite can also emit radon, and ventilation is recommended for granite buildings to reduce the risk of lung cancer.

## ACTIVITY: Evidence for ions

### ATL

- Organization skills: Bring necessary equipment and supplies to class; understand and use sensory learning preferences (learning styles); select and use technology effectively and productively

You now know that all atoms consist of negatively charged electrons and a positive nucleus. This demonstration provides an opportunity to compare copper atoms with one of its ions.

**Safety:** Wear eye protection and gloves. If the solution touches skin, wash with copious water.

### Materials and equipment

- a flat glass dish (e.g. a Petri dish)
- a stock solution of an aqueous ammonium nitrate–ammonia mixture (0.5 M)
  [To make up a 0.50 $dm^3$ stock mixture, dissolve 20 g $NH_4NO_3$ in 0.45 $dm^3$ water; then add 0.05 $dm^3$ concentrated $NH_3$ solution]
- a strip of polished copper, approximately 4 × 2 cm
- a strip of copper mesh (e.g. copper fly screen), approximately 1 × 2 cm
- a DC power supply (10 V)
- 2 connecting wires with alligator clips.

### Method

1. Set up the equipment as shown in Figure 3.16.
2. Cover the base of the dish with the ammonium nitrate–ammonia solution, and turn on the power supply for a few minutes. Recall that in this circuit, electrons are lost at the anode, and delivered at the cathode.

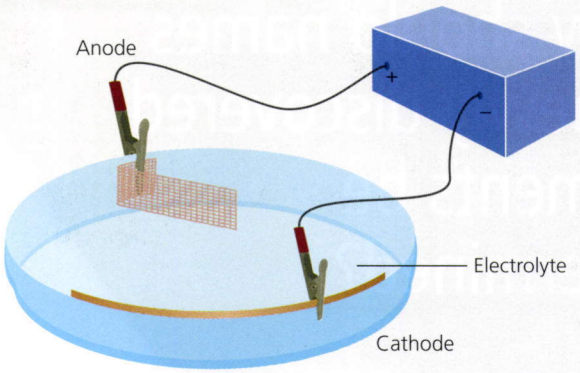



**Figure 3.16** Two copper electrodes in a Petri dish, connected to a 10 V power supply

### Analysing results

1. **Identify** evidence suggesting that the blue colour came from the copper metal.
2. **Identify** the terminal to which the blue solution is attracted. **Deduce** the charge of the particles in the blue solution.
3. **List** the evidence for ions having different properties from their atoms.
4. If the solution is neutral, **suggest** what is happening at the other terminal.
5. **Suggest** what would happen if you reversed the electrodes.

### Assessment opportunities

- In this activity you have practised skills that are assessed using Criterion C: Processing and evaluating.

## ACTIVITY: Comparing metals and non-metals

### ATL

- Critical-thinking skills: Practise observing carefully in order to recognize problems; interpret data; draw reasonable conclusions and generalizations

The aim of this task is to familiarize yourself with up to six metals and non-metals. The metals and non-metals should be as pure as possible (elements) and any equipment you use must be readily available in your school or from home.

- **Which properties will you observe or investigate?**
- **Can this type of comparative study have a 'control'?**

### Assessment opportunities

- In this activity you have practised skills that are assessed using Criterion B: Inquiring and designing and Criterion C: Processing and evaluating.

# How should names of newly discovered elements be determined?

## CHEMICAL SYMBOLS

Before exploring the relationships of the elements known today, it may be useful to recognize the ways the names of chemicals are summarized. Each symbol of a known element consists of one or two letters. The first letter is always capitalized. If the chemical symbol includes a second letter, this is always presented in lower case.

If you speak a Romance language, one that evolved from Latin, you may be able to recognize the elements that must have been known since ancient times, when Latin was the universal language of science in Europe. Because English has Latin roots, the chemical symbols are often also the same as the first two letters of the English name for the element. Ancient Arabic knowledge is also sometimes recognized in names that use similar sounds, even though the element may not have been isolated and assigned a symbol based on Latin until much more recently. Examples are sodium (derived from *Sudâ*, meaning soda) and boron (derived from *buraq*, meaning borax). With experience, you will soon become familiar with the chemical symbols for elements you will use at school.

Table 3.2 lists the names of elements that are exceptions to the rule that the symbols have letters in the same order as their names in English.

| Symbol | English name | Origin of the symbol |
|---|---|---|
| Ag | Silver | Latin *argentum* |
| Au | Gold | Latin *aurum* |
| Cu | Copper | Latin *cuprum*, 'from Cyprus' |
| Fe | Iron | Latin *ferrum* |
| Hg | Mercury | Greek *hydrargyrum*, 'silver water' |
| K | Potassium | Arabic *qalay* translated to Latin, *kalium* |
| Na | Sodium | Latin *natrium*, named in 1813 |
| Pb | Lead | Latin *plumbum* |
| Sb | Antimony | Latin *stibium* |
| Sn | Tin | Latin *stannum* |
| W | Tungsten | German *wolfram* |

**Table 3.2** Origins of 'irregular' chemical symbols for elements

### DISCUSS

1. **Suggest** whether science can be considered to have its own language.
2. **Outline** the features all languages have and **compare** this to how scientific knowledge is communicated.
3. **Evaluate** whether your developing skills in the language of chemistry support your communication in other languages, **justifying** your response.

### Links to: Language acquisition

Scientific language uses symbols and mathematics. Chemical communication requires familiarity with the names and symbols for the chemical elements and expressions to describe chemical change. This scientific language is international, and mastering it will help you develop as a global citizen.

## ACTIVITY: Exploring the names of chemical elements

### ATL

- Communication skills: Make inferences and draw conclusions; use and interpret a range of discipline-specific terms and symbols

What determines the name of an element? All over the world, place names are often the last remnants of forgotten languages. Often elements are named after a mythological concept, mineral, property or a scientist involved in its discovery. Some of these relationships are easy to guess, but others may be lost in time. This activity aims to help you become familiar with some of this history.

1. **In teams, discuss your general knowledge to suggest origins for the names of elements listed below.**
   - a **Identify the work of scientists honoured by the names of these elements:**
     **bohrium, curium, einsteinium, fermium, gadolinium, mendelevium, meitnerium, nobelium, lawrencium, roentgenium, rutherfordium, seaborgium, copernicium.**
   - b **Identify the countries or continents these elements are named after:**
     **americium, europium, francium, gallium, germanium, polonium, ruthenium, scandium, thulium.**
   - c **Suggest the place and/or country after which these elements are named:**
     **berkelium, californium, copper, darmstadtium, dubnium, erbium, hafnium, hassium, holmium, lutetium, magnesium, rhenium, strontium, terbium, ytterbium, yttrium.**
   - d **Research and suggest the names of astronomical bodies these elements have been named after: helium, neptunium, palladium, plutonium, selenium, tellurium, uranium.**
2. **If you have access to the Internet, check the information for unfamiliar names of the elements. Is there any pattern in your lack of knowledge that enables you to suggest the reason?**
3. **Suggest why some important global players are missing.**
4. **Evaluate whether names are a fair way to reflect on the history of chemistry.**

### Assessment opportunities

- In this activity you have practised skills that are assessed using Criterion A: Knowledge and understanding.

## EXTENSION: EXPLORE FURTHER!

On 31 December 2015 the IUPAC announced that four new elements had been added to the periodic table: **iupac.org/discovery-and-assignment-of-elements-with-atomic-numbers-113-115-117-and-118/**. Laboratories located in different countries have been awarded naming rights for **temporary working names for new elements**, currently called ununtrium (Uut), ununpentium (Uup), ununseptium (Uus) and ununoctium (Uuo). Watch this space!

# How does recognizing patterns contribute to a deeper understanding of the nature of elements?

| No. | | No. | | No. | | No. | | No. | | No. | | No. |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| H 1 | F 8 | Cl 15 | Co & Ni 22 | Br 29 | Pd 36 | I 42 | Pt & Ir 50 |
| Li 2 | Na 9 | K 16 | Cu 23 | Rb 30 | Ag 37 | Cs 44 | Tl 53 |
| G 3 | Mg 10 | Ca 17 | Zn 25 | Sr 31 | Bd 38 | Ba & V 45 | Pb 54 |
| Bo 4 | Al 11 | Cr 19 | Y 24 | Ce & La 33 | U 40 | Ta 46 | Th 56 |
| C 5 | Si 12 | Ti 18 | In 26 | Zr 32 | Sn 39 | W 47 | Hg 52 |
| N 6 | P 13 | Mn 20 | As 27 | Di & Mo 34 | Sb 41 | Nb 48 | Bi 55 |
| O 7 | S 14 | Fe 21 | Se 28 | Ro & Ru 35 | Te 43 | Au 49 | Os 51 |

(NOTE.—Where two elements happen to have the same equivalent, both are designated by the same number.)

**Figure 3.17** A first periodic table of the elements, arranged in 'octaves'

## ENGAGING WITH PATTERNS

As a science, chemistry is concerned not so much with isolated facts as the relationships elements have with each other, based on comparisons with their properties. Today we know of 118 elements, but two millennia ago the situation was very different. Like an incomplete jigsaw, the ten elements known at that time (Table 3.3) did not suggest a bigger picture, including whether there was an upper limit for the total number of elements.

As more elements were discovered, it remained difficult to distinguish between elements and compounds. An early grouping by Antoine Lavoisier (see Chapter 1) listed light and heat with gases, and a problematic category he called earths that he knew did not contain identical atoms. When John Dalton claimed atoms in compounds combine in simple, whole-number ratios (see Chapter 1), he provided the first practical method for calculating their relative atomic mass, and this made the investigation of classification systems possible. Soon afterwards, the chemical similarity of groups began to be noticed. Johann Wolfgang Döbereiner (1780–1849) observed that in groups of three elements with similar chemistry, the middle element had a relative atomic mass that was approximately the mean of the two elements on either side. By 1845, more 'triads' had been discovered, and some had been extended to groups of four or five elements (Table 3.4).

Another chemist, J.A.R. Newlands, began exploring arrangements of elements in order of increasing relative atomic mass. In 1865 he produced a table that placed the 62 known elements into eight columns, sometimes with two elements sharing a position (Figure 3.17). Newlands explained this arrangement showed that 'members of the same group stand to one another as the extremities of one or more octaves of music', a first recognition of a recurring pattern linking all elements.

The scientists who took Newlands' ideas further all realized the potential for classification to have predictive power. Within five years there was a version that left gaps for the possibility of an unknown group, now filled by noble gases, and others that recognized patterns of reactivity and atomic densities revealed gaps in a sequence based on relative atomic masses. Both Julius Lothar Meyer (1830–1895) and Mendeleev (see Chapter 1) independently developed similar understandings, but it is the Russian chemist who is now most often remembered. Mendeleev was so confident his arrangement revealed an underlying order that he sometimes ignored strictly sequencing the elements by their relative atomic mass, and published a list of properties he predicted for the missing elements, including their atomic masses, density, melting points and the composition of their compounds. As missing elements were discovered and isolated, many of his or sometimes Meyer's alternative proposals were found to be remarkably accurate. With approximately a third of the naturally occurring elements remaining to be discovered (Table 3.3) a definite picture of the chemistry of matter was emerging.

| Time | Number | Element, symbols (atomic number)<br>New elements discovered during interval after the preceding date |
|---|---|---|
| 2000 years ago | 10 | Carbon, C (6); sulfur, S (16); iron, Fe (26); copper, Cu (29); silver, Ag (47); tin, Sn (50); antimony, Sb (51); gold, Au (79); mercury, Hg (80); lead, Pb (82) |
| 1780 | 20 | Hydrogen, H (1) nitrogen, N (7); oxygen, O (8); phosphorus, P (15); cobalt, Co (27); nickel, Ni (28); zinc, Zn (30); arsenic, As (33); platinum, Pt (78); bismuth, Bi (83) |
| 1803 (Dalton) | 40 | Beryllium, Be (4); fluorine, F (9); chlorine, Cl (17); titanium, Ti (22); chromium, Cr (24); manganese, Mn (25); strontium, Sr (38), yttrium, Y (39); zirconium, Zr (40); niobium, Nb (41); molybdenum, Mo (42); rhodium, Rh (45); palladium, Pd (46), tellurium, Te (52); cerium, Ce (58); tantalum, Ta (73); tungsten, W (74); osmium, Os (76); iridium, Ir (77); uranium, U (92) |
| 1869 (Mendeleev) | 62 | Lithium, Li (3); boron, B (5); sodium, Na (11); magnesium, Mg (12); aluminium, Al (13); silicon, Si (14); potassium, K (19), calcium, Ca (20); vanadium, V (23), selenium, Se (34); bromine, Br (35); rubidium, Rb (37); ruthenium, Ru (44); cadmium, Cd (48); indium, In (49); iodine, I (53); caesium, Cs 55); barium, Ba (56); lanthanum, La (57); erbium, Er (68); thallium, Tl (81); thorium, Th (90) |
| 2015 | 118 | to date |

**Table 3.3** A time line of history of knowledge of the elements

| | Average RAM | | Average RAM | | Average RAM | | Average RAM | | Average RAM |
|---|---|---|---|---|---|---|---|---|---|
| | | | | N<br>14.0 | | O<br>16 | | F<br>19 | |
| Li<br>6.9 | | Mg<br>24.3 | | P<br>31.0 | 44.5 | S<br>32.1 | 47.5 | Cl<br>35.5 | 49.5 |
| Na<br>23 | (6.9+39.1)/2<br>= 23 | Ca<br>40.1 | 56 | As<br>74.9 | 76.4 | Se<br>79 | (32.1 + 127.6)/2<br>= 79.8 | Br<br>80 | (35.5 + 127)/2 =<br>81.25 |
| K<br>39.1 | | Sr<br>87.6 | (40.1 + 137.3)/2<br>= 88.7 | Sb<br>121.8 | 142 | Te<br>127.6 | | I<br>127 | |
| | | Ba<br>137.3 | | Bi<br>209 | | | | | |

**Table 3.4** Döbereiner's triads of elements (discovered in 1829, shown outlined) superimposed on Gmelin's triads, tetrads and pentad (discovered in 1843) and their relative atomic mass (RAM), compared with the average RAM (shown in red) of the two elements that bracket them. The calculations are shown only for the average RAM discovered by Döbereiner

## How the distribution of mass in an atom determines the sequence of the elements

Mendeleev's first periodic table was produced in 1869, many decades before physicists discovered any of the atom's subatomic particles.

- **Electrons** were identified by J.J. Thomson (1856–1940) in 1897. He also determined that they contributed only 0.05 per cent to the total mass of atoms.
- **Protons**, carrying positive charge to balance the negative charge of electrons, were discovered by Ernest Rutherford (1871–1937) in 1911. He determined they were part of the dense matter of the atomic nucleus.
- The **neutron** was discovered by James Chadwick (1891–1974) in 1932. Neutrons carry no charge, but account for the remainder of the mass in the nucleus. Individual neutrons have almost the same mass as protons.

The **proton number** of an atom is constant, and determines the element's **atomic number**. Unlike electrons, which can be gained or lost to form ions, the particles of the nucleus never participate in chemical reactions. The number of neutrons, calculated by subtracting an atom's atomic number from its **mass number** (sum of protons and neutrons), does not have a consistent relationship to the number of protons, explaining some of the anomalies observed by Mendeleev when he mapped the properties of elements to a sequence of increasing relative atomic mass.

# THE MODERN PERIODIC TABLE

Modern periodic tables order the elements by increasing atomic number. The rows are called **periods**, and their lengths vary. For convenience, the series of elements making up the lanthanides (atomic numbers 57–71), and **actinides** (89–103) are listed below the main block of elements. Uranium (92) is the heaviest naturally occurring element. Heavier elements have been created artificially in nuclear facilities, but all quickly break up by radioactive decay. The **groups** form columns, and you are already familiar with the general properties of **alkali metals**, **alkaline earth metals**, **halogens** and **noble gases**. Notice how the rare earth elements include the group headed by scandium (21), yttrium (39) and all the lanthanides. One group that has not been considered separately is the **transition metals**, forming the block of elements shown in yellow in Figure 3.18. These elements often have more than one **valency**, which means their atoms can form compounds with other elements in different ratios.

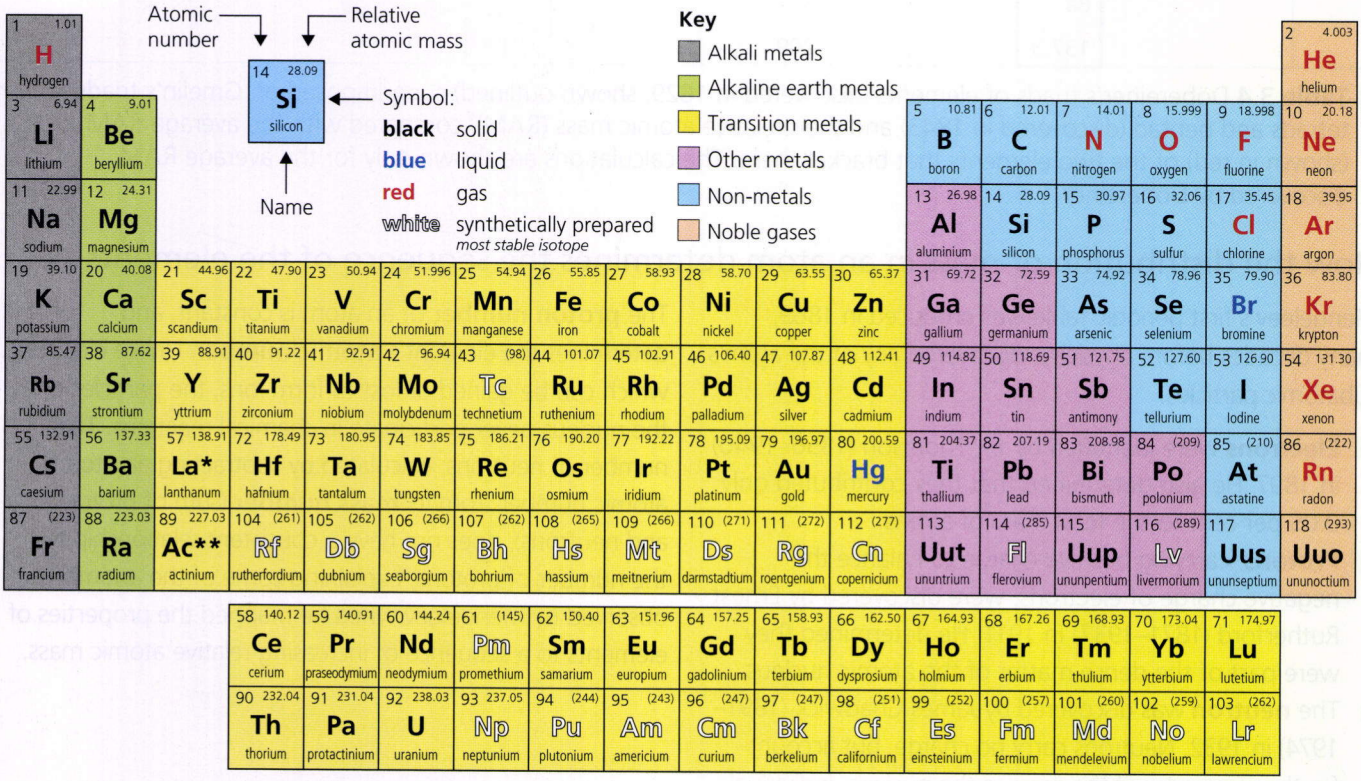



**Figure 3.18** The 'medium-long' periodic table is the most popular current arrangement using our modern understanding

When the atoms are arranged in this format, the periodic table reveals consistent patterns in the chemistry of the elements. Across each period, the elements are ordered from 'metallic', to 'non-metallic' to 'noble gases'. The groups at the extremes of the period, the alkali metals and halogens, are very reactive compared to groups located at the centre of the period. The noble gases are not part of this trend.

Down each group, the reactivity changes with atomic size. In metals, the bigger the atom, the more reactive it is. In non-metals, the smaller the atom, the more reactive it is. You may recall that fluorine is the strongest known oxidizing agent or oxidant (substance that attracts electrons). Why do you think the large block of elements in the centre of this arrangement might be called *transition* metals?

These unarguable patterns provide a powerful incentive for further investigation into chemical relationships.

## EXTENSION

Here is a comprehensive database of periodic tables and periodic system formulation:
**www.meta-synthesis.com/webbook/35_pt/pt_database**

## ACTIVITY: The development of chemical knowledge

### ATL

- Reflection skills: Develop new skills, techniques and strategies for effective learning; Focus on the process of creating by imitating the work of others

After attempting these questions independently, use conversation triads to discuss your ideas with others, and annotate your notes. Some people may have responded differently to some of these questions, but parts of their answers may also be right!

1 **Identify** the sequence of discoveries of elements (Table 3.3) on a blank copy of the modern, medium-long periodic table, perhaps using different colours. (You can download one here: http://web.lincoln.k12.mi.us/buildings/hs/gurganus/psa_periodic_table_rows.jpg.)
   - a **Suggest** reasons for elements being discovered in the order they were.
   - b **Suggest** why so many of the synthetic elements, shown in white in Figure 3.18, are named after famous scientists.
2 In the history of the periodic table, predictions based on patterns became successful when about two-thirds of the natural elements had been discovered.
   - a **Identify** characteristics of collections that assist people in understanding patterns. (Hint, do you have personal experience completing jigsaws?)
   - b **Evaluate** whether the number of groups of elements helped or hindered the development of the modern periodic table.
3 **Comment** on the claim that *classification systems have predictive power.* Is a classification system a type of *hypothesis*? **Identify** other examples of classification systems that lead to further knowledge.
4 **Summarize** the similarities and differences of the subatomic particles of an atom (electrons, protons and neutrons) by comparing their relative size, charge and location in a table.

When Mendeleev was first told about the discovery of electrons in 1897, he rejected the idea and predicted they would go the way of phlogiston (a substance with no mass or even negative mass once believed to be part of flammable materials), arguing atoms were indivisible.

5 **Comment** on what this story reveals about
   - a human fallibility
   - b how knowledge develops and
   - c whether we can ever be certain.
6 **Suggest** whether new elements remain to be discovered.

### Assessment opportunities

- In this activity you have practised skills that are assessed using Criterion A: Knowledge and understanding.

# How can the relationships between chemical elements be represented?

## *THE* PERIODIC TABLE OR *A* PERIODIC TABLE?

Figure 3.19 shows an alternative representation of the periodic table.

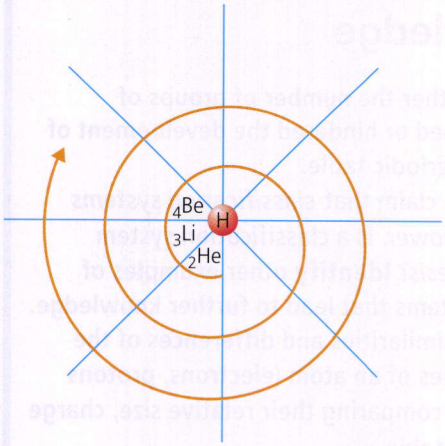



**Figure 3.19** An example of the spiral form of the periodic table

## DISCUSS

Refer to Figure 3.18 to add the names and atomic numbers for the first 20 elements to a sketch of Figure 3.19.

1. **Identify** the 'segments' that are:
   - a alkali metals
   - b alkaline earth metals
   - c noble gases
   - d halogens.
2. **Describe** how this format supports the idea that the properties of elements have 'periodicity'.
3. **Suggest** how the transition metals, lanthanides and actinides could be introduced into this format.

## ACTIVITY: The past and future of the periodic table

### ATL

- Creative-thinking skills: Consider multiple alternatives, including those which might be unlikely or impossible; create novel solutions to authentic problems; create original works and ideas, use existing works and ideas in new ways

Imagine your school is hosting an exhibition, 'The past and future of the periodic table'.

Your task is to create an exhibit of an alternative representation of the periodic table. It can be linear, two-dimensional or three-dimensional. To be more than a periodic table, you should include a written description (perhaps an A3-sized poster) with your model that explains the following:

- **How the scientific discovery of elements was the impetus for their purification and refinement. You should highlight one particular group or chemical element as an example.**
- **How understanding of the periodicity and groupings is useful, and explain the interaction of the group or chemical element you have highlighted with a moral, ethical, social, economic, political, cultural or environmental factor as a result of its use.**
- **Labels and other forms of explanations should use scientific language simply and concisely. Clear communication of scientific understanding for the public is an important skill.**
- **Sources should be fully documented on a separate reference list, in a way that does not detract from the presentation of your display.**

### Assessment opportunities

- In this activity you have practised skills that can be assessed using Criterion D: Reflecting on the impacts of science.

Within a few years of Mendeleev's and Meyer's schemes for arranging elements, many others were suggested. Today, at least 600 different versions have been proposed. These generally fall into two categories: mapping the elements in a continual line, spirals and three-dimensional 'trees', or 'descendants' of Mendeleev's table, in which groups and periods are arranged in a matrix.

In either type of presentation, there is considerable scope to highlight different aspects of the chemistry of groups. In every type of arrangement, there are always a small number of 'problem' elements that do not quite fit the regular trends and patterns of the arrangement.

## Links to: Design Technology

Scientific concepts and ideas are enhanced and clarified by the way they are presented. How can the skills of design technology contribute to the representation of the periodic table?

## ! Take action: Create a game based on the periodic table to help others learn!

### ATL

- Collaboration skills: Practise empathy; encourage others to contribute; help others succeed
- Creative thinking skills: Create original works and ideas; use existing works and ideas in new ways

! Some of your learning in this chapter used a strategy called 'jigsaw', named after the puzzle, itself a metaphor for how chemical relationships were eventually understood as a 'big picture'. All sorts of games are excellent tools for learning, whether these are social skills, or familiarize people with general knowledge.

! Create a game of any type for use as a teaching resource to support junior students of science at your school. It should include some correct factual knowledge about the periodic table, or information about the innovative technologies that enabled scientific discoveries of different groups of elements. Perhaps you will be able to spend a lesson with your peers or younger students to share your understanding!

**REFLECTION**

1 **Discuss how it makes you feel to spend time with students who are not in your immediate peer group.**
2 **Evaluate whether the game you developed will be a valuable resource for your school. Identify other ways to contribute to develop a 'community of learners'.**
3 **If you had to do this again, suggest how you would change your game to make it even better (more exciting and engaging, more robust, sustaining the learning involved etc.).**




**Figure 3.20** Many of the rules of a well-known board game have been adapted to incorporate facts about elements in this outstanding example of a game based on the periodic table, developed by students

### Assessment opportunities

- In this activity you have practised skills that are assessed using Criterion A: Knowledge and understanding.

## SOME SUMMATIVE PROBLEMS TO TRY

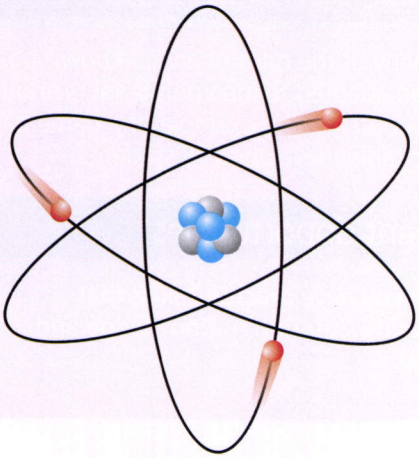
Use these problems to apply and extend your learning in this chapter. The problems are designed so that you can evaluate your learning at different levels of achievement in Criterion A: Knowing and understanding.

A copy of a periodic table should be available for reference.

### THESE PROBLEMS CAN BE USED TO EVALUATE YOUR LEARNING IN CRITERION A TO LEVEL 1–2

1 **State** the difference between
   - a an atom and an ion
   - b a metal and a non-metal
   - c an anode and a cathode.

2 It is quite common to see illustrations modelling a 'typical' atom, such as the one in Figure 3.21.
   - a **Label** the three sub-atomic particles, and **state** the charge each carries.
   - b **Suggest** one change you could make to this diagram, to better reflect the scale of the sub-atomic particles.



■ **Figure 3.21** A representation of an atom

3 Imagine that a new element called MYPium had been isolated. It has low density, and is a solid which is soft and easily cut with a knife. It is extremely reactive with both air and water. It is a good conductor of heat and electricity, and also has a low melting point.

**Interpret** this information to judge:
   - a in which group in the periodic table you would place MYPium
   - b how you would you store it
   - c the method that was probably used to purify MYPium to its metal state.

### THESE PROBLEMS CAN BE USED TO EVALUATE YOUR LEARNING IN CRITERION A TO LEVEL 3–4

4 **Outline** the trends in the chemistry of the patterns in the medium-long periodic table
   - a across each period
   - b down the groups of metals
   - c down the groups of non-metals.

5 **Suggest** the chemical group that might be a source of elements to **solve** the following problems.

| | Problematic situation | Chemical group or groups |
|---|---|---|
| a | Nitrogen gas is normally inert, but at the high pressures inhaled by deep sea divers can cause a dangerous condition called *narcosis*. Perhaps a different unreactive gas ... | |
| b | Teeth are a form of calcium phosphate, a substance that can react with acids produced in the mouth by bacteria. Perhaps a reactive substance that can change the mineral ... | |
| c | Normal iron magnets are not strong enough for use in tiny modern electronic devices. Perhaps if the magnetic elements are alloyed with another substance.... | |
| d | These two groups are commonly presented as cations but difficult to isolate as pure elements without using electrolysis. | |

6 The following poem by Vernon Newton is called 'Mistress Fluorine':

Fervid fluorine, though just Nine,
Knows her aim in life: combine!
In fact, of things that like to mingle,
None's less likely to stay single.

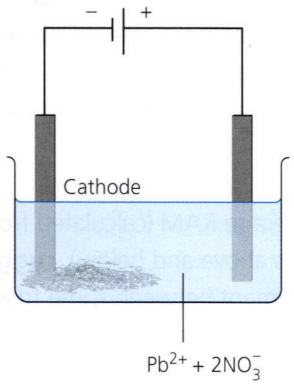
**Interpret** this information to make scientifically supported judgments about the chemistry of fluorine.

### THESE PROBLEMS CAN BE USED TO EVALUATE YOUR LEARNING IN CRITERION A TO LEVEL 5–6

7 In a similar activity to one in which you observed the formation of copper(II) ions, students completed an electric circuit using two electrodes in a solution that had lead(II) ions in it.

After some time, grey crystals were observed collecting at the negative electrode (Figure 3.22).

**Describe** the process that is happening at the cathode, and the evidence that this is occurring.




■ **Figure 3.22** Electrolysis of lead(II) nitrate solution between inert electrodes

8 The table provides information on different ratios (as percentages by mass) of copper–tin alloys used as bronzes.

| Percentage copper | Percentage tin | Properties |
|---|---|---|
| 80 | 20 | Too brittle to be useful for large weight-bearing objects |
| 84 | 16 | |
| 86 | 14 | Maximum strength |
| 88 | 12 | |
| 90 | 10 | Too malleable to be useful for large weight-bearing objects |

All over the world, most Bronze Age cultures used mixtures of about 87–88 per cent copper and 10–11 per cent tin, the remainder made up of impurities including lead and antimony.

a **Describe** how alloys can have different physical properties from each of the metals they are made of.

b **Suggest** how the presence of small amounts of impurities changed the pattern of the properties shown in the table above.

### THESE PROBLEMS CAN BE USED TO EVALUATE YOUR LEARNING IN CRITERION A TO LEVEL 7–8

9 **Explain** how delocalized electrons in metals contribute to the following physical properties:

a lustre

b conductivity of heat

c conductivity of electricity

d malleability and ductility.

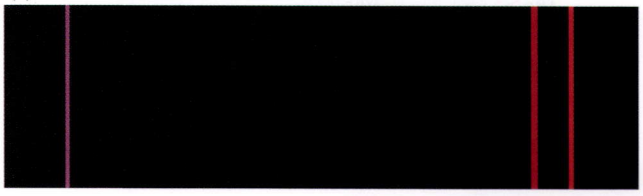
10 The images in Figure 3.23 represent flame emission spectra of purified salts of (a) potassium and (b) an element discovered in 1861.

Analyse the images. **Suggest**

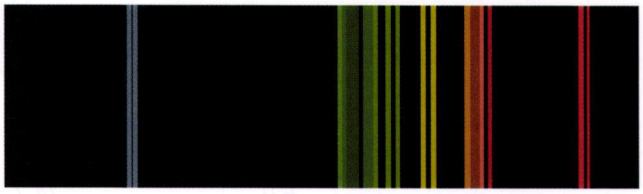
a why Bunsen and Kirchhoff knew the second sample did not contain potassium

b the reason the new element was called 'rubidium'.

(a)



(b)



■ **Figure 3.23**

11 Figure 3.24 maps relative atomic size (volume) to atomic mass, revealing relationships similar to those published by Meyer in 1870.

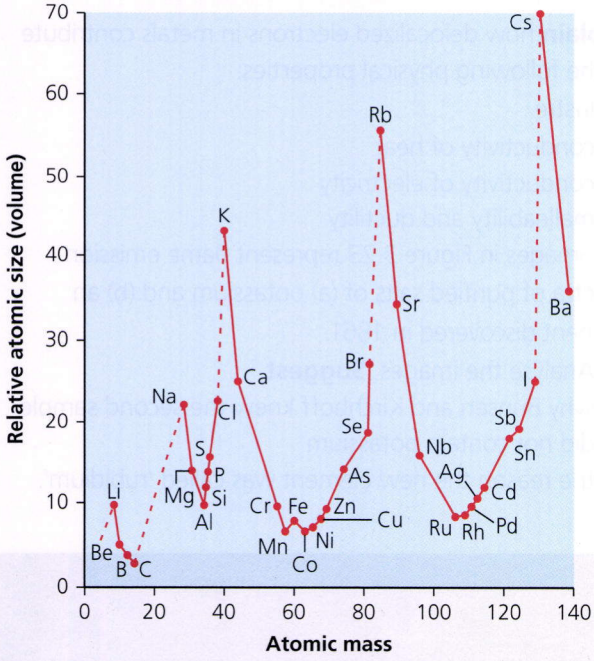



**Figure 3.24** A historic graph relating atomic volumes to atomic mass

**Apply** your knowledge of patterns in the periodic table to:

- **a** **explain** why this graph is incomplete
- **b** **identify** the groups represented at the series of peaks, and the series of troughs. How does this pattern relate to the reactivity of the elements?
- **c** **describe** the periodic pattern that recurs within this representation. If an additional period could be included in this Meyer's curve, **estimate** the atomic volume of the element at the next peak.

12 Table 3.5 lists Gmelin's triad, tetrads and a pentad and with Döbereiner's triads superimposed. Although the average RAM of Dobereiner's triads (shown in red) were very similar to the means of the elements above or below in the same group, this relationship was not necessarily always true in the examples suggested by Gmelin.

- **a** Judge the scientific basis for Gmelin's patterns.
- **b** With reference to the average RAM (calculated from the RAM of the elements above and below), **suggest** why there is better agreement between some triads of elements (which are shown in red) than others (shown in black).

| | Average RAM | | Average RAM | | Average RAM | | Average RAM | | Average RAM |
|---|---|---|---|---|---|---|---|---|---|
| | | | | N 14.0 | | O 16 | | F 19 | |
| Li 6.9 | | Mg 24.3 | | P 31.0 | 44.5 | S 32.1 | 47.5 | Cl 35.5 | 49.5 |
| Na 23 | (6.9+39.1)/2 23 | Ca 40.1 | 56 | As 74.9 | 76.4 | Se 79 | 79.8 | Br 80 | 79.8 |
| K 39.1 | | Sr 87.6 | 88.7 | Sb 121.8 | 142 | Te 127.6 | | I 127 | |
| | | Ba 137.3 | | Bi 209 | | | | | |

**Table 3.5** Gmelin's triad, tetrads and pentad (1843), with Döbereiner's triads superimposed

# Reflection

In this chapter you developed your understanding of the periodic table as an organizer of elements according to their chemical properties, and were introduced to chemical nomenclature. You observed evidence that ions and atoms have different properties and began to investigate the properties of metals.

| **Use this table to reflect on your own learning in this chapter** | | | | | |
|---|---|---|---|---|---|
| Questions we asked | Answers we found | Any further questions now? | | | |
| **Factual:** What are some of the chemical characteristics of broad groups of elements? | | | | | |
| **Conceptual:** How does recognizing patterns contribute to a deeper understanding of the nature of elements? How can the relationships between chemical elements be represented? | | | | | |
| **Debatable:** How should names of newly discovered elements be determined? | | | | | |
| Approaches to learning you used in this chapter: | Description – what new skills did you learn? | How well did you master the skills? | | | |
| | | Novice | Learner | Practitioner | Expert |
| **Communication skills** | | | | | |
| **Collaboration skills** | | | | | |
| **Organization skills** | | | | | |
| **Reflection skills** | | | | | |
| **Creative-thinking skills** | | | | | |
| **Learner profile attribute(s)** | How did you demonstrate your skills as a communicator in this chapter? | | | | |
| **Communicators** | | | | | |

# 4 How do atoms bond?

Chemical and physical properties provide **evidence** of the **relationships** both **between and within atoms**.

## CONSIDER AND ANSWER THESE QUESTIONS:

**Factual:** What does the IUPAC name of a chemical compound tell you? How is valency used to balance the atoms in a compound?

**Conceptual:** How do differences in chemical bonding contribute to the physical properties of its compounds? How do electrons of atoms contribute to the chemistry of their compounds? How does the difference in electronegativity of their elements determine the type of chemical bond in a compound?

**Debatable:** To what extent can ionic, metallic and covalent bonds be manipulated to create compounds with unique properties?

Now **share and compare** your thoughts and ideas with your partner, or with the whole class.

## IN THIS CHAPTER, WE WILL ...

- **Find out** how different types of bonding affect physical and chemical properties.
- **Explore:**
  - the relationship between bond types in molecules and the location of their elements in the periodic table;
  - how bonding relationships, including intermolecular forces, affect macromolecular properties of substances.
- **Take action** by creating educational mobiles featuring bond types.

## These Approaches to Learning (ATL) skills will be useful ...

- Communication skills
- Collaboration skills
- Organization skills
- Critical-thinking skills
- Information literacy skills

## We will reflect on this learner profile attribute ...

- Communicators: What special vocabulary do you need to communicate chemical information to others? Why are elements usually represented by symbols? How good are you at choosing the best way to present data, results and conclusions, in your oral, visual and written presentations? Do you take advantage of learning from others in class?



**Figure 4.1** The stickiness of the gecko's feet help it move across many types of surface. How does matter bond, both temporarily and permanently?

## Assessment opportunities in this chapter:

- Criterion A: Knowing and understanding
- Criterion B: Inquiring and designing
- Criterion C: Processing and evaluating
- Criterion D: Reflecting on the impacts of science

**KEY WORDS**

attract bond repel

## ACTIVITY: How do the particles in matter connect (bonding)?

### ATL

- Communication skills: Negotiate ideas and knowledge with peers and teachers; write for different purposes; take effective notes in class

This activity uses the 'chain notes' method. On a long strip of paper, your teacher will write a question. The sheet will be passed around the class. When it reaches you, read the last response and then add a note or a short question to the list. It should be no longer than a sentence or two. Then fold the paper accordion-style so that the next student can only see your response.

When the sheet has gone round the whole class, your collective responses will be shared and discussed.

To prepare for your response before the activity starts, pause and think about what you have learnt so far about matter. Jot down some notes and ideas about your understanding of identities and relationships, how matter behaves and how it connects.

### Conversation triads

1. **Identify** examples of ideas you shared with others in your class. Did any comments by your peers intrigue you?
2. **Evaluate** how you feel about being required to respond to a 'chain note'.
3. **Suggest** how your knowledge will develop in this chapter.

# How does chemical bonding contribute to the physical properties of compounds?

## ACTIVITY: Puzzling out bonds

**ATL**

- Collaboration skills: Build consensus; help others succeed
- Organization skills: Keep an organized and logical system for information files/notebooks; understand and use sensory learning preferences (learning styles)

The six workstations are intended to provide you with a practical understanding of the characteristics of four major types of **chemical bond**. The workstations can be experienced in any order, and each should take no longer than a few minutes to complete, including the tidying up for the next group. The relationships and identities of these connections will be revealed later.

### Recording data

Make a copy of Table 4.1, pencilling in your observations under the categories listed. You can then change your responses as you learn more.

### Discuss

After you have visited all the workstations, develop collective responses to these statements:

1. **Identify** the bonding categories for copper, table salt, wax, sucrose, sand and oil.
2. **List** the solid substances that conduct electricity.
3. **List** the liquids or solutions that conduct electricity.
4. **Consider** the claim that a substance which is liquid at room temperature must have a low melting point. **Identify** the example/s in this category.
5. **Consider** the claim that 'solubility in water', alone, could be a basis for distinguishing between categories.
6. **Suggest** why you didn't test any gases. In which category should they be included?

| Property | Type of bonding likely to be present in the substance | | | |
|---|---|---|---|---|
| | Metallic | Ionic | Covalent molecular | Covalent network |
| Melting point | | | | |
| Hardness | | | | |
| Malleability | | | | |
| Electrical conductivity: | | | | |
| as a solid | | | | |
| dissolved in water | | | | |

**Table 4.1** Recognizing bonding features by testing common substances

## 1 Sugar and sand

Materials and equipment

- a labelled container of dry, white sand (silicon dioxide, $SiO_2$)
- a labelled container of sugar (sucrose)
- metal spatulas
- a heat source (e.g. a candle or spirit burner)
- test tubes
- access to hot tap water

Method

1. List the similarities and differences you can observe by sight, touch or smell.
2. Heat a small amount of each substance by holding it in a spatula over a flame for about a minute.
3. Add a very small amount of another sample of each substance to a test tube, and test whether it dissolves in hot tap water.

**Hint**

*One of the substances is an example of a covalent network solid, and one is a covalent molecular substance.*

## 2 Sugar and salt

Materials and equipment

- a labelled container of table salt (sodium chloride, NaCl)
- a labelled container of sugar (sucrose)
- water
- spatulas
- small beakers
- a power source, ammeter and three leads

Method

1. List the similarities and differences you can observe by sight, touch or smell.
2. Add about a teaspoon of each of these substances to a small beaker, and test whether it dissolves in about 0.5 $dm^3$ (50 $cm^3$) of water.
3. Now test whether either of the solutions conducts electricity, by including it in a circuit with a power pack (set at about 3 V) and an ammeter.

**Hint**

*One of the substances is an example of an ionic solid, and the other is a covalent molecular solid.*

## 3 Metal and wax

Materials and equipment

- pieces of wax, e.g. candles
- metal foil, e.g. copper foil cut into pieces, 4 cm × 2 cm
- a small hammer
- a heat mat, or other means to protect the bench
- a power source, ammeter and three leads

Method

1. List the similarities and differences you can observe by sight, touch or smell.
2. Using the mat to protect the bench, gently tap the copper and the wax with the hammer. Can you make an impression?
3. Now test whether either conducts electricity, by including it in a circuit with a power pack (set at about 3 V) and an ammeter.

**Hint**

*One of these substances is an example of a metal, and one is a covalent molecular solid.*

## 4 Salt and wax

Materials and equipment

- pieces of wax, e.g. candles
- coarse salt (sodium chloride, NaCl) crystals
- a small hammer
- Petri dishes or similar
- a stereo dissecting microscope
- a heat mat, or other means to protect the bench

Method

1. List the similarities and differences you can observe by sight, touch or smell.
2. Use the mat to protect the bench. Firmly hit the salt crystals and the wax with the hammer.
3. Place the results in a Petri dish and observe the effect of the impact using the stereo dissecting microscope.

**Hint**

One of these substances is an example of an ionic solid, and one is a covalent molecular solid.

## 5 Oil and sugar

Materials and equipment

- a bottle of oil (e.g. a light vegetable oil. If using paraffin this *must* be kept away from naked flames, including workstation 1)
- a labelled container of table sugar (sucrose)
- test tubes

Method

1. List the similarities and differences you can observe by sight, touch or smell.
2. Note the state of each substance at room temperature.
3. Place a small amount in a test tube, to compare its solubility in water.

**Hint**

Both of these substances are in the same category.

## 6 Sand and salt

Materials and equipment

- a labelled container of table salt (sodium chloride, NaCl)
- a labelled container of sand (silicon dioxide, $SiO_2$)
- water
- spatulas
- small beakers
- a power source, ammeter and three leads

Method

1. List the similarities and differences you can observe by sight, touch or smell.
2. Test whether either of the solids conducts electricity, by including it in a circuit with a power pack (set at about 3 V) and an ammeter.
3. Add about a teaspoon of each of these substances to a small beaker, and test whether it dissolves in about 0.5 $dm^3$ of water.
4. Now test whether either of the solutions conducts electricity, by including it in a circuit with a power pack (set at about 3 V) and an ammeter.

**Hint**

One of these substances is an example of an ionic solid, and the other is a covalent network solid.

### Assessment opportunities

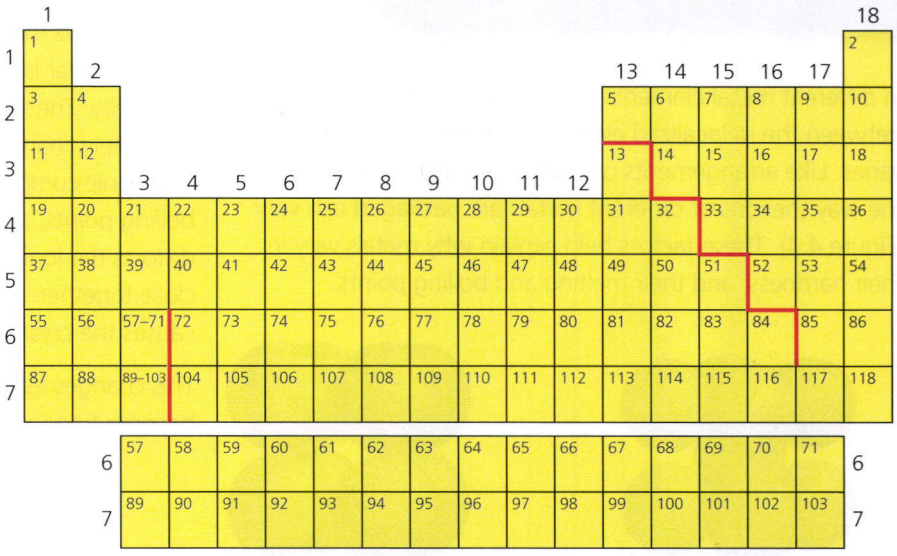
- In this activity you have practised skills that can be assessed with Criterion C: Processing and evaluating.

# How do electrons of atoms contribute to the chemistry of their compounds?

## BONDING RELATIONSHIPS ACROSS THE PERIODIC TABLE

You may recall that when the elements are arranged in a standard periodic table, the trend that emerges across each period is that very reactive metals are found on the left-hand side, transition metals are found in the centre, and that elements become increasingly non-metallic towards the right-hand side.

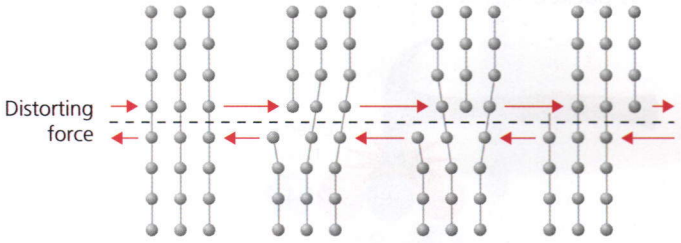
Vertical groups are usually numbered (Figure 4.2) as a shorthand way to refer to their chemistry. You will recognize group 1 refers to alkali metals; 2, alkaline earth metals; 17, halogens; 18, noble gases; and that transition metals may be found in groups 3–12, with a number of 'other metals' located in groups 13–16. The way these elements bond with others falls into distinctive patterns.




■ **Figure 4.2** A blank copy of the periodic table classifying groups and periods by number

### Metallic bonding, found in metallic elements of groups 1–16

You have already seen (Chapter 3) that metals consist of a continuous lattice of positive ions within a 'sea' of delocalized electrons. These are the electrons involved in chemical reactions, or valence electrons. The electrical attraction between these delocalized electrons and the positive metal ions explains how the atoms of metals are bonded. This attraction acts in all directions and decreases with distance. As a consequence, **metallic bonds** are able to resist forces such as bending or hitting the metal with a hammer. Instead, the ions slip to new relationships with delocalized electrons (Figure 4.3). Metals are insoluble, although some will react with water to produce a soluble product. The delocalized electrons also explain other metallic properties (see Chapter 3).




■ **Figure 4.3** Metals are 'plastic' (bendable or malleable, and ductile) because in response to stress the lattice of positively charged ions instantly forms new attractions with the delocalized electrons surrounding them. In this diagram, the circles represent the metallic ions and the lines indicate their relationships in the lattice, to show how it may be distorted

In different metal elements, the strength of the attraction between the delocalized electrons and the positive ions varies. Like arrangements of oranges in boxes at a market, the way the ions of different metals are packaged can vary (Figure 4.4). These factors help explain why metals vary in their hardness, and their melting and boiling points.

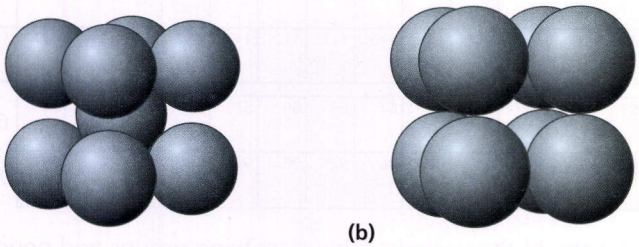



**Figure 4.4** Two different lattice arrangements of metallic ions. (a) A 'body-centred cubic' arrangement. This is how the metallic ions of iron, vanadium, chromium, molybdenum and tungsten are arranged. (b) A 'simple cubic' arrangement, that does not pack the nuclei as closely. Polonium is an example of a metal that is packed this way

## Ionic bonding, found in solid compounds consisting of positive and negative ions

You have already seen that compounds of metals and non-metals are examples of ionic compounds (in Chapter 3). In the solid state, the electrostatic attraction between positive and negative ions fixes them firmly in alternating positions in the regular lattice. In this state, they cannot conduct electricity. The strong electrostatic attraction between oppositely charged ions explains the general pattern that solid ionic compounds are hard and have high melting and boiling points, and are brittle. Hitting them with a hammer distorts the ionic lattice, bringing ions of the same charge close together. The **repulsion** between like-charged ions causes the crystal to shatter (Figure 4.5).

This changes as soon as they dissolve in water, and the ions become free to move.

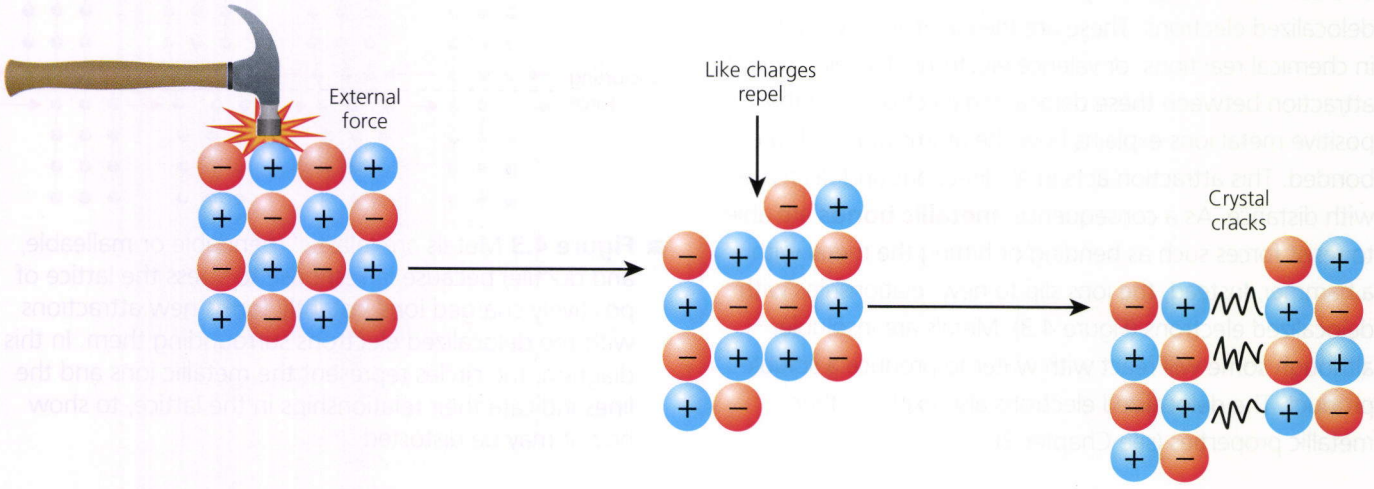



**Figure 4.5** Ions are located in specific positions in ionic solids. A hammer blow distorts the arrangement, bringing like-charged ions close together, and explaining why these compounds are brittle and shatter

## Covalent molecular substances

Most non-metal elements in groups 14–17 bond this way with other non-metals. Covalent bonds involve sharing pairs of electrons between atoms of a molecule. The shared electron pairs are localized between adjacent nuclei. A **single bond** consists of one pair of shared electrons, a **double bond** of two and a **triple bond** of three. The number of shared electron pairs affects the strength of the **intramolecular** bond, and how much they are able to pull the two positively charged atomic nuclei together (Figure 4.6). The actual distance between the nuclei is a balance between the attractive forces of the bond, and the repulsion between the positive nuclei.

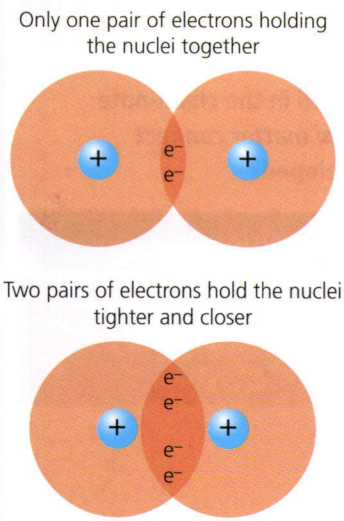



**Figure 4.6** A schematic representation comparing single and double covalent bonds, and the effect it has on the proximity of the nuclei within a molecule

Many covalent molecular substances are simple, consisting of a small number of atoms. However, elements that are able to form covalent bonds with up to four other atoms can generate complex branched structures and long chains. The diversity of compounds structured around carbon 'backbones' lies at the heart of **organic chemistry**, the subject of Chapter 12. Both carbon and silicon can form long molecules consisting of many repeating subunits, called **polymers**.

By comparison with the attractive forces within a covalently bonded molecule, the **intermolecular** forces that attract these molecules to each other are much weaker. For this reason, covalently bonded substances tend to have low melting and boiling points. They exist as gases, volatile liquids or soft solids at room temperature. When a covalent compound melts, only the weak intermolecular forces between molecules are broken. The strong molecular forces between the atoms of the molecules stay intact. As an example, consider what happens to water molecules, when ice melts.

## Covalent molecular networks

Covalent network substances are formed when non-metal elements, particularly carbon and silicon of group 14, bond with other non-metals to form an extended, continuous lattice. Network solids are 'endless', without a defined number of atoms.

Because the strength of the covalent bond extends throughout the system, substances that have purely this type of bonding between atoms are extremely hard and have high melting and boiling points. Examples are diamond and silicon dioxide (sand). The electrons in purely covalently networked substances are localized within their bonds or on their atoms. As a result, these substances are non-conductors as solids. These substances are also non-conductors when molten, because the atoms in them are uncharged. These extremely strong covalent bonds can sometimes be broken by strong distortion, but the substances are hard and not brittle.

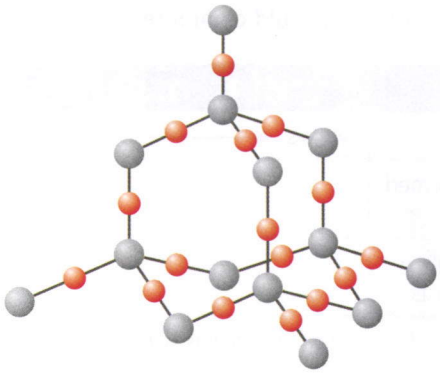


**Figure 4.7** In silicon dioxide, each silicon atom (black) is covalently bonded with two oxygen atoms (red)

# ACTIVITY: Bonds and the periodic table

## ATL

- Critical-thinking skills: Evaluate evidence and arguments; identify trends and forecast possibilities

**1** **For each type of crystalline solid described in Table 4.2, name up to five examples of substances found in your home that have this chemical structure.**

| | Description | Examples |
|---|---|---|
| a | Giant structure of atoms joined by covalent bonds | |
| b | Small molecules joined by covalent bonds | |
| c | Giant structure of positive and negative ions | |
| d | Giant metallic structure | |

**Table 4.2**

**2** **Imagine you are an archaeologist exploring an ancient monument. Inside the monument is a scattering of round objects, made of a dark, dense, hard material.**

- **a** **List tests you could conduct to determine what type of bonds might be found in the substance.**
- **b** **Evaluate your confidence that you could categorize almost any solid material with these tests.**

**3** **Suggest information that could complete Table 4.3.**

**4** **From the patterns described in Table 4.3, state the group that**

- **a** **shares physical properties with noble gases**
- **b** **forms ionic solids with groups 1 and 2.**

**5** **Within the same period, suggest which bond in an ionic solid is likely to be the stronger:**

- **a** **an element in group I or 2 with an element in group 17, or**
- **b** **an element in period 1 or 4 with a highly reactive halogen, e.g. chlorine.**

**Hint**

*Consider trends in metal and non-metal reactivities, in Chapter 3.*

**6** **Reflect on knowledge shared in the chain-note activity, *How do particles in matter connect (bonding)*? How has it developed?**

## Assessment opportunities

- In this activity you have practised skills that can be assessed using Criterion A: Knowing and understanding.

| Group | 1 | 2 | 3–13 | 14 | 15 | 16 | 17 | 18 |
|---|---|---|---|---|---|---|---|---|
| Element | Metals ← | | | | | | → Non-metals | |
| Type of bond formed by elements | | | | | | | | n.a. |
| Melting and boiling points of elements | | | | | | | | |
| Type of compound formed by elements | Form ionic solids with non-metals ← | | | | | → Form ionic solids with metals | | Very few compounds |

**Table 4.3** The relationship between bond trends and groups in the periodic table

## ACTIVITY: A curious effect

### ATL

- Critical-thinking skills: Practise observing carefully in order to recognize problems; revise understanding based on new information and evidence

Have you ever walked across a synthetic floor and felt an electric shock when you touched the door handle? Have you ever stroked a cat in a darkened room and seen small sparks fly from its ears to your hand? Heard crackles as you pulled tightly wound plastic wrapping from a package?

The friction of your movements removed electrons, building up a 'static' electrical charge difference that was restored on contact with a 'neutral' substance that could remove or provide electrons. What do you think may have happened in these electrically 'neutral' objects just before contact with the charged object?

**Safety:** This experiment needs to be demonstrated by a teacher in a fume hood. Methanol is toxic and both methanol and hexane are highly flammable.

### Materials and equipment

- **water**
- **methanol**
- **hexane**
- **a burette, retort stand, clamps**
- **a beaker**
- **a glass rod and a piece of dried silk**
- **an ebonite rod and a piece of dried wool**
- **gloves**

### Method

1. **Set up the burette and fill it with water, placing the beaker about 10 cm below the tip.**
2. **Open the tap so a fine, continuous stream of water emerges.**
3. **Negatively charge the glass rod by rubbing it briskly with the silk. Bring the glass rod close to, but not touching, the stream of water.**
4. **Positively charge the ebonite rod by rubbing it briskly with the wool. Bring the ebonite rod close to, but not touching, the stream of water.**
5. **Repeat the activity using methanol.**
6. **Repeat the activity using hexane.**

### Assessment opportunities

- In this activity you have practised skills that can be assessed using Criterion A: Knowing and understanding.

## SUMMARY REFLECTION

1. **State the type of bonding that is likely to be present in each of the three liquids.**
2. **Identify patterns:**
   - **a in the behaviour of each of the three liquids**
   - **b in whether the charge on the rods made a difference to any effect.**
3. **What does this demonstration suggest about the nature of the molecules in the liquids?**

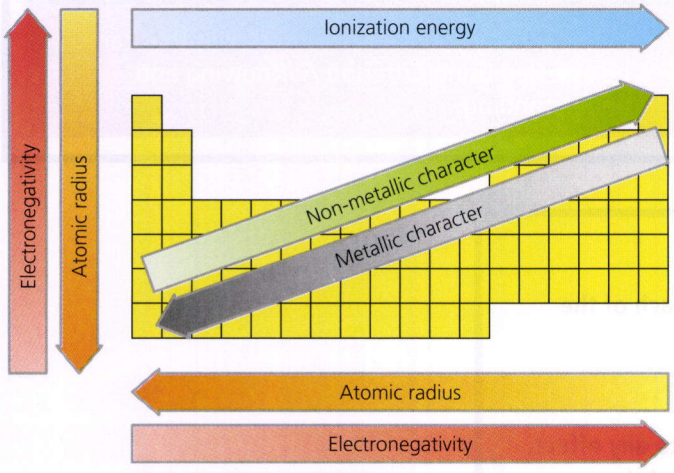
# How does the electronegativity of elements determine the type of chemical bond in a compound?

## MOLECULES BIG AND SMALL

### How chemical relationships are affected by electrostatic interactions

Within an atom, **electronegativity** is a measure of the attraction of the nucleus for a pair of electrons in a covalent bond. Except for noble gases, there is a trend for electronegativity to increase moving from left to right across each period of the table. The addition of each extra proton to the nucleus increases its attraction for the similarly sized 'electron cloud'. As a result, atoms tend to decrease in size across the period (Figure 4.8). The most electronegative atom is fluorine.

Moving down each group of the periodic table, even though the nuclei of elements in lower periods have many more protons, there is a decrease in electronegativity. One explanation is that every period has an extra layer of electrons, called a shell, added around the nucleus (see Chapter 8). These outer electrons are further away from the attractive positive force of the nucleus, and are also shielded by inner **electron shells**. As a result, atoms tend to increase in size down each group. The least electronegative atom is caesium.




■ **Figure 4.8** Patterns of electronegativity and size in the periodic table

**Intramolecular** attractions between atoms of molecules depend on the extent that electrons are gained or lost (**ionic bonds**) or shared (covalent bonds) between nuclei. The type of intramolecular bond explains properties like electrical conductivity, which depend on the formation and mobility of ions, and the strength, hardness and density of ionic solids, metals and covalent network solids, and why they are nearly always solids at room temperature.

**Intermolecular** attractions, also called **van der Waals'** forces, involve various competing interactions between electrons and nuclei of different molecules. Together, these interactions determine whether the generally smaller molecules of covalent molecular substances are solids, liquids or gases at room temperature. These forces determine properties like slipperiness, stickiness and viscosity. Although van der Waals' forces are often described as weak compared with intramolecular bonds, they increase with molecular size. These interactions can explain how geckos are able to stick to ceilings (Figure 4.1) and how water moves up trees via cohesion of the molecules to each other and adhesion to the walls of xylem vessels. Let's consider some examples of intermolecular forces.

### Dispersion forces

**Dispersion forces** are interactions between charged subatomic particles of any two neighbouring atoms. Dispersion forces can also be 'induced' by the closeness of other local charged particles, for example ions.

Examples of dispersion forces include

- attraction between the electrons of one atom and the protons in the nucleus of a neighbouring atom (called **London dispersion forces**)
- repulsion between the 'cloud' of negatively charged electrons surrounding each nucleus
- repulsion between the positively charged nuclei of neighbouring atoms.

The sum of these competing forces is related to the physical properties of covalent molecular substances. In gases, the high average kinetic energy of the particles limits the interaction of these intermolecular forces at room temperature. In molecular substances that are solids at room temperature, such as graphite, London dispersion forces attract the covalently bonded sheets of graphene together.

Graphite, the substance that provides the 'lead' in pencils, is an **allotrope** of carbon (Figure 4.9). In graphite, each carbon atom is bonded covalently with three others. The fourth remaining electron of each atom is 'delocalized', and free to move, attracted to the protons of carbon nuclei above and below its sheet of graphene. As in metals, these mobile electrons can conduct electricity; however, in graphite they are sandwiched between covalently bonded networked sheets. As a consequence, graphite is a **semi-conductor**, because its electrical conductivity is affected by its orientation. The weaker London dispersion forces between the covalently bonded layers of carbon explain why graphite has a soft, greasy and slippery feel.

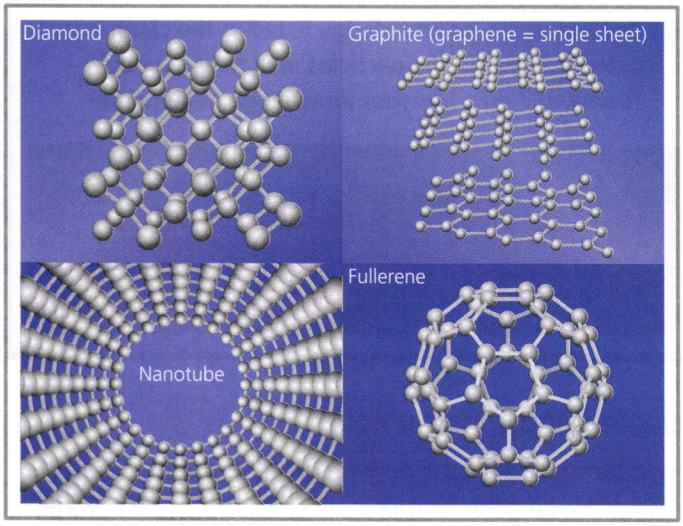



**Figure 4.9** Allotropes are alternative structural arrangements of atoms in the same element. Allotropes of carbon include diamond, in which each carbon atom is bonded covalently to four others by single bonds, and graphite, nanotubes and fullerene-60, a member of the fullerenes family, in which each carbon is bonded covalently to three others

## Dipole–dipole forces

Two conditions affect whether molecules will have dipole–dipole interactions: the elements of their composition and their shape.

In some molecules, the interaction of the nucleus of one atom with the electrons of another atom results in a permanent separation of electrical charge within the molecule. The more electronegative atom will attract the electrons of the bonded atom more strongly. The resulting bond is described as '**polar**', because the unequal sharing of electrons gives it 'direction'. This is shown diagrammatically in Figure 4.10 for a molecule of hydrogen chloride. Notice that the arrow points towards the negative end of the **dipole**.

Molecules with identical atoms, like **diatomic** gases ($H_2$, $O_2$ and halogen gases) cannot be polar.

Molecules with polar bonds are not ions, because their net charge is zero. However, different regions of the molecule carry small negative or positive charges.

Some molecules have polar bonds but their overall symmetry or linear shape means the directions of their bond dipoles cancel each other out. For example, carbon dioxide has two bond dipoles between the oxygen atoms on either side of the carbon atom, but no resultant force. In asymmetric molecules, the forces of these bond dipoles cannot cancel each other. As a consequence, these molecules possess a 'dipole' that interacts with other electric fields including those on other molecules.

Compared with molecules of similar size that do not behave as dipoles, molecules with dipole–dipole interactions have higher boiling points and melting points. These properties emerge because the molecules orient themselves so they are attracted to the oppositely charged dipole of neighbouring molecules in liquid and solid states, creating 'order'.




**Figure 4.10** A diagrammatic representation of the separation of charge in a molecule of hydrogen chloride. The lower case Greek letter delta, $\delta^-$ or $\delta^+$, is used to indicate the tiny charge separation, which is much smaller than the charge on an electron

## ACTIVITY: Intra- and inter-particle forces

1 **Suggest** how the concept of 'electronegativity' affects
   a whether an element loses or gains electrons
   b the reactivity of a metal
   c the reactivity of a non-metal.
2 **Summarize** your developing knowledge about typical properties of four groups of substances.

**ATL**

- Critical-thinking skills: Recognize and evaluate propositions; revise understanding based on new information and evidence

| Type of structure | Particles present | Forces operating between particles | Melting point | Electrical conductivity when solid | Electrical conductivity when liquid (molten) |
|---|---|---|---|---|---|
| Metallic | | | | | |
| Ionic | | | | | |
| Small covalent molecules (simple molecular) | | | | | |
| Giant covalent/ macromolecular/network solid | | | | | |

3 **Sketch** representations of two atoms, showing the positive nuclei and 'cloud' of negatively charged electrons. Use arrows to represent the attraction and repulsion (e.g. ⇒ and ↔) that describe examples of London forces between subatomic particles of these two atoms.
4 **State** the meaning of 'allotrope'. **Identify** the location of carbon in the periodic table and suggest how this may help explain its ability to form more than one kind of bond.
5 **Reflect** on your observations of the differences between water, methanol and hexane in the demonstration activity, *A curious effect.*
   a **Suggest** why streams of water and methanol molecules were equally affected by the presence of positive or negative electric fields.
   b **Suggest** why hexane did not respond to an electric field.
   c **Evaluate** the evidence that one/some of these molecules possessed a dipole.
   d **Identify** the substance/s that are likely to be miscible with each other.
   e **Suggest** reasons for the 'like-dissolves-like' observation (see Chapter 2).
6 **Reflect** again on knowledge listed in the chain-note activity, *How do the particles in matter connect (bonding)?* How has your knowledge developed?

**Assessment opportunities**

- In this activity you have practised skills that can be assessed using Criterion A: Knowing and understanding.

### Hydrogen bonds are an especially strong type of dipole–dipole interaction

You may recall learning in Chapter 2 that water and oil are examples of immiscible liquids. Oil molecules do not have dipoles, but water molecules have a particularly strong net dipole, which attracts them to other charged molecules, including ions. In a water molecule, the oxygen atom is strongly electronegative compared with the hydrogen atoms (Figure 4.11). The consequence of this difference in electronegativity is that the oxygen atom of a water molecule carries a slight negative charge $\delta^-$ balanced by smaller, positive charges $\delta^+$ shared on each of its two hydrogen atoms (Figure 4.11). These dipole–dipole interactions explain why ionic substances dissolve in water (Figure 4.12), but not in oil.

The intermolecular interactions between atoms of hydrogen and oxygen are so strong they have a special name: **hydrogen bonds**. These powerful attractions are vital for life on Earth, explaining the tensile strength of the transpiration stream inside plants and the stability of DNA and its ability to replicate (copy itself).

## TUG OF WAR!

What is your position? Take a stand to show how you respond to each of these statements:

1. **Schools should allow students to choose which classes they attend.**
2. **Anyone should be allowed to say anything they like.**
3. **It is more important to be kind than to be truthful.**
4. **People who think very differently from me do not bother me.**
5. **Being tolerant means you don't really care.**
6. **In relationships, opposites attract.**

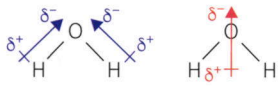



**Figure 4.11** In a water molecule, there are two bond dipoles, one between each hydrogen atom and the oxygen atom. Because of the shape of the molecule, these two forces add up to a resultant force, called a molecular dipole

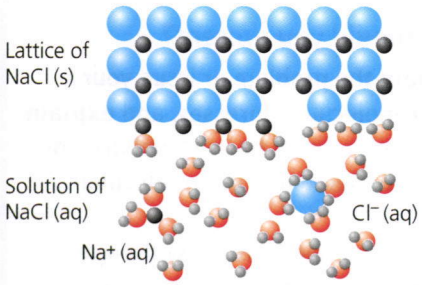



**Figure 4.12** Water dissolving solid sodium chloride NaCl(s) into its component ions, $Na^+(aq)$ and $Cl^-(aq)$. The term (aq) means these ions are hydrated in an aqueous solution. Water is an excellent solvent of ionic substances because each ion in the solid is attracted to a different part of the polar water molecule

## ! Take action: Finding the balance

### ATL

- Communication skills: Give and receive meaningful feedback
- Collaboration skills: Practise empathy; help others to succeed; encourage others to contribute

! Whether particles (atoms or ions) will bond is a result of a tug of war between forces of attraction and forces of repulsion, and the chemical stability is a consequence of the balance achieved between these forces.

! Fairness dilemmas help expose conflicts of opinion and their impact on communities. Consider the claim: In human relationships, agreement and disagreement can result in harmony or disharmony.

! Respond to the statements in the 'Tug of war!' box by forming a 'human scatter plot', positioning yourself between two walls of your classroom labelled 'strongly agree' and 'strongly disagree'.

1. **Identify how the attitudes and opinions revealed by the human scatter plot 'pulled' at each side of the dilemma.**
2. **Suggest reasons why others may have supported a different side of the dilemma.**
3. **Explore how contributing attitudes impact any dilemma. Could competing forces revealed by this activity also be a metaphor for chemical relationships?**

! Do you think our attitudes form part of our identities? Brainstorm examples of attitudes that foster effective, peaceful relationships in communities. Suggest how your message of understanding might be promoted in your school (Figure 4.13).

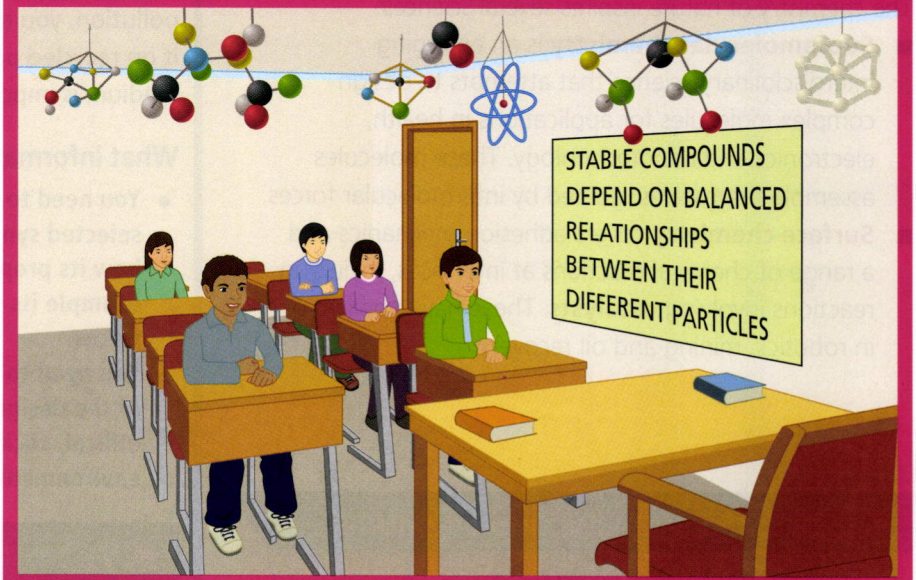



**Figure 4.13** An example of how a chemistry class celebrated 'messages of bonding' to suggest how different patterns of relationships between particles symbolise an inclusive environment

# Is chemistry defined only through the relationships of electrons with atomic nuclei?

## THE 'BRAVE NEW WORLD' OF SYNTHETIC COMPOUNDS

Materials with more than one type of chemical bond can show more than one kind of physical property. Complex molecular covalent substances are common in biological systems, where the property of each type of bond has advantages in different contexts. For example, the strong **covalent bonds** in natural polymers like DNA provide stability. This is important in a molecule where the nucleotide sequence stores genetic information through time. In the same molecule, the weaker hydrogen bonds between the two strands are easily manipulated by enzymes for copying and transcription. These features of biological molecules are not accidental; they have been selected for over time.

The chemistry of nature inspires several sciences:

- **Supramolecular chemistry** is an emerging interdisciplinary science that attempts to design complex molecules for applications in health, electronics and nanotechnology. These molecules assemble themselves, guided by intermolecular forces.
- **Surface chemistry** covers adhesion mechanics and a range of chemical reactions at interfaces, including reactions involving **catalysts**. These have applications in robotics, mining and oil recovery.

### ▼ Links to: Language and Literature

This task requires a reflective approach towards the use of your medium as well as the message. How does your learning in Language and Literature support your understanding of 'voice' and 'audience'?

## ACTIVITY: Synthetic chemistry

### ■ ATL

- Communication skills: Use appropriate forms of writing for different purposes and audiences; paraphrase accurately and concisely
- Information literacy skills: Make connections between various sources of information

**Select** key words from the preceding passage and search the Internet for examples of **synthetic molecules**. You should look for resources that explain the **chemical and physical interactions of the application**.

**Evaluate** further examples to reflect how you could present the information in a way that would be exciting for a reader.

'*The medium is the message*' is a famous phrase coined by Canadian philosopher Marshall McLuhan (1911–1980), meaning that the form of a medium is itself part of the message. For example, if your synthetic molecule has exciting applications in an entertaining, futuristic technology, you may want to present your ideas as a Prezi presentation, cartoon or another form that may excite a potential reader. If your synthetic molecule has applications for reducing environmental pollution, you may want to present information about it on recycled paper to appeal to 'green' readers. Your medium is important in marketing your ideas.

### What information should you present?

- **You need to explain the problem or issue your selected synthetic molecule addresses, and explain how its properties are related to its chemistry, for example its shape, bonding and intermolecular forces.**
- **You need to discuss and evaluate how the use of the designer molecule interacts with a moral, ethical, social, economic, political, cultural or environmental factor.**

### ◆ Assessment opportunities

- This activity can be assessed using Criterion D: Reflecting on the impacts of science.

# What does the IUPAC name of a chemical compound tell you?

## WHAT'S IN A NAME?

In Chapter 3, you were introduced to the use of symbols to represent elements, and the idea of valency: the ratio in which elements in the compound bond with others. This section introduces you to the system of naming compounds and writing chemical formulas correctly.

### What do the names of molecules indicate about their composition?

The formula of a molecular substance indicates the ratio and composition of its molecules. In substances that exist as continuous lattices, the formula is the simplest ratio of the ions or atoms in the lattice. This is known as the **empirical formula**.

## ACTIVITY: Put your chemistry language into practice!

### ATL

- Critical-thinking skills: Practise observing carefully in order to recognize problems; interpret data

Read page 88 to find out about naming compounds.

**1 Deduce the names of the following metal–non-metal compounds.**

| Symbol | Name | Symbol | Name | Symbol | Name |
|---|---|---|---|---|---|
| MgO | | CuO | | $MnO_2$ | |
| $FeCl_2$ | | ZnS | | $MnCl_2$ | |
| $CuCl_2$ | | AgCl | | $CoCl_2$ | |
| $CaBr_2$ | | KBr | | NaF | |
| FeO | | $SnBr_2$ | | NiS | |

**2 Deduce the names of the following non-metal–non-metal compounds.**

| Symbol | Name | Symbol | Name | Symbol | Name |
|---|---|---|---|---|---|
| CO | | NO | | $SO_3$ | |
| $CO_2$ | | $NO_2$ | | $SO_2$ | |
| $NCl_3$ | | $SCl_2$ | | $P_4O_6$ | |
| HF | | HBr | | HI | |
| $SF_6$ | | $NF_3$ | | $P_4O_{10}$ | |

**Hint**

Consider the subscripted numbers of the second part of the formula, in these names.

**3 Deduce the names of the following compounds, which all contain polyatomic ions.**

| Symbol | Name | Symbol | Name | Symbol | Name |
|---|---|---|---|---|---|
| $NH_4Cl$ | | $HNO_3$ | | $AgNO_3$ | |
| $NH_4HCO_3$ | | $H_2CO_3$ | | $NaHCO_3$ | |
| $(NH_4)_2CO_3$ | | NaOH | | $LiHSO_3$ | |
| $CaSO_4$ | | $Mg(OH)_2$ | | $Na_2SO_3$ | |
| $CaCO_3$ | | $NH_4Br$ | | $Ca(OH)_2$ | |

**Hint**

Ignore the subscripted numbers, and ignore brackets in the formulas.

**4 Evaluate whether the chemical name of a compound indicates the**

- **a types of ions present**
- **b numbers of each type of atom.**

**5 Suggest how being able to use a system of nomenclature (naming), for example having the skill to name a chemical compound correctly, supports your global citizenship.**

### Assessment opportunities

- In this activity you have practised skills that are assessed using Criterion A: Knowing and understanding.

## Naming a compound consisting of two elements, where one is a metal

1 Name the metal element first.

2 Name the non-metal element second, shortening the name with 'ide'.

Examples of common compounds, formulas and their chemical names:

- table salt: NaCl, sodium chloride
- galena: PbS, lead(II) sulfide.

Notice that, unlike for chemical symbols, there is no need to capitalize any of the words for the chemical name.

## Naming a compound consisting of two non-metal elements

1 As for metal–non-metal combinations, the name of the second element is shortened to 'ide'.

2 The less electronegative element is named first:
   a Hydrogen is further to the left of the periodic table (and less electronegative) compared to most non-metals, and is therefore named first.
   b When both elements are in the same group of the periodic table, the lower (and less electronegative) element is named first.

   The exception to this rule is when oxygen is combined with a halogen: it is always named last.

3 Prefixes are used to indicate the number of atoms in the formula, as indicated by the number appearing as a subscript immediately after the symbol. If there is no number, assume this means only one atom of that element is present.

   Common prefixes are: mono- (1), used only for compounds where there are alternative combinations of the same non-metal elements; di- (2), tri- (3), tetra- (4), penta- (5), hexa- (6), hepta- (7), octa- (8), nona- (9) and deca- (10).

Examples of non-metal compound formulas and chemical names:

- $H_2S$, hydrogen sulfide
- $SO_2$, sulfur dioxide
- $Br_2O$, dibromine oxide.

## Naming a compound that includes a polyatomic ion

**Polyatomic ions** (also known as **molecular** or **compound ions**) are groups of atoms that behave like single units, staying together when the compounds they are part of react (Table 4.4).

| Positive ions | | Negative ions | |
|---|---|---|---|
| $NH_4^+$ | Ammonium | $CO_3^{2-}$ | Carbonate |
| | | $HCO_3^-$ | Hydrogencarbonate |
| | | $SO_4^{2-}$ | Sulfate |
| | | $HSO_4^-$ | Hydrogen sulfate |
| | | $SO_3^{2-}$ | Sulfite |
| | | $HSO_3^-$ | Hydrogen sulfite |
| | | $NO_3^-$ | Nitrate |
| | | $NO_2^-$ | Nitrite |
| | | $PO_4^{3-}$ | Phosphate |
| | | $OH^-$ | Hydroxide |

**Table 4.4** Formulas of polyatomic or compound ions

Their valency is indicated by the charge next to their symbols. Polyatomic ions which include oxygen have names ending in 'ate' or 'ite', the 'ite' ending being consistently associated with the polyatomic ion that has fewer oxygen atoms. There is no specified number of oxygen atoms associated with each suffix, and their number is shown in the subscript immediately after the symbol.

1 The first name, depending on its presence, can be
   a the metal
   b the less electronegative non-metal, for example hydrogen or a solid non-metal, or
   c a positive polyatomic ion, named as shown in Table 4.4.
2 The second name, depending on its presence, can be
   a the non-metal, ending changed to 'ide', or
   b the negative polyatomic ion, named as shown in Table 4.4.

Examples of formulas of common compounds and their chemical names:

- $NH_4Cl$, ammonium chloride
- (chalk) $CaCO_3$, calcium carbonate
- $N_2O_4$, dinitrogen tetroxide.

Formulas for compounds often include numerical subscripts. Unless there is more than one way the same elements can combine, these are generally ignored in the name. Transition metals often have more than one way they can combine. Their valency, or the number of bonds involved, is indicated by a Roman numeral immediately after the name of the metal. There should be no gap between this number and the brackets.

## Writing and understanding the formulas of compounds

If words identify chemical components, then using formulas adds detail, for example by clarifying the number of atoms of each element that are present in a compound. As with any language, the grammar makes a difference. Table 4.5 outlines the rules for describing compounds with their chemical symbols.

| | Feature | Rule | Examples |
|---|---|---|---|
| **1** | Chemical symbol | First letter upper case, second letter (if present) lower case.<br>This rule helps us tell apart elements that start with the same letter. | **H, O, C** are atoms of three different elements.<br>**He, Os, Cl** are also atoms of three different elements. |
| **2** | Number of atoms present in the compound | The number subscripted immediately after the symbol, where more than one atom is present.<br>This number applies only to the element it follows. | **$H_2O$** has two atoms of hydrogen and one of oxygen.<br>**$CO_2$** has one atom of carbon and two atoms of oxygen.<br>**$CH_3OH$** has one atom of carbon, one atom of oxygen and four atoms of hydrogen. |
| 3 | Number of polyatomic ions in the compound<br>(Refer to Table 4.4 for examples) | Brackets, followed by a number indicating the number of polyatomic ions present, if there are more than one.<br>This number applies only to the elements in the brackets that it follows.<br>As in a mathematical equation, all the atoms inside the brackets are multiplied by this number. | **$CuSO_4$** has one ion of copper(II), $Cu^{2+}$ and one sulfate polyatomic ion, $SO_4^{2-}$ (consisting of one sulfur atom and four oxygen atoms), with an overall charge of –2.<br>**NaOH** has one sodium ion, $Na^+$ and one hydroxide polyatomic ion (consisting of one oxygen atom and one hydrogen atom), with an overall charge of –1.<br>**$Cu(NO_3)_2$** has one copper(II) ion, $Cu^{2+}$ and two nitrate polyatomic ions (each consisting of one nitrogen atom and three oxygen atoms) with an overall charge of –1. |
| 4 | Numbers of molecules or formula units | The number shown in front of the symbol indicates the number of molecules present.<br>As in a mathematical equation, the numbers of all the atoms of the compound are multiplied by the number in front of the symbol. | **2HCl** means two molecules, therefore two hydrogen atoms and two chlorine atoms.<br>**$2CuCl_2$** means two copper(II) ions, $Cu^{2+}$ and four chloride ions (i.e. 2 × 2), $Cl^-$.<br>**$2Zn(OH)_2$** means two zinc ions and four hydroxide polyatomic ions (each consisting of one oxygen atom and one hydrogen atom), i.e. (2 × 2) oxygen and (2 × 2) hydrogen in the two molecules.<br>**$3Ni(NO_3)_2$** means three ions of nickel, six nitrate polyatomic ions (each consisting of one nitrogen atom and three oxygen atoms), i.e. (3 × 2) nitrogen and (3 × 3 × 2) oxygen atoms in the molecules. |

■ **Table 4.5** The composition of compounds with chemical symbols for the elements

# How is valency used to balance the atoms in a compound?

The valency of an element or its ions indicates the number of bonds it can form with others. Notice the relationship between the charge of an element's ions (Tables 4.6 and 4.7) and its location in the periodic table (Figure 4.14). You can probably work out the charges of elements not shown in Table 4.6, on the basis of the group they belong to.

| Elements that form positive ions | Charge | Elements that form negative ions | Charge |
|---|---|---|---|
| Hydrogen | 1+ | Bromine | 1– |
| Aluminium | 3+ | Chlorine | 1– |
| Barium | 2+ | Fluorine | 1– |
| Calcium | 2+ | Iodine | 1– |
| Copper(I), (II) | 1+, 2+ | | |
| Iron(II), (III) | 2+, 3+ | | |
| Lead(II), (IV) | 2+, 4+ | | |
| Lithium | 1+ | | |
| Magnesium | 2+ | | |
| Manganese(II), (IV) | 2+, 4+ | | |
| Mercury(I), (II) | 1+, 2+ | | |
| Nickel | 2+ | | |
| Potassium | 1+ | | |
| Silver | 1+ | | |
| Sodium | 1+ | | |
| Tin(II), (IV) | 2+, 4+ | | |
| Zinc | 2+ | | |

**Table 4.6** Charges of common ions formed by elements

| Element | Valency | Element | Valency |
|---|---|---|---|
| Carbon | 4+, 4– | Oxygen | 2– |
| Silicon | 4+, 4– | Nitrogen | 3– |
| | | Phosphorus | 3– |
| | | Sulfur | 2– |

**Table 4.7** Valencies of elements that usually form covalent bonds

## ACTIVITY: Developing your proficiency with the chemistry toolkit

### ATL

- Communication skills: Use and interpret a range of discipline-specific terms and symbols

1 **Deduce the chemical formulas of the compounds below with reference to Tables 4.4 and 4.6:**
   - **a calcium sulfate**
   - **b sodium carbonate**
   - **c potassium hydroxide**
   - **d ammonium chloride**
   - **e copper(II) sulfite**
   - **f lithium hydrogencarbonate**
   - **g silver(I) nitrate**
   - **h barium sulfate.**

2 **Deduce the valency of the unknown component of these compounds, with reference to the elements and polyatomic ions in Tables 4.4 and 4.6. The first example is done for you.**

| | Compound | Formula | Valency |
|---|---|---|---|
| a | Manganese(II) chromate(VI) | $MnCrO_4$ | $Mn^{2+}$; $CrO_4^{2-}$ |
| b | Rubidium chloride | RbCl | |
| c | Beryllium sulfide | BeS | |
| d | Copper(I) manganate(VII) | $Cu(MnO_4)_2$ | |
| e | Cobalt(II) chloride | $CoCl_2$ | |
| f | Aluminium iodate(V) | $Al(IO_3)_3$ | |
| g | Iron(III) dichromate(VI) | $Fe_2(Cr_2O_7)_3$ | |

### Assessment opportunities

- In this activity you have practised skills that are assessed using Criterion A: Knowing and understanding.

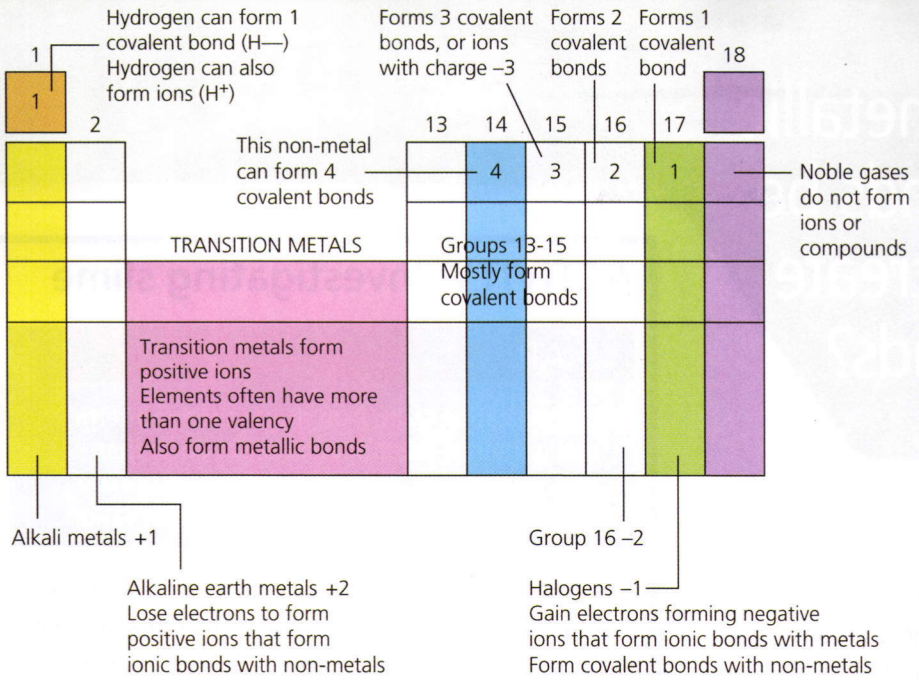



**Figure 4.14** Valencies of elements and their general location in the periodic table

Ionic compounds have no net charge. The skill of writing chemical formulas correctly simply requires that the total number of positive charges be equal to the total number of negative changes. Relationships between positive and negative ions carrying the same charge are easy to visualize, because they join in a one-to-one ratio.

## The jigsaw method

The jigsaw method uses cards to represent ions, and a 'tongue and groove' to represent the combining of positive with negative charges to form neutral compounds. In this model (Figure 4.15) positive ions have slots, to match up with the cards with tabs, which represent negative charges. More than one card of the same ion may be needed to form a 'compound', which will form a rectangle.

The number of particles, whether it is an ion or a polyatomic ion, is normally written as subscript.

Can you visualize how the following compounds might appear, using the cards shown in Figure 4.15?

- NaCl
- CaO
- $CaCO_3$
- $Fe_2O_3$

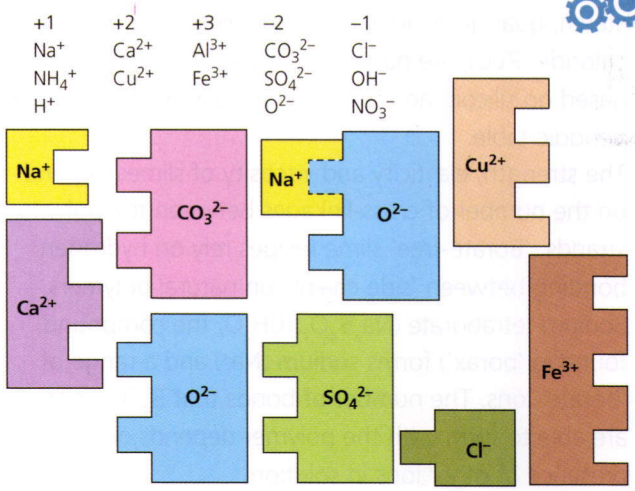



**Figure 4.15** The jigsaw method asks you to visualize positive ions as providing 'slots' and negative ions as providing 'tabs'. To 'make a compound', the shapes need to be matched to form a rectangle

## Which graph communicates my data best?

**ATL**

- Communication skills: Organize and depict information logically.

What are the advantages of different styles of data representation? Which is most appropriate for your experimental data? All graphs need titles, and axes require labels as well as units. Attention to data transformation can make a difference to your message.

# How can ionic, metallic and covalent bonds be manipulated to create unique compounds?

Materials that are soft at room temperature, including slimes and water-soluble gels, are usually covalent molecular substances. Slimes and gels have many uses, but the reason for the presence of so many recipes online is because they can be very entertaining, and are often sold as 'scientific toys'! All slimes consist of polymers stabilized with cross-linkages.

- Most polymers used to make slimes, including glue, starch, guar gum, agar agar and solutions of poly vinyl chloride (PVC), are based on carbon. 'Silly putty' is based on silicon, an element in the same group of the periodic table.
- The strength, elasticity and viscosity of slimes depend on the number of cross-linkages between the polymer strands. 'Borate-free' slime recipes rely on hydrogen bonding between 'side chains' on natural polymers. Sodium tetraborate ($Na_2B_4O_7.10H_2O$, the compound found in 'borax') forms sodium ($Na^+$) and a range of 'borate' ions. The number of bonds that $B_4O_7^{2-}$ ions are able to form with the polymer depends on the presence of other ions in solution.

## ACTIVITY: Investigating slime

### ATL

- Organization skills: Plan short- and long-term assignments; meet deadlines; set goals that are challenging and realistic; use appropriate strategies for organizing complex information

The aim of this task is to evaluate the consequences on a measurable physical property of a slime or gel of introducing a soluble substance. You may again want to refer to the inquiry cycle described in Chapter 1 for guidance (Figure 1.11, see page 16). Both a risk analysis and completed environmental impact analysis must be included in your plan.

### Background and planning

Use the Internet to find a slime recipe. Consider **PVC slime**, **washable glue slime**, or **gak**. Source the ingredients and conduct preliminary tests of its physical properties. These preliminary tests will indicate whether the standard 'recipe' requires manipulation, and help you identify properties that may be measured. Rough notes of your observations could be included as an appendix to your report.

### Developing a hypothesis

Your hypothesis should link an independent variable with the effects you plan to measure (dependent variable), and your scientific reasoning should include an explanation of changed bonding in the slime.

### Reporting your investigation

**Present** your data effectively, and **discuss** your results with reference to the scientific reasoning of your hypothesis.

### Assessment opportunities

- This activity can be assessed using Criterion B: Inquiring and designing and Criterion C: Processing and evaluating.

# SOME SUMMATIVE PROBLEMS TO TRY

Use these problems to apply and extend your learning in this chapter. The problems are designed so that you can evaluate your learning at different levels of achievement in Criterion A: Knowing and understanding.

A copy of a periodic table should be available for reference.

## THESE PROBLEMS CAN BE USED TO EVALUATE YOUR LEARNING IN CRITERION A TO LEVEL 1–2

**1** **State** the difference between an *intra*molecular interaction and an *inter*molecular interaction in a substance.

**2** **a** In the list below, **identify** which of the following substances you would expect to show metallic bonding:

- **i** potassium (K)
- **ii** silicon dioxide ($SiO_2$)
- **iii** sulfur (S)
- **iv** lead(II) iodide ($PbI_2$)
- **v** sucrose ($C_{12}H_{22}O_{11}$)
- **vi** graphite (C)
- **vii** methane ($CH_4$)
- **viii** iron (Fe)
- **ix** lead (Pb)
- **x** gold (Au)

**b** Of the substances you selected from the list above, **suggest** which would be most suitable for the following familiar situations:

- **i** making a kitchen utensil for cooking
- **ii** a small, treasured decorative ornament
- **iii** in thin sheets, to clad roofs to prevent water penetration.

**3** **Interpret** the properties given for materials **A**, **B**, **C** and **D** in the table below, to **classify** the substances as metallic, ionic, covalent molecular network or covalent molecules.

| Substance | Melting point/°C | Electrical conductivity | | Classification |
|---|---|---|---|---|
| | | Solid | Molten | |
| **A** | 770 | Very low | High | |
| **B** | 327 | High | High | |
| **C** | >3000 | None | None | |
| **D** | –96 | None | None | |

## THESE PROBLEMS CAN BE USED TO EVALUATE YOUR LEARNING IN CRITERION A TO LEVEL 3–4

**4** **Sketch** a sequence of diagrams to illustrate how single, double and triple bonds between the two carbon atoms affect the relative positions of their nuclei.

**5** **Outline** *a process* you could use to write the correct formulas of compounds consisting of the following pairs of ions:

- **a** $A^{2+}$, $B^{3-}$
- **b** $C^{4+}$, $D^{2-}$

**6** X represents a different mystery element in each of the empirical formulas of compounds below. **Suggest** the possible valency for X in each context.

- **a** XCl
- **b** $XF_2$
- **c** XO
- **d** $XBr_3$
- **e** AlX
- **f** $XPO_4$
- **g** $(NH_4)_2X$

**7** The strength of a bond is related to the size of the atoms, and electronegativity. **Interpret** the general pattern of the elements in the periodic table (Figure 3.18) to make a scientifically supported judgment about which in each pair of covalent bonds below is likely to have the larger dipole:

- **a** an H–F bond or an H–S bond
- **b** an H–O bond or an H–F bond
- **c** a H–Cl bond or a Cl–Cl bond.

## THESE PROBLEMS CAN BE USED TO EVALUATE YOUR LEARNING IN CRITERION A TO LEVEL 5–6

8 Use a **labelled** diagram to **describe** how different types of bonds result in the different physical properties of two allotropes of carbon, graphite and diamond.

9 Hydrated cobalt(II) chloride ($CoCl_2.6H_2O$) is pink but anhydrous cobalt(II) chloride ($CoCl_2$) is blue. **Suggest** how this compound might be used to determine the probability of rain.

10 **Analyse** the information in Table 4.8 and make scientifically supported judgments about the nature of the bonds between atoms in the first three molecules, compared to the nature of the bonds between atoms in the second group of three molecules.

| Substance | Formula | RMM (relative molecular mass*) | Melting point/°C | Boiling point/°C |
|---|---|---|---|---|
| Water | $H_2O$ | 18 | 0 | 100 |
| Ammonia | $NH_3$ | 17 | –78 | –33 |
| Hydrogen fluoride | HF | 20 | –83 | 20 |
| Nitrogen monoxide | NO | 30 | –164 | –152 |
| Oxygen | $O_2$ | 32 | –210 | –183 |
| Nitrogen | $N_2$ | 28 | –210 | –196 |

*Relative molecular mass is calculated by adding the relative atomic mass (RAM) of all the atoms together.

**Table 4.8** Two groups of three molecules with similar molecular mass, and their boiling and melting points

## THESE PROBLEMS CAN BE USED TO EVALUATE YOUR LEARNING IN CRITERION A TO LEVEL 7–8

11 **Explain** how the physical and chemical properties of substances are consequences of the following types of bonds:
- a metallic bonds
- b ionic bonds
- c London (dispersion) forces and intermolecular forces
- d hydrogen bonding and intermolecular forces.

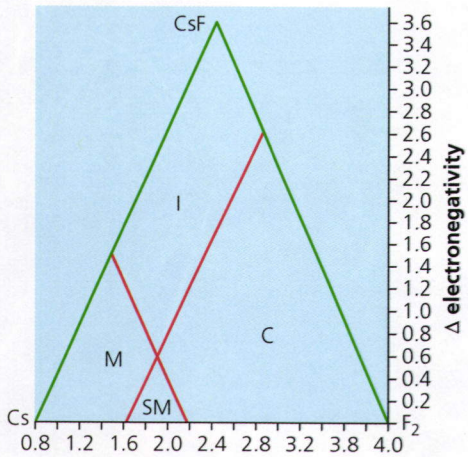
12 Use Table 4.9 to **apply** your knowledge and understanding about electronegativity patterns and bonding.
- a Which periods and groups are represented by the elements listed, and how do you **explain** the trends in electronegativity shown in this table?
- b Use the values in the table to **calculate** the predicted difference in electronegativity between the atoms in the following diatomic molecules:
  - i lithium fluoride
  - ii beryllium oxide
  - iii nitrogen monoxide.
- c **Suggest** which of these molecules will be the most
  - i ionic in its properties
  - ii covalent in its properties.
- d **Describe** an investigation you could conduct to test your ideas about (c).

| Element | Electronegativity value (Pauling scale) |
|---|---|
| H | 2.2 |
| Li | 1.0 |
| Be | 1.6 |
| B | 2.0 |
| C | 2.6 |
| N | 3.0 |
| O | 3.4 |
| F | 4.0 |
| Na | 0.9 |

**Table 4.9** A summary of electronegativity values using the Pauling scale

13 **Analyse and evaluate** the information in Figure 4.16 to make scientifically supported judgments.

- **a** What does this diagram **suggest** about the pattern of average electronegativities across the periodic table? Where are the 'semi-metals' or metalloids located in this pattern?
- **b** How does the difference in electronegativity **compare** between
  - **i** atoms in a metal and ions in an ionic compound
  - **ii** atoms in a metal and atoms in covalent compounds?
- **c** **Predict** which element (group and period) might have electronegativity close to the location where the two trend lines cross in this diagram, and **explain** your reasoning.




■ **Figure 4.16** The triangular 'bonding diagram' summarizes how bond types depend on the difference in electronegativity between the atoms involved in compounds they form. Key: [I] ionic, [M] metallic, [C] covalent. [SM] refers to the small number of 'semi-metallic' elements: boron, silicon, germanium, arsenic, antimony, tellurium and polonium. These elements are also known as metalloids

# Reflection

In this chapter you explored how relationships between atoms or their ions contribute to the properties of the substances they form. An example you investigated experimentally involved a property of slime, and one you researched concerned the futuristic applications of synthetic chemistry. Your understanding of valency developed and your new skill of using chemical nomenclature has prepared you a quantitative understanding of chemical relationships and change.

| Use this table to reflect on your own learning in this chapter | | | | | | |
|---|---|---|---|---|---|---|
| Questions we asked | Answers we found | Any further questions now? | | | | |
| **Factual:** What does the IUPAC name of a chemical compound tell you? How is valency used to balance the atoms in a compound? | | | | | | |
| **Conceptual:** How do differences in chemical bonding contribute to the physical properties of its compounds? How do electrons of atoms contribute to the chemistry of their compounds? How does the difference in electronegativity of their elements determine the type of chemical bond in a compound? | | | | | | |
| **Debatable:** To what extent can ionic, metallic and covalent bonds be manipulated to create compounds with unique properties? | | | | | | |
| Approaches to learning you used in this chapter: | Description – what new skills did you learn? | How well did you master the skills? | | | | |
| | | | Novice | Learner | Practitioner | Expert |
| **Communication skills** | | | | | | |
| **Collaboration skills** | | | | | | |
| **Organization skills** | | | | | | |
| **Critical-thinking skills** | | | | | | |
| **Information literacy skills** | | | | | | |
| **Learner profile attribute(s)** | How did you demonstrate your skills as a communicator in this chapter? | | | | | |
| **Communicators** | | | | | | |

# 5 What are the impacts of chemical industry?

Chemical industry has brought **change** that affects global **interactions** with **positive and negative environmental impacts**.



**Figure 5.1** What ions pollute the water of this stream?

## CONSIDER AND ANSWER THESE QUESTIONS:

**Factual:** How can I distinguish acids and bases? What do the symbols of a chemical equation show?

**Conceptual:** Why must a chemical equation be balanced? How do atoms and their compounds persist in the environment?

**Debatable:** What is the fairest way to use our chemical resources?

Now **share and compare** your thoughts and ideas with your partner, or with the whole class.

## IN THIS CHAPTER, WE WILL ...

- **Find out** how communities are interrelated.
- **Explore:**
  - ions in solution;
  - how to balance equations;
  - how to develop a heavy metal detector.
- **Take action** locally, by investigating global problems related to chemical pollution.

## We will reflect on this learner profile attribute …

- Principled – What is the role of ethics in guiding or limiting scientific research? Does everyone have the right to use science as they please? How can chemists provide honest, impartial advice to support decisions about the interactions of science with other factors?

## Assessment opportunities in this chapter …

- Criterion A: Knowing and understanding
- Criterion B: Inquiring and designing
- Criterion C: Processing and evaluating
- Criterion D: Reflecting on the impacts of science

## These Approaches to Learning (ATL) skills will be useful …

- Communication skills
- Collaboration skills
- Organization skills
- Affective skills
- Critical-thinking skills
- Transfer skills

**KEY WORDS**

| | |
|---|---|
| acid | product |
| neutralize | reaction |
| precipitate | salt |

# A TALE OF TWO COMMUNITIES

Read the following two case studies about communties: batik-dying and ecotourism.

## Batik-dying

It was the perfect home-based business for Gemma. She valued her creativity and independence, and was proud of her entrepreneurship. The business she had developed over the past 10 years employed many of the young adults in her remote village, which had become a place where all generations could support each other.

Her inspiration had been the colourful residue from the disused mine. The flooring fabrics, leatherwork and wearable textiles produced by Stone-Dyed Inc. were extremely popular, and for the first time she could remember, her community was nearly prosperous. Nor was commercial competition ever likely.



**Figure 5.2** Batik-style dying

The batik-style process she had invented used a complex series of staining, waxing and acid bleaching steps, alternately washed in water from one of the rare waterfalls in her region.

The word 'batik' is Indonesian in origin, although the approach of using wax to control the parts of a fabric exposed to the dye process is used in many parts of the world. Dyes are applied in increasingly strong colours, often with additional layers of wax. The final step of the process involves boiling the cloth in water to melt the wax, removing it from the cloth.

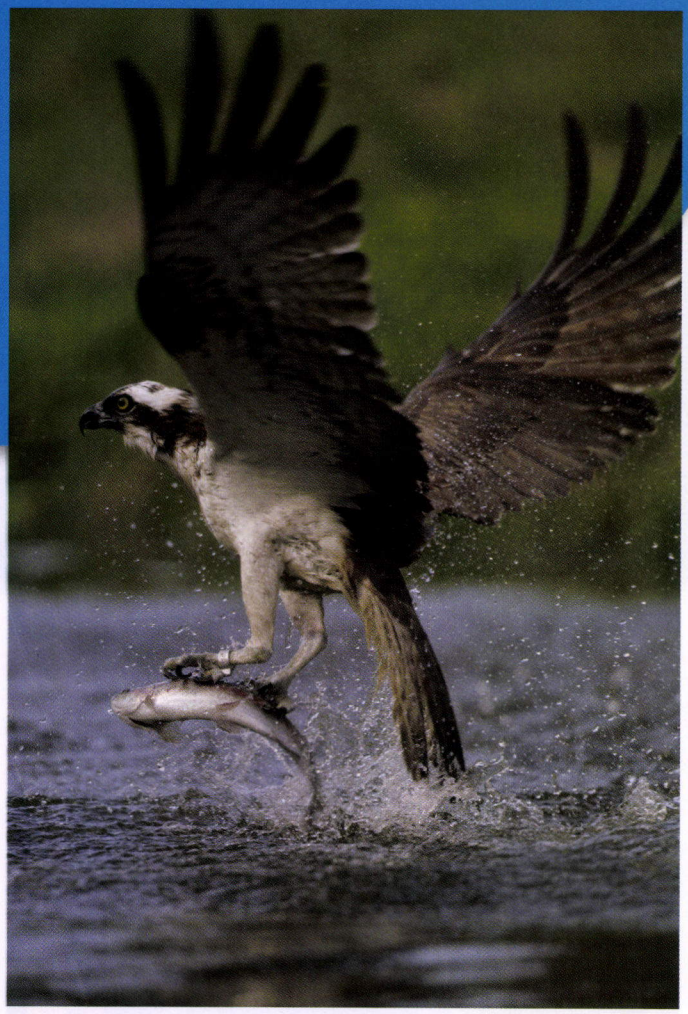


**Figure 5.3** Ospreys are also known as sea eagles. They are the top predators in aquatic ecosystems because their diet consists entirely of fish

## Ecotourism

At the Estuarine Eco-lodge, a group of tourists were discussing their stay:

'The brochure promised ospreys but the skies are empty', Ms Twitcher sniffed, strapping up the cover of her expensive SLR camera. 'Just wait till I tweet about this!'

'I won't be coming back either,' said Mr Fisher, tossing his rod into his convertible car. 'The fish are smaller every year. There's no sport in catching fingerlings.'

'Maybe it's interrelated,' Coral Shores soothed. 'Eight years ago this place was really special, but I've just had the most boring snorkelling holiday ever. They need to do something about it.'

'I enjoyed my cooking classes,' countered M. Gourmand. 'It was all flown in, but the sea food they provided was absolutely fantastic.'

## ACTIVITY: Should the success of some come at a cost to others?

### ATL

- Communication skills: Negotiate ideas and knowledge with peers and teachers; make inferences and draw conclusions
- Collaboration skills: Listen carefully to other perspectives and ideas
- Affective skills: Mindfulness – practise focus and concentration

**Compare and contrast** the two case studies.

*Gemma's industry*:

1 **Elements in traditional batik dye compounds include cadmium, lead, zinc, copper, chromium and iron.**
   - a **Identify where these elements are located on the periodic table. Suggest why most are known as 'heavy metals'.**
   - b **Outline evidence that Stone-Dyed Inc's dye process uses heavy metals.**

2 **Gemma's industry relies on water from a nearby stream.**
   - a **Discuss to what extent natural resources are 'free'.**
   - b **Evaluate the impact on Gemma's business if it needed to treat its waste water properly.**

*Estuarine Eco-lodge*:

3 **Ecotourism depends on natural environmental attractions.**
   - a **Identify the ethical and legal responsibilities this industry has for the natural resources it uses.**
   - b **List examples of how this community is managing change, and evaluate the impact on other communities.**

4 **The eco-lodge is supported by tourism. Comment on the financial privilege of tourists, and the consequences of this for some of the communities they visit.**

5 **Suggest how chemistry may contribute solutions to the interactions revealed in these two scenes.**

### Assessment opportunities

- In this activity you have practised skills that are assessed using Criterion D: Reflecting on the impacts of science.

## FISHBOWL-THINK-ALOUD

**Fishbowl-think-aloud** is a learning strategy that aims to make thinking and discussion transparent. You should initially respond to a passage by discussing it in groups. Then, one member from each group will be selected randomly to move to the 'fishbowl' in the centre of the room. Everyone else sits around the 'fishbowl' in a circle, listening to the 'fish' discuss their reasoning, including the further questions they may have developed. The process of mentally comparing and contrasting the fishbowl's responses with your own will help clarify your own ideas.

## DISCUSS: Learning from the fishbowl

1. **Did this activity help you understand the complexity of moral, ethical, social, economic, political, cultural or environmental interactions of science and communities?**
2. **Being in the fishbowl is a kind of performance. Did knowing you might be selected for the fishbowl help you concentrate on the discussion questions?**

Matter persists in the environment because it cannot be created or destroyed, but when its atoms form new compounds, their electrons may be gained or lost. Compared to their atoms, all ions are much more soluble in water (Chapter 4). As the case studies suggest, environmental water, streams, rivers and oceans (and sometimes rain) can disperse matter in the form of ions to unexpected locations.

Dissolved in water, ions are mobile, which means they can also react together. Describing how they do this is the subject of this chapter.

# What do the symbols of a chemical equation show?

## INVESTIGATING IONS IN SOLUTION: CATIONS AND ANIONS

In an equation that describes a chemical change, the arrow (→) represents a boundary between the starting substances, called **reactants**, and the resulting substances, called **products**. The symbol in brackets following the formula represents its phase, whether it is solid, liquid, gas, liquid or dissolved in water (**aqueous**). **Word equations** representing the formation of a potassium iodide solution can be written in two ways:

(aq) + potassium iodide(s) → potassium iodide(aq)

(aq) + potassium iodide(s)
→ potassium cations(aq) + iodide anions(aq) (ionic form)

In this equation, the symbol (aq) indicates that excess water is being used to dissolve the solid (s) ionic compound to form a solution. When ions are mobilized, as they are in solutions, they can interact with others. If a new combination of ions has a stronger attraction to each other than to the surrounding water molecules, an ionic compound forms, and it will be less soluble than either of the compounds in the original ionic solutions. The **insoluble** compound makes the mixture appear cloudy and it will settle out of the solution as a **precipitate**, sometimes abbreviated as ppt. or shown in some conventions using a downward-pointing arrow ↓ instead of (s).

Word equations of the reaction between solutions of two ionic compounds will reveal that the cations have changed their relationship to the anions. This type of reaction is therefore called a **double displacement** reaction.

As an example, consider the reaction between solutions of potassium iodide and lead(II) nitrate: **lead(II) iodide precipitation ww.youtube.com/watch?v=bq_eV95wJBI**. A moment's reflection will help you recognize that an ionic solid produced in a **precipitation** reaction is very different in its properties from ions in aqueous solutions. Unlike ions in solutions, ionic solids do not have a defined number of particles. They consist of a large number of ions in a fixed ratio.

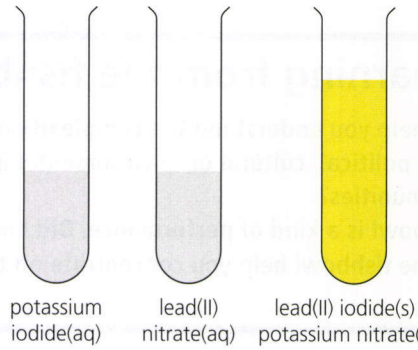



**Figure 5.4** Two clear colourless solutions of potassium iodide and lead(II) nitrate, and mixture of these solutions showing the bright yellow lead(II) iodide precipitate

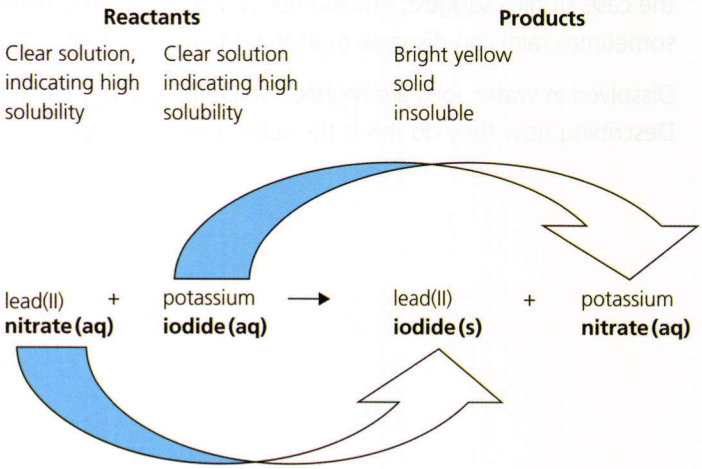



**Figure 5.5** Equation describing the potassium iodide and lead(II) nitrate reaction. The products can be separated by filtration

## ACTIVITY: A systematic approach

### ATL

- Organization skills: Keep an organized and logical system of information files/notebooks

You will be provided with solutions of six ionic compounds in dropper bottles (or in test tubes with disposable pipettes). To test whether a pair of solutions reacts, place a few drops (no more than ten) of each in the same cavity of a spotting tile. If a compound is slightly soluble, it may precipitate when the solutions mix but then dissolve again. Therefore, leave the mixtures for about 10 minutes before recording the presence and colour of any precipitates.

**Safety:** Wear safety goggles and avoid contact with skin.

### Materials and equipment

- **10 $cm^3$ samples of dilute (0.1 M)**
  - **copper(II) sulfate (aq)**
  - **sodium carbonate (aq)**
  - **lead(II) nitrate (aq)**
  - **potassium hydroxide (aq)**
  - **barium chloride (aq)**
  - **iron(II) sulfate (aq)**
- **one or more spotting tiles**
- **rinse bottle with water**
- **beaker for waste**
- **six disposable pipettes / dropper bottles**

### Method

1. **Design** a table to enable you to record the results of systematic tests between each of the solutions and the other five.
2. After testing a set of solutions, rinse the waste mixtures into the beaker. At the end of the activity, dispose of this substance in the laboratory's '**heavy metal** waste' bottle.

### Analysing results

1. If a pair of solutions formed a precipitate, write the word equation for the reaction.
2. **State** whether there were any anions that appeared not to form precipitates.
3. **Identify** where the elements forming cations are located on the periodic table.
4. If a precipitate formed, **suggest** the identity of the solid product.
5. Can you **suggest** any general patterns or trends?

### Assessment opportunities

- In this activity you have practised skills that are assessed using Criterion C: Processing and evaluating.

When the equation in Figure 5.5 is shown in ionic form, you will notice that some of the ions are not involved in the chemical reaction:

lead(II) ions (aq) + nitrate ions (aq) + potassium ions (aq) + iodide ions (aq) → nitrate ions (aq) + potassium ions (aq) + lead(II) iodide (s)

Just as in mathematical equations, the expression can be simplified by removing the '**spectator ions**' which do not participate in the reaction from both sides of the equation. The resulting '**ionic equation**' then identifies only the ions involved in the reaction:

lead(II) ions (aq) + iodide ions (aq) → lead(II) nitrate (s)

## DISCUSS

1. **State** evidence that new ionic compounds were created.
2. **Suggest** whether the results of these reactions could be reversed using separation techniques based on physical properties.
3. Safety concerns are very important to the practice of science.
   a. **Identify** which of the solutions you used included 'heavy metals'.
   b. **Suggest** why you should not dispose of solutions containing heavy metals down the sink.
4. **Suggest** how chemical and physical reactions resulting in changes of state might be distinguished.
5. **Predict** what you might observe if you could measure the electrical conductivity of ions in a solution during a precipitation reaction.
6. **Evaluate** the claim that precipitation reactions are not chemical 'reactions' at all, because they only involve a change of phase of a pair of ions. As the ionic equation reveals, no new substances are made – there is merely a change of phase.



**Figure 5.6** Shells are precipitates of $Ca^{2+}$ with $CO_3^{2-}$. The colours result from the mollusc's controlled precipitation of other minerals, particularly iron

| Solubility ($g\,dm^{-3}$ $H_2O$) | Soluble (>10) | Sparingly soluble (1–10) | Insoluble (<1) |
|---|---|---|---|
| Cations (+ve ions) | *All* compounds with **Group 1 metals, $NH_4^+$** (the 'soluble cations' referred to below) | – | – |
| Anions (–ve ions) | *All* compounds with **$NO_3^-$** | – | *Most* compounds with **$PO_4^{3-}$, $SO_3^{2-}$** except those with the soluble cations |
| | *Most* compounds with **$Cl^-$, $Br^-$, $I^-$** except those with $Ag^+$ and $Pb^{2+}$ | $MgCO_3$ | *Most* compounds with **$CO_3^{2-}$** except those with $Mg^{2+}$ and the soluble cations |
| | *Most* compounds with **$SO_4^{2-}$** except those with $Ag^+$, $Pb^{2+}$, $Ba^{2+}$, $Sr^{2+}$ and $Ca^{2+}$ | $Ag_2SO_4$ $CaSO_4$ | *Most* compounds with **$S^{2-}$** except those with Group 2 and the soluble cations |
| | — | $Ca(OH)_2$ | *Most* compounds with **$OH^-$, $O^{2-}$** except those with $Ba^{2+}$ $Sr^{2+}$ $Ca^{2+}$, $Mg^{2+}$ and the soluble cations |

**Table 5.1** Patterns of solubility in ionic compounds

## Solubility rules for ionic compounds

Precipitation is a natural occurrence. Most minerals, including limestone cave formations and the 'scale' that forms in our electric kettles, are precipitates. Bones and teeth, corals, bird eggs and mollusc shells are vital examples of precipitation products in living organisms. As you develop familiarity with the '**solubility** rules' for common ions, you will recognize this chemistry is everywhere, every day.

## ACTIVITY: Chemical scenarios

### ATL

- Critical-thinking skills: Interpret data; revise understanding based on new information and evidence
- Transfer skills: Apply knowledge and skills to unfamiliar situations; make connections between subject groups and disciplines; change the context of an inquiry to gain different perspectives

Use the information in Table 5.1 and consider these scenarios.

1. **Imagine a truck carrying chemicals being involved in an accident, and spilling its load into a river.**
   - a **Identify which of the following compounds would be insoluble, based on information in the table: $CuSO_4$, PbS, $Ag_2SO_4$, $Cd(OH)_2$, $Ca(NO_3)_2$, $Cr_2(SO_4)_3$, $FeCl_3$, $ZnBr_2$, and $MgI_2$.**
   - b **Could an insoluble precipitate of an ionic compound pose a danger to the environment? Explain your reasoning.**
2. **Calcium nitrate is a fertilizer. Suggest an example of an ionic compound (aq) that will react with calcium nitrate to produce a precipitate.**
3. **Imagine the labels had peeled off from three old jars of stock chemicals. Your teacher knows the jars contain solid sodium carbonate, sodium chloride and sodium sulfate, but hopes you are able to suggest a strategy for determining the compound in each jar. Outline how you could solve this problem in a safe manner.**
4. **Arsenic poisoning is a favourite method for committing murder in Victorian crime novels. Arsenic is a semi-metal, found below phosphorus in the periodic table. Arsenate ($AsO_4^{3-}$) has similar properties to phosphate, but it can also form the cation $As^{3+}$. Imagine a scene featuring a victim lying face down in his shaving basin, a jug of clear 'water' and an empty glass at his side.**
   - a **Suggest how to determine that drowning had not been the cause of death.**
   - b **The solution in the jug is transparent. Suggest examples of arsenic compounds that may be dissolved in the water.**

### Assessment opportunities

- In this activity you have practised skills that are assessed using Criterion A: Knowing and understanding.

# Why must a chemical equation be balanced?

## WRITING BALANCED CHEMICAL EQUATIONS

To synthesize means to combine different ideas in order to create new understanding. A balanced chemical equation synthesizes the information given by a word equation with chemical formulas (Chapter 4).

In chemistry, a **balanced equation** accounts for every atom involved in a chemical change. Atoms have mass and are composed of neutrons, protons and electrons. Therefore, the act of balancing the numbers of atoms of each element of the reactants with those of the products is not simply a satisfying mathematical exercise; it is an expression of a scientific law.

The law of conservation of mass states that during a chemical reaction, matter cannot be created or destroyed. The balancing of a chemical equation represents a rearrangement of atoms in space. The law applies to every chemical reaction, and developments in nuclear chemistry (discussed in Chapter 7) have refined this understanding further.

Balancing equations involves *only* manipulating the coefficients in front of the formulas of the compounds involved, until the numbers of atoms on either side of the arrow are identical. Each formula represents a unique chemical compound. Although balancing equations may help identify the composition of an unknown product in an experiment, when the products are provided as part of a balancing problem, the subscripted numbers within a formula should not be changed.

There are several ways to balance chemical equations.

### By inspection

This method is recommended for equations involving pairs of compounds consisting of positive and negative ions in simple ratios. The process of balancing an equation 'by inspection' may seem intuitive.

Example:

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

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

The following outline reveals the process:

1. Some methods recommend listing the total number of atoms of each element at each side of the equation first. This may be useful when several products are compounds that include the same elements.
2. (Some methods recommend leaving hydrogen and oxygen till last, because these are likely to appear in several products.) **Select** the most complicated compound (e.g. $Pb(NO_3)_2$ in this example), or the compound represented by a single molecule with a unique element. This element should be balanced first, if necessary multiplying the number of molecules on each side of the equation until the numbers of this element match.
3. Check the numbers of atoms of all elements on the opposite sides of the equation again. (In this example, this process reveals more anions are needed to provide sufficient numbers of relevant atoms on either side of the equation.) It is also acceptable to use fractions at this stage, if necessary. The subscripted number implied in the composition of a product (e.g. one nitrate ion ($NO_3^-$) in potassium nitrate or two iodide ions ($I^-$) in this example) can provide the clue for the multiple needed for reactant molecules.
4. Return to the opposite side of the arrow to balance the remaining parts of the reaction.
5. Once all the atoms are balanced, multiply any fractions by the denominators until the equation has the smallest whole number coefficients.

# ACTIVITY: Balancing simple chemical equations 'by inspection'

## ATL

- Communication skills: Use and interpret a range of discipline-specific terms and symbols

1 **Deduce** how these examples should be correctly balanced:
   a $PbO(s) \rightarrow Pb(s) + O_2(g)$
   b $H_2(g) + Cl_2(g) \rightarrow HCl(g)$
   c $SO_2(g) + O_2(g) \rightarrow SO_3(g)$
   d $AgNO_3(aq) + Cu(s) \rightarrow Cu(NO_3)_2(aq) + Ag(s)$
   e $MgO(s) + HNO_3(aq) \rightarrow Mg(NO_3)_2(aq) + H_2O(l)$
   f $CH_4(g) + O_2(g) \rightarrow CO_2(g) + H_2O(g)$
   g $C_8H_{18}(l) + O_2(g) \rightarrow CO_2(g) + H_2O(g)$
   h $N_2(g) + 3H_2(g) \rightarrow NH_3(g)$
   i $H_2S(aq) + I_2(aq) \rightarrow HI(aq) + S(s)$
   j $Al(s) + HCl(aq) \rightarrow AlCl_3(aq) + H_2(g)$
   k $CaCO_3(s) + HCl(aq) \rightarrow CaCl_2(aq) + H_2O(l) + CO_2(g)$
2 **Find** correct formulas and state symbols, and then balance the equations for the word equations shown:
   a oxygen + hydrogen → water
   b aluminium + bromine → aluminium bromide
   c nitrogen + oxygen → dinitrogen pentoxide
   d dinitrogen monoxide → nitrogen + oxygen
3 **Formulate** balanced chemical equations for the precipitation reactions of the activity on page 101. The formulas for the ionic compounds you tested are copper(II) sulfate, $CuSO_4$; sodium carbonate, $Na_2CO_3$; lead(II) nitrate, $Pb(NO_3)_2$; potassium hydroxide, KOH; barium chloride, $BaCl_2$, and iron(II) sulfate, $FeSO_4$.

## Assessment opportunities

- In this activity you have practised skills that are assessed using Criterion A: Knowing and understanding.

## Using an algebraic approach

This method is recommended for equations involving compounds in which there are several products or reactants, or which cannot be easily solved by simple inspection. It is more time consuming but has the advantage that it is foolproof.

Example:

$PCl_5(s) + H_2O(l) \rightarrow H_3PO_4(aq) + HCl(aq)$ (unbalanced)

$PCl_5(s) + 4H_2O(l) \rightarrow H_3PO_4(aq) + 5HCl(aq)$ (balanced)

How was this achieved? The following outline reveals the process:

1. Start by assigning an algebraic value to each formula.
   $aPCl_5(s) + bH_2O(l) \rightarrow cH_3PO_4(aq) + dHCl(aq)$ (unbalanced)
2. **Solve** the equation for these 'unknowns' initially by comparing molecules that have the same number of atoms, or a simple ratio of atoms of a particular element. In the example the number of phosphorus (P) atoms in $PCl_5 = H_3PO_4 = 1$, suggesting $a = c = 1$.
3. Now consider ratios of other elements, based on its ratio in compounds on either side of the equation.
   Solving for $d$:
   chlorine (Cl), in $PCl_5$ and HCl:
   $5a = d$
   Solving for $c$:
   hydrogen (H), in $H_2O$ and $H_3PO_4$ + 5Hl:
   $c = \frac{1}{2}(3 + 5) = 4$
4. Check the numbers of atoms of remaining elements, e.g. oxygen, on both sides of the equation.
5. Once all the atoms are balanced, multiply any fractions by the denominators until the equation has the smallest whole number coefficients.

## ACTIVITY: Balancing simple chemical equations 'algebraically'

### ATL

- Communication skills: Use and interpret a range of discipline-specific terms and symbols; understand and use mathematical notation; organize and depict information logically

1. **Deduce** how these examples should be correctly balanced:
   a. $H_3BO_3(aq) \rightarrow H_4B_6O_{11}(aq) + H_2O(l)$
   b. $P_2I_4(s) + P_4(s) + H_2O(l) \rightarrow PH_4I(s) + H_3PO_4(aq)$
   c. $AsCl_3(aq) + NaBH_4(aq) \rightarrow AsH_3(g) + NaCl(aq) + BCl_3(l)$
   d. $Cu(s) + HNO_3(l) \rightarrow Cu(NO_3)_2(aq) + NO(g) + H_2O(l)$
   e. $KIO_3(aq) + KI(aq) + H_2SO_4(aq) \rightarrow K_2SO_4(aq) + H_2O(l) + I_2(aq)$
2. **Many of the examples include compounds of phosphorus and arsenic. Identify where phosphorus and arsenic are located on the periodic table. What do the compounds they form suggest about their reactivity and electronegativity?**

### Assessment opportunities

- In this activity you have practised skills that are assessed using Criterion A: Knowing and understanding.

### Links to: Mathematics

Numeracy is part of daily life and common to all subjects. Procedural fluency in calculations, estimation and quantitative comparisons in chemistry will reinforce your understanding of mathematics. What do the formulas of chemical compounds and balancing equations have in common with factorization and algebraic processes?

The skills you have learnt in mathematics, particularly the operational skills of multiplication and addition, are fundamental to how the law of conservation of mass applies to chemical change.

# How do atoms and their compounds persist in the environment?

## ACTIVITY: Managing 'heavy metal' water pollutants

### ATL

- Critical-thinking skills: Gather and organize relevant information to formulate an argument; evaluate and manage risk; propose and evaluate a variety of solutions; interpret data

Dissolving substances to reduce their concentration reduces their environmental impact. In this activity you will investigate the factors that affect solubility.

**Inquiry question:** How can a toxic, poisonous ion be detected and disposed of safely? What happens to the heavy metal waste collected in your school laboratory?

**Safety:** Work with care, using protective clothing and wash hands – heavy metals are toxic. Be sure to consider carefully how you will dispose of any reaction products. Minimize the quantities you use.

In this investigation, you have two, related, aims:

1. **To develop a kit that can detect a 'heavy metal' of your choice dissolved in water. The kit may detect more than one type of ion, but it must include the ion you are investigating.**
2. **To develop a method for precipitating these ions out of the solution. The remaining solution should not include the heavy metal ions.**

### Planning

- **Explain the general hazards caused by heavy metals. Before selecting a specific heavy metal ion for your investigation, check whether ionic compounds containing the element are available in your school.**
- **Your scientific reasoning should outline examples of reactions involved in the precipitation of the heavy metal ion out of solution. Include solubility information (g $dm^{-3}$) for ionic compounds of the heavy metal you selected. Anticipate using your own 'detector kit' to evaluate the efficiency of your decontamination process in the second part of your investigation.**
- **Present a list of all the chemicals you plan to use.**

### Analyses

Reporting your investigation: interpreting results

1. **Interpret your results.**
2. **Discuss their validity (whether there could be an alternative explanation for the effects you measured) and reliability (how consistent the effects you measured were).**

Reporting your investigation: interpreting the science

3. **Present your results to show trends effectively.**
4. **Discuss your results with reference to your method and evaluate its validity.**
5. **Discuss your method, and evaluate its validity.**
6. **Suggest improvements and extensions of this investigation.**

### Assessment opportunities

- In this activity you have practised skills that can be assessed with Criterion B: Inquiring and designing and Criterion C: Processing and evaluating.

## Risk management

Having opportunities to learn chemistry through independent practical investigations is fundamental to the inquiry approach in science. At the same time, you have a responsibility to work safely, to protect yourself, others and the natural environment around you. Risk management in science is about evaluating activities for their potential to cause harm, and taking steps to control or limit these possible outcomes. This is particularly important in any activity that may involve unfamiliar chemicals and breakable glassware.

The checklist in Table 5.2 is intended as a guide. It should help you identify protective actions that can be included as part of your planning and scientific method.

Hazard identification/Method of risk management in science – student investigation planner

| Hazard category | Hazard | Hazard present? Yes/No | Action to minimize risk (insert number) |
|---|---|---|---|
| Chemical | Inhalation | | |
| | Handling | | |
| | Explosive | | |
| | Flammable | | |
| | Corrosive | | |
| | Irritant | | |
| | | | |
| Mechanical energy | Cutting | | |
| | Puncture | | |
| | Falling/moving object | | |
| | | | |
| Heat | Scalds/burns | | |
| | | | |
| Radiation | Intensity (lasers) | | |
| | Type (UV, X-rays, etc.) | | |
| | | | |
| Sound | Intensity | | |
| | | | |
| Electricity | Shock | | |
| | Burns | | |
| | | | |
| Biological | | | |
| | | | |

| Actions to minimize risks | |
|---|---|
| 1 | Goggles |
| 2 | Gloves |
| 3 | Apron |
| 4 | Lab coat |
| 5 | Safety screen |
| 6 | Fume hood |
| 7 | Verbal warning |
| 8 | Wash hands |
| 9 | Hair back |
| 10 | Ventilation |
| 11 | Disinfectant |
| 12 | Special disposal |
| 13 | Aseptic techniques |
| 14 | Non-contact |
| 15 | Minimal quantities |
| 16 | Flammable |
| 17 | Static discharge |
| 18 | First aid kit |
| 19 | People risk/instructions |
| 20 | Demonstration only |
| 21 | Other (specify) |

Approved by: _____ Science Teacher

Date: _____

■ **Table 5.2** General risk management checklist for science investigations

# How can I distinguish acids and bases?

## ACIDS AND BASES

The concept of ions is largely credited to a Swedish chemist, Svante Arrhenius (1859–1927). While studying the conductivity of electrolytes for his doctorate, he discovered that **acids**, compounds that in pure form are covalently bonded polar molecules, dissociate into hydrogen ions and anions when they dissolve in water. The extent to which molecules dissociate is an indicator of the strength of the acid and its electrical conductivity.

Many foods contain weak acids (Table 5.3) and there is a direct relationship between our perception of sourness and the concentration of hydrogen ions ($H^+$) they contain. Similarly, for Arrhenius, a **base** (alkali) was a compound that produced hydroxide ions ($OH^-$) and cations when it dissolved in water. Bases are used to make soaps, so you may know from experience that they have a bitter, alkaline taste. This has been attributed to the high concentration of hydroxide ions in their solutions.

Arrhenius's definition helped people recognize that acidity and alkalinity were associated with particular ions in aqueous solutions, but did not explain why substances such as ammonia ($NH_3$) were also bases. In 1923 two chemists (Figure 5.8) independently developed a new definition. Danish Johannes Brønsted (1879–1947) and English Thomas Lowry (1874–1936) extended Arrhenius's concept by defining an acid as a 'proton donor' and a base as a 'proton acceptor'. A proton is another term for a hydrogen ion. Their theory explained how ammonia and hydrogencarbonate ions became weak bases when they reacted with water (Table 5.3).

According to the **Brønsted–Lowry theory**, acids and bases interact in pairs. For example, when molecules dissociate in water, a water molecule accepts the hydrogen ion, and therefore acts as a base; and when ammonia reacts with water, the water molecule donates a proton and therefore acts as an acid. Molecules with dual acid–base properties involving proton transfer, like water, are described as **amphiprotic**. The prefix *amphi* is from the Greek word meaning 'both' and *protic* refers to the proton.




**Figure 5.7** Svante Arrhenius as a young man





**Figure 5.8** *Left:* Johannes Brønsted; *and right:* Thomas Lowry. In the history of science, there have been several occasions when important theories were developed independently by different people. What does this suggest about the nature of scientific knowledge?

# ACTIVITY: Clarifying your understanding of acids and bases

## ATL

- **Critical-thinking skills**: Revise understanding based on new information and evidence

1 **Outline** common properties of acids and bases listed in Table 5.3. **Suggest** how you might **define** acids and bases from your interpretations of the pattern.

2 **Predict** which acids and bases in Table 5.3 will be the best electrolytes, assuming the same number of molecules is dissolved in water for comparison.

3 **Discuss** whether strong acids and bases are simply special examples of ionic solutions.

4 **Explain**, using a diagram, why a proton ($H^+$) is another name for a hydrogen ion.

**Hint**

*Refer to the periodic table.*

5 **In the examples below, the gas is being bubbled through water.**

a **Identify the pairs of acids and bases in the two reactions.**

i $HCl(g) + H_2O(l) \rightarrow Cl^-(aq) + H_3O^+(aq)$

_____ + _____ → _____ + _____

ii $NH_3(g) + H_2O(l) \rightarrow NH_4^+(aq) + OH^-(aq)$

_____ + _____ → _____ + _____

b **Suggest what is happening to the water molecule in the two reactions.**

6 a **Predict the result of the interactions between ions, if you mixed equal volumes and concentrations of each of these pairs of acids and bases. Complete (and balance) the equations below to find out!**

i $HCl(aq) + NaOH(aq) \rightarrow$ _____ + _____

ii $HNO_3(aq) + KOH(aq) \rightarrow$ _____ + _____

iii $H_2SO_4(aq) + Mg(OH)_2(s) \rightarrow$ _____ + _____

b **Identify the pH of the reaction products in (a).**

## Assessment opportunities

- In this activity you have practised skills that are assessed using Criterion A: Knowing and understanding.

| Category | Formula | Ions |
|---|---|---|
| **Strong acids** | | |
| hydrochloric acid | $HCl(aq)$ | $H^+(aq) + Cl^-(aq)$ |
| nitric acid | $HNO_3(aq)$ | $H^+(aq) + NO_3^-(aq)$ |
| sulfuric acid | $H_2SO_4(aq)$ | $2H^+(aq) + SO_4^{2-}(aq)$ |
| **Weak acids** | | |
| carbonic acid (in soft drinks) | $H_2CO_3(aq)$ | $H^+(aq) + HCO_3^-(aq)$ |
| citric acid ( in citrus fruit; lemons, oranges) | $C_6H_8O_7(aq)$ | $H^+(aq) + C_6H_7O_7^-(aq)$ |
| ethanoic acid ( in vinegar) | $CH_3COOH(aq)$ | $H^+(aq) + CH_3COO^-(aq)$ |
| methanoic acid (in ant and nettle stings) | $CHCOOH(aq)$ | $H^+(aq) + HCOO^-(aq)$ |
| phosphoric acid | $H_3PO_4(aq)$ | $H^+(aq) + H_2PO_4^-(aq)$ |
| sulfurous acid | $H_2SO_3(aq)$ | $H^+(aq) + HSO_3^-(aq)$ |
| 'tannic' acid (in wine) | $C_{76}H_{52}O_{46}(aq)$ | $H^+(aq) + C_{76}H_{51}O_{46}^-(aq)$ |
| **Strong bases (alkalis)** | | |
| sodium hydroxide | $NaOH(aq)$ | $Na^+(aq) + OH^-(aq)$ |
| potassium hydroxide | $KOH(aq)$ | $K^+(aq) + OH^-(aq)$ |
| barium hydroxide | $Ba(OH)_2(aq)$ | $Ba^{2+}(aq) + 2OH^-(aq)$ |
| **Weak bases that react with water** | | |
| ammonia | $NH_3(g)$ | $NH_4^+(aq) + OH^-(aq)$ |
| hydrogencarbonate ions (e.g. from $NaHCO_3$) | $HCO_3^-(aq)$ | $H_2CO_3(aq) + OH^-(aq)$ |

**Table 5.3** Some examples of common acids and bases, and the ions they form in water

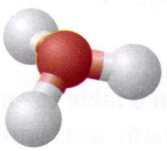


**Figure 5.9** Brønsted and Lowry proposed $H^+(aq)$ should be shown as $H_3O^+(aq)$, arguing that showing the hydrogen ion bonded to a water molecule was a more accurate representation of how the ion would interact with water. The species, with symbol $H_3O^+(aq)$, is called a '**hydronium** ion'

## ACTIVITY: Observing indicators of acids and bases

### ATL

- Organization skills: Keep an organized and logical system of information files/notebooks; understand and use sensory learning preferences (learning styles)

**Safety:** Avoid contact with skin. Solvents used for indicators may be flammable.

### Materials and equipment

- examples of several acid–base indicators, as solutions in dropper bottles or as indicator papers (e.g. red and blue litmus papers, phenolphthalein, methyl orange, bromothymol blue and universal indicator solutions; natural examples such as brewed 'black' tea, juices from crushed plants, e.g. red cabbage leaves, grapes and petals from various flowers)
- one or more spotting tiles
- rinse bottle with water
- beaker for waste
- a dropper bottle of an acidic solution, e.g. 0.1 M HCl
- a dropper bottle of a basic solution, e.g. 0.1 M NaOH

### Method

1. **Design** a table to enable you to record the results of systematic tests with each type of indicator and a few drops of HCl, water or NaOH.
2. **Develop the habit of using small quantities of solutions to avoid waste. A single drop of indicator solution, or a small piece of indicator test paper should be sufficient to determine any colour change of up to 10 drops of either test solution.**
3. **After testing a set of solutions, rinse the waste into the beaker. Later, it can be washed down the sink.**
4. **What happens to the colour of an indicator in a basic solution as you add up to ten drops of the acid solution, drop by drop: or vice versa? What is happening?**

### Analysing results

1. **State** general trends in colours of indicators in their response to acids and bases.
2. **List** properties you value most in an indicator. **Suggest** circumstances in which some of the indicators you used may have an advantage.
3. **State** what happened to the colour of an indicator as you added acids to a basic solution, or vice versa. How does your observation relate to the equations you balanced in question 6 In the Activity *Clarifying your understanding of acids and bases*, above?
4. **Suggest** how the acid spill kit in Figure 5.10 works. **List** examples of solutions that might be in the kit. **Describe** workplaces that might use kits like this.




**Figure 5.10** An example of an acid spill kit

### Assessment opportunities

- In this activity you have practised skills that are assessed using Criterion A: Knowing and understanding.

# INDICATORS OF ACIDS AND BASES

In pure water, the concentration of hydrogen and hydroxide ions is very low. Water is amphiprotic, its ions able to act as either an acid or a base, and it can self-ionize:

$$H_2O(l) + H_2O(l) \rightarrow H_3O^+(aq) + OH^-(aq)$$

This equation shows the ratio of these ions is equal and therefore pure water is considered neutral. Various substances, including the pigments found in many plants and fungi, respond to the presence of hydrogen ions by changing their shape and structure, and this can affect their colour. These **'indicator'** molecules provide a useful visual sign of a solution's acidity or alkalinity.

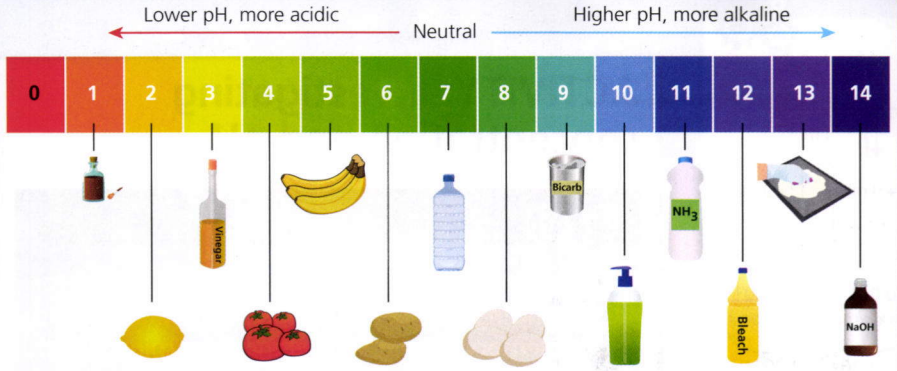



**Figure 5.11** The colour range of 'universal indicator' superimposed with examples of household products of a range of **pH** values. Note that the pH scale has no units; the pH is a measure of the concentration of hydrogen ions in the solution

## pH: THE SCALE FOR ACIDS AND BASES

What do the numbers of the pH scale mean? The pH scale is a negative logarithmic one. pH is based on an exponent; the value of pH 7 for water at 25 °C refers to a hydrogen ion concentration of $10^{-7}$ mol dm$^{-3}$, a very small number. We usually think of water as a covalently bonded molecular substance, but it can naturally dissociate very slightly, into protons and hydroxide ions, a reaction that occurs constantly and is reversible. Water is a **neutral** liquid because the number of hydrogen ions is always balanced by the number of hydroxide ions.

All acid solutions contain more hydrogen ions than pure water. Acid solutions have lower pH than water because the number refers to the negative exponent in the concentration factor; $10^{-6}$ is a value ten times larger than $10^{-7}$. Acidic solutions have a pH of less than 7.

The smaller the pH value, the more $H^+$ ions are in the solution. Each value in the pH scale represents a tenfold increase in the number of hydrogen ions. Clearly, the more concentrated the solution of acid, the greater the number of hydrogen ions. Secondly, the extent of the dissociation of a molecule into ions depends on the temperature and therefore the higher the temperature, the greater the number of hydrogen ions. Thirdly, the type of acid makes a difference; at the same concentration, a **'strong' acid** will ionize much more than a **'weak' acid** (Table 5.3). However, it is a principle of equilibrium that the lower the concentration of a solute, the more the molecules will dissociate into ions (see Chapter 11). This affects very dilute solutions of weak acids in particular, and means there is no direct relationship between the concentration of a dilute, weak acid and the hydrogen ions in the solution. In summary, the pH of a solution depends on several variables: the acid, the concentration of the acid and temperature.

An **alkaline solution** is one which contains a water-soluble base. The hydroxide ions of the base react with the hydrogen ions of water, and this means the concentration of hydrogen ions in alkaline solutions is lower than in pure water. Alkaline solutions have a pH value greater than 7. The greater the pH value, the lower the concentration of hydrogen ions, and the higher the corresponding concentration of hydroxide ions. As with acids, the alkalinity of a solution depends on several variables, including the base, the concentration of the base, and the temperature.

## ACTIVITY: pH

### ATL

- Critical-thinking skills: Revise understanding based on new information and evidence

1 **Identify** whether a solution is acidic, alkaline or neutral, if its pH is: 9, 4, 7, 1, 10, 2.

2 **Compare** two solutions with pH 8 and pH 10. In the more alkaline solution, by what factor is the number of hydrogen ions decreased?

3 Imagine $10^{20}$ molecules of each of the following pairs of acids were each dissolved in 0.1 dm$^3$ water. (Refer to Table 5.3.)
   - a **Deduce** which of these pairs has the most hydrogen ions, and why:
     - i ethanoic acid and hydrochloric acid
     - ii sulfuric acid and citric acid.
   - b **For each pair of solutions, identify** which is the better conductor of electricity.

4 a **Compare** the expressions:
   - i a concentrated solution of an acid
   - ii a solution of a strong acid.
   - b **Sketch** a diagram representing the particles in a concentrated solution and a dilute solution.
   - c **Explain** the difference in their meaning, with an example (e.g. refer to Table 5.3).

### Assessment opportunities

- In this activity you have practised skills that can be assessed with Criterion A: Knowing and understanding.

## Serial dilutions

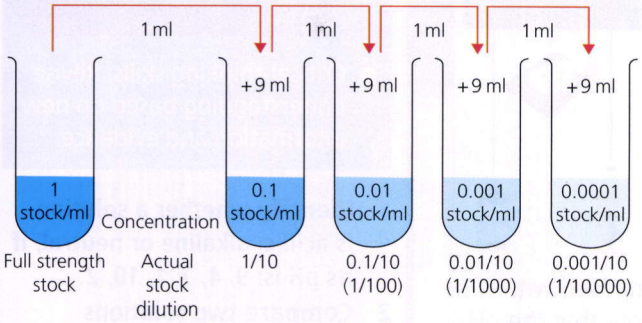



**Figure 5.12** The process of preparing a serial dilution by making successive solutions

A serial **dilution** is one in which each successive sample is a further dilution of the previous sample. To make a serial dilution in which each sample is diluted by a factor of 10, add 0.01 $dm^3$ (1 ml) of the stock to 0.09 $dm^3$ (9 ml) of water (Figure 5.12). A fresh pipette should be used for each of these steps.

After mixing, repeat the process, using the diluted sample instead of the stock (Table 5.4).

| Sample (test tube no.) | Source of the 0.01 $dm^3$ amount | Water added | Dilution factor (of the original) |
|---|---|---|---|
| 1 | Original stock | – | 1 |
| 2 | Test tube 1 | + 0.09 $dm^3$ | $\frac{1}{10}$ |
| 3 | Test tube 2 | + 0.09 $dm^3$ | $\frac{1}{100}$ |
| 4 | Test tube 3 | + 0.09 $dm^3$ | $\frac{1}{1000}$ |
| 5 | Test tube 4 | + 0.09 $dm^3$ | $\frac{1}{10000}$ |
| 6... | ... | ... | ... |

**Table 5.4**

Because the dilution factor is carefully controlled, serial dilutions are useful for investigating properties that are difficult to interpret at high concentrations, for example bacterial counts or reactions involving strongly pigmented materials.

## EXTENSION

Explore acids and bases in environmental contexts by researching **water pollution**, **air pollution**, **knows no borders**.

## ACTIVITY: Investigating concentration and pH

### ATL

- Organization skills: Use appropriate strategies for organizing complex information; understand and use sensory learning preferences (learning styles)

### Materials and equipment

- **Stock solutions (0.1 M):**
  - **HCl**
  - **$CH_3COOH$**
  - **NaOH**
  - **$NaHCO_3$**
- **test tubes**
- **1.0 ml graduated pipettes**
- **10 ml graduated pipettes**
- **universal indicator or pH probe**

### Method

1. **Prepare a serial dilution of each of the four stock solutions. You may wish to divide the task between separate groups in the class.**
2. **Prepare a table and predict the pH values for each of the dilutions in the series.**
3. **Test your predictions by measuring pH using universal indicator or a pH probe.**

### Analysing results

1. **Compare the 0.10 M solutions, by ranking them from lowest to highest pH.**
2. **Describe the variation in colour with each dilution, in terms of the hydrogen ion concentration.**
3. **Explain why the strong acid or base required more dilutions to reach the same pH as the weak acid or base.**
4. **Explain why the pH is a measure of concentration, rather than of acid 'strength'.**

### Assessment opportunities

- In this activity you have practised skills that are assessed with Criterion C: Processing and evaluating.

### Links to: Geography

Have you studied **acid rain**, **ocean acidification**, **deforestation** in your Geography classes? How do acids and bases impact the environment?

## ACTIVITY: Reactions of metal carbonates with acids

### ATL

- Transfer skills: Inquire in different contexts to gain a different perspective
- Organization skills: Use appropriate strategies for organizing complex information

### Materials and equipment

- sodium hydrogencarbonate (s)
- calcium carbonate (s)
- 1 M nitric acid
- 1 M ethanoic acid and/or citric acid
- universal indicator solution
- test tubes, stand
- limewater

### Method

1. Add a small spatula of each carbonate to test tubes; complete the following steps separately.
2. Add 10 $cm^3$ of nitric acid to a test tube, then add a drop of universal indicator solution
3. Pour the acid mixture over one of the dry carbonate solids.
4. Test the gas emitted during the reaction by bubbling it through limewater.
5. Repeat the neutralization process using the other carbonate.
6. Repeat the neutralization process with calcium carbonate and a weak acid of the same concentration.

### Analysing results

1. **State** (a) evidence that neutralization occurred and (b) the role of water in the reaction.
2. **Formulate** word and balanced chemical equations for each of the three reactions. **Identify** the gas, source of the gas, and salt produced.
3. **Summarize** the pattern by completing this sentence: *When a metal carbonate reacts with an acid, the products are the _____, water and _____ gas.*
4. **Describe** how the reaction changed when a weak acid was used in place of the strong acid.
5. **Describe** the change in nature of bonding properties of the molecules involved in the reactants and products. Predict the effect on the reactants of the (a) removal of carbon dioxide from the product, and (b) addition of water molecules to the reactants.
6. A student completing a science fair project decided to test the effects of soda drinks on tooth decay. She obtained sheep teeth from her local butcher, and tested them by covering them with various soft drinks.
   a. **State** the acid/s found in soda drinks.
   b. **Predict** the reactions she might expect to observe.
   c. Is it valid to transfer the results of her experiment directly to the context of a human consuming soda drinks? **Explain** your reasoning.

### Assessment opportunities

- In this activity you have practised skills that are assessed using Criterion A: Knowing and understanding.

## NEUTRALIZATION REMOVES EXTREMES: RECOGNIZING PATTERNS

A **neutralization** reaction is one that removes acidity. An operational definition of a base is any substance that removes hydrogen ions from an acid. Bases include **alkalis** (dissolved bases), ammonia solution, metal oxides, metal carbonates and metal hydrogencarbonates. Bases can be neutralized by reactions with acids.

A general equation for the reaction between an acid and an alkali is:

$$\text{acid (aq)} + \text{alkali (aq)} \rightarrow \text{salt (aq)} + \text{water (l)}$$

One of the products of this reaction is water. The other product will be a **salt**. A salt is an ionic compound that contains a metal cation and the anion of an acid. For example, hydrochloric acid will produce chlorides; sulfuric acid, sulfates; and nitric acid, nitrates. Salts can be prepared by many types of reactions, including **synthesis** reactions, in which two elements combine, **decomposition** reactions, in which an ionic substance or a molecule is broken down to simpler substances, and double and single **displacement** reactions. Examples of some of these reactions are the action of acids with alkalis and ammonia solution, with some metals, metal carbonates, metal hydrogencarbonates and metal oxides.

# ACTIVITY: Comparing domestic acids and alkalis

## ATL

- Transfer skills: Inquire in different contexts to gain a different perspective
- Organization skills: Use appropriate strategies for organizing complex information

**Safety:** Avoid skin contact with oven and drain cleaners. Wear safety goggles and gloves.

### Materials and equipment

- a range of alkaline household substances: ammonia, soap, toothpaste, 'bicarbonate of soda' ($NaHCO_3$), bleach, and oven and drain cleaners
- a range of acid household substances: fruit juice, vinegar, tomato sauce and shampoo
- a range of laboratory acids and alkalis: 0.1 M solutions of HCl(aq), NaOH(aq), $NH_3$(aq) and $CH_3COOH$(aq)
- universal indicator and spotting tile
- familiar materials: paper, aluminium foil, cotton, silk cloth

### Method

1. Determine the pH of each acid or alkali.
2. Place a drop of each on a labelled sample of each familiar material.
3. Inspect the effects every few days for up to two weeks.

### Analysing results

1. **List** the pH range of the tested acids and alkalis from most alkaline to most acidic.
2. A substance is said to be corrosive if it is harmful and destructive. Based on your results, justify the claim that either group is more corrosive.
3. **Summarize** the pattern for the neutralization of alkalis with acids by reacting both $OH^-$ and $H^+$ together by completing this sentence:
   *When an acid reacts with an alkali, the products are a ____ and _____.*
4. The following word equation shows how metal hydroxides react with ammonium compounds:
   sodium hydroxide(s) + ammonium chloride(aq) → sodium chloride(aq) + water(l) + ammonia ($NH_3$)(g)
   a. **Identify** the ionic compounds in the reaction.
   b. **Formulate** a balanced equation for the reaction.
   c. **Suggest** how this reaction differs from a neutralization reaction.

## Assessment opportunities

- In this activity you have practised skills that are assessed using Criterion C: Processing and evaluating.

# ACTIVITY: Investigating a factor that affects solubility

## ATL

- Organization skills: Plan short- and long-term assignments and meet deadlines
- Critical-thinking skills: Gather and organize relevant information to formulate an argument; evaluate and manage risk; propose and evaluate a variety of solutions; interpret data

Dissolving substances to reduce their concentration reduces their environmental impact. In this activity you will investigate the factors that affect solubility.

**Inquiry question:** Which conditions influence the solubility of an ionic compound?

### Hypothesizing

Consider some of the variables that might cause molecules to dissociate. Suggest a hypothesis, explaining how one of these may affect the solubility of a salt (ionic compound).

### Planning

Review the investigation inquiry cycle introduced in Chapter 1. Potential hazards associated with the chemicals can be located by searching for the **Material Safety Data Sheet (MSDS)**. Check the availability of chemicals and other safety materials with your teacher before proceeding. A risk analysis and environmental impact analysis must be included in your plan.

### Reporting

An important aspect of reporting is the evaluation of your hypothesis and your method, including suggestions for improvements and extensions of the method.

## Assessment opportunities

- This activity can be assessed using Criterion B: Inquiring and designing and Criterion C: Processing and evaluating.

# What is the fairest way to use our chemical resources?

## THE ROLE OF SCIENTISTS IN GOVERNMENT AND BUSINESS POLICY DEVELOPMENT

Not all scientists are employed in active laboratory investigations. Many scientists are employed for their expert knowledge and ability to provide impartial advice to guide public (government) and private enterprise. Could you have the skills for a role like this?

Evaluations where scientific input may be needed include:

- assessing the potential for the development of a mine, for example the size of the resource required for economic viability
- solutions to consequences of human activity, for example how environmental damage of emissions, spills or other wastes resulting from industry may be limited or reduced
- manipulating the chemical conditions of a natural resource so it can be exploited for a commercial activity, such as farming.

### ! Take action: Responsible waste disposal

#### ATL

- Communication skills: Use a variety of media to communicate with a range of audiences; write for different purposes

! Waste is an inevitable consequence of living and working. Building renovations, restaurants, garages, hospitals, farms and factories are just some of the many enterprises that produce chemical waste. You may be familiar with some of these categories:

- oils and greases
- solvents and paint strippers
- corrosive substances (acids and caustics)
- soils contaminated with low level radioactive wastes, heavy metals and other solids
- plastic waste
- antibiotics.

! You may have seen instructive notices of the type 'No dumping' or 'Spill kit – acid neutralizer'. A business displaying posters of this nature not only encourages principled practice, it is assuring its community that it is environmentally aware and complies with by-laws. Often located in public areas, these reminders help protect their communities.

! Research one of the categories of waste listed. How will this waste impact your community if it is not disposed of carefully? How is it disposed of safely in your community? Approach a local business that may produce this type of waste. Ask the owner or manager whether they would like to publicize their awareness of safe practice. Offer to help them by producing an extra, more striking or more informative poster. A notice created by a student from their local school will also reinforce the message that they support their unofficial community partnerships.

#### ◆ Assessment opportunities

- This activity can be assessed using Criterion D: Reflecting on the impacts of science.

# How can I distinguish acids and bases?

## ACIDS AND BASES IN THE PERIODIC TABLE

You will recall that the elements in groups 1 and 2 are known as the 'alkali metals' and 'alkaline earth metals', and this is an important clue about their chemistry. Their metal oxides react with water to form strong bases and metal hydroxides. For example, sodium and potassium hydroxide are strong bases. Calcium oxide is called quicklime because of its reaction with water to produce calcium hydroxide:

$$CaO(s) + H_2O(l) \rightarrow Ca(OH)_2(aq)$$

Solid calcium hydroxide is called slaked lime (because its 'thirst' for water has been 'slaked' or satisfied), and is a base. It is used in agriculture to neutralize 'sour', unproductive soil.

Consider what happens when the oxides of non-metals react and dissolve in water. For example:

$$CO_2(g) + H_2O(l) \rightarrow H_2CO_3(aq)$$

$$SO_2(g) + H_2O(l) \rightarrow H_2SO_3(aq)$$

$$P_4O_{10}(s) + 6H_2O(l) \rightarrow 4H_3PO_4(aq)$$

From this pattern, we should predict that most non-metal oxides will form acids when dissolved in water. We could infer this trend is caused by the increasing electronegativity of elements from left to right in the periodic table. You will recall that pure acids are covalently bonded molecules, that only show their ionic properties when they dissolve and react in water.

Let's reflect on the group of elements in between the metals and non-metals, the '**metalloids**' or **semi-metals**. The oxides of these metals are **amphoteric**, able to react with both acids and bases. As an example, consider the reactions of aluminium oxide with an acid and a strong base.

$$Al_2O_3(s) + 6HCl(aq) \rightarrow 2AlCl_3(aq) + 3H_2O(l)$$

$$2NaOH(aq) + Al_2O_3(s) + 3H_2O(l) \rightarrow 2Na[Al(OH_4)](aq)$$

The ionic compound $Na[Al(OH_4)]$ is called sodium aluminate. In this convention the square brackets around the aluminate ion $[Al(OH_4)]^-$ have the same meaning as in algebraic equations, describing groups within groups.

| | 1 | 2 | 13 | 14 | 15 | 16 | 17 | 18 |
|---|---|---|---|---|---|---|---|---|
| 1 | | | | | | | | |
| 2 | $Li_2O$ | BeO | $B_2O_3$ | $CO_2$ | $N_2O_5$ / $N_2O_3$ | | | |
| 3 | $Na_2O$ | MgO | $Al_2O_3$ | $SiO_2$ | $P_4O_{10}$ / $P_4O_6$ | $SO_3$ / $SO_2$ | $Cl_2O_7$ / $Cl_2O$ | |
| 4 | $K_2O$ | CaO | $Ga_2O_3$ | $GeO_2$ | $As_2O_5$ / $As_4O_6$ | $SeO_3$ / $SeO_2$ | $Br_2O$ | |
| 5 | $Rb_2O$ | SrO | $In_2O_3$ / $In_2O$ | $SnO_2$ / SnO | $Sb_2O_5$ / $Sb_4O_6$ | $TeO_3$ / $TeO_2$ | $I_2O_5$ | |
| 6 | $Cs_2O$ | BaO | $Tl_2O$ | $PbO_2$ / PbO | $Bi_2O_3$ | $PoO_2$ / PoO | | |
| 7 | $Fr_2O$ | RaO | | | | | | |

**Key**

- Strongly basic
- Weakly basic
- Amphoteric
- Strongly acidic
- Moderately acidic
- Weakly acidic

**Figure 5.13** The location of acidic, amphoteric and basic oxides in the main groups of the periodic table. Notice how the metalloid elements mostly form amphoteric oxides

## ACTIVITY: Investigating oxides

### ATL

- Transfer skills: Inquire in different contexts to gain a different perspective
- Collaboration skills: Help others succeed; encourage others to contribute; give and receive meaningful feedback

**Safety:** Make sure you use safety equipment: wear gloves and eye protection.

### Materials and equipment

- a range of solid metal oxides, e.g. $Na_2O$, CaO, MgO, $Fe_2O_3$
- spotting tile
- universal indicator
- water (e.g. in rinse bottle)
- limewater – dilute $Ca(OH)_2(aq)$
- drinking straw
- 250 ml small conical flask

### Method

1. Check the pH of the solid oxides by adding small amounts (0.5 g) of the solid to the spotting tile, and adding water and universal indicator.
2. The 'limewater' test is a classic test for carbon dioxide. Add about 0.1 $dm^3$ of limewater to the small conical flask and gently blow through it using a straw. You may want to add a little indicator solution, to observe evidence of changes in acidity.
3. Continue blowing until the solution goes clear.

### Analysing results

1. **State** whether the dissolved oxides show the patterns you predicted. **Suggest** explanations for anomalies.
2. The reaction between limewater and the exhaled carbon dioxide in your breath is

   $Ca(OH)_2(aq) + CO_2(g) \rightarrow CaCO_3(s) + H_2O(l)$

   a. **Identify** the solid forming the cloudy precipitate.
   b. **Deduce** what the formation of the precipitate suggests about the solubility of calcium carbonate.
3. Later, as you introduced more carbon dioxide to the solution, calcium carbonate reacted with weak carbonic acid to form calcium hydrogencarbonate (aq).

   **Formulate** a chemical equation for the further reaction of calcium carbonate with dissolved carbon dioxide, identifying the salt.

### Assessment opportunities

- In this activity you have practised skills that are assessed using Criterion C: Processing and evaluating.

## HOW OXIDE FORMATION PROVIDES THE CLUE TO OXIDATION AND REDUCTION

For a long time, chemists called any reaction of a substance with oxygen 'oxidation'. However, you may recall from the simple demonstration of electrolysis (Chapter 3) that the term now has a much broader meaning. An atom or ion is oxidized when it loses electrons. An ion or an atom is reduced when it gains electrons. Just as Brønsted and Lowry's theory encompassed an earlier definition of acids and bases, reflecting on the movement of electrons between particles has introduced new ways of thinking about chemical change.

'**Redox**' (a contraction of reduction and oxidation) reactions require a transfer of electrons between reacting particles, much as the Brønsted–Lowry theory involves a transfer of protons between acid and base pairs. The **oxidizing agent** (or oxidant) is the substance that accepts electrons from the substance that is being oxidized, and the **reducing agent** (or reductant) provides electrons to the substance that is being reduced. Redox requires charges to change!

Not all reactions are redox reactions. This chapter introduced chemical change by considering reactions between ions in solution. The formation of precipitates was evidence for the 'double displacement' of positive and negative ions. Neutralization reactions in which acidity or alkalinity is removed by reacting acids and bases together are of the same pattern. Chemical equations for these changes have the form,

$$aAC + bBD \rightarrow cAD + dBC$$

The electrostatic charge of the ions A, B, C and D does not change as a result of the reaction. By definition, these reactions are examples of **non-redox** reactions.

The distinction between redox and non-redox reactions will become much more important as we investigate other types of chemical change over the next chapters.

# SOME SUMMATIVE PROBLEMS TO TRY

Use these problems to apply and extend your learning in this chapter. The problems are designed so that you can evaluate your learning at different levels of achievement in Criterion A: Knowing and understanding.

A copy of a periodic table should be available for reference.

### THESE PROBLEMS CAN BE USED TO EVALUATE YOUR LEARNING IN CRITERION A TO LEVEL 1–2

1 **State** the chemical names for the formulas, and the physical state of the compounds listed below:
   - **a** $H_2SO_4(aq)$
   - **b** $NH_3(aq)$
   - **c** $Ca(OH)_2(aq)$
   - **d** $Cu(NO_3)_2(s)$
   - **e** $SO_2(g)$
   - **f** $H_2O(g)$

2 **State** numbers to balance these chemical reactions:
   - **a** ____ $Na_3PO_4(aq)$ + ____ $KOH(aq)$ → ____ $NaOH(aq)$ + ____ $K_3PO_4(aq)$
   - **b** ____ $MgF_2(aq)$ + ____ $Li_2CO_3(aq)$ → ____ $MgCO_3(s)$ + ____ $LiF\ aq)$
   - **c** ____ $P_4(s)$ + ____ $O_2(g)$ → ____ $P_4O_{10}(s)$
   - **d** ____ $RbNO_3(aq)$ + ____ $BeF_2(aq)$ → ____ $Be(NO_3)_2(aq)$ + ____ $RbF(aq)$
   - **e** ____ $AgNO_3(aq)$ + ____ $Cu(s)$ → ____ $Cu(NO_3)_2(aq)$ + ____ $Ag(s)$

3 Sea water has a very high concentration of dissolved sodium chloride. **Suggest** why it is unsafe to swim in the ocean during an electrical storm.

4 **Outline** why
   - **a** calamine solution (which contains zinc carbonate) is effective for relieving pain from bee stings (which contain methanoic acid)
   - **b** milk of magnesia (which contains magnesium hydroxide) is given to people suffering from 'heart burn', a pain caused by their acidic stomach contents (which contain hydrochloric acid) backing up into their oesophagus
   - **c** quicklime (calcium oxide), slaked lime (calcium hydroxide) and chalk (calcium carbonate) can all be used to improve soils that are too acidic to be useful for agriculture.




**Figure 5.14** Calamine solution is a suspension of zinc carbonate

5 Five solutions at the same temperature and with the same concentrations, sucrose (table sugar), nitric acid, ammonia solution, sodium hydroxide and methanoic acid, were tested with universal indicator.
   - **a** **Suggest** which of these solutions should be matched to each pH measurement listed in the table, and the information about the properties of these substances that guided your identification.

| pH value | Identity of the solution | Property of the substance in solution |
|---|---|---|
| 1 | | |
| 4 | | |
| 7 | | |
| 9 | | |
| 11 | | |

**b** Of the solutions you listed in (a), **suggest** pairs of combinations that *could* be mixed in different volumes, to give neutral solutions. **Explain** your thinking.

**6** The table below lists the pH of one of a pair of solutions, in standard conditions (at 1.0 M, 25 °C and 100 kPa).

**a** **Suggest** the missing pH of the solutions listed in the table.

| | Clue | Solution A | Solution B |
|---|---|---|---|
| i | Solution B has a hydrogen ion concentration about 100 times **less** concentrated than solution A | pH 5 | |
| ii | Solution B has a hydrogen ion concentration about 1000 times **more** concentrated than solution A | pH 11 | |
| iii | Solution B has a hydrogen ion concentration about 10 times **more** concentrated than solution A | | pH 10 |
| iv | Solution B has a hydrogen ion concentration about 10 000 times **less** concentrated than solution A | | pH 12 |
| v | Solution A has a hydrogen ion concentration about 10 times **less** concentrated than solution B | pH 3 | |

**b** **Identify** which of the solutions in (a) is likely to have the most dissociated ions.

**c** **Identify** which of the solutions in (a) is likely to have the greatest electrical conductivity.

## THESE PROBLEMS CAN BE USED TO EVALUATE YOUR LEARNING IN CRITERION A TO LEVEL 5–6

**7** **a** **Describe** what you expect to observe, and the movement of electrons between the reactants, when

**i** a piece of magnesium is added to dilute sulfuric acid

**ii** an iron nail is added to dilute nitric acid

**iii** aluminium is added to dilute hydrochloric acid.

**b** **Describe** the redox features of each of these reactions.

**8** **a** As a solution of barium hydroxide is mixed with an aqueous solution of sulfuric acid, a white precipitate forms and the electrical conductivity decreases markedly.

**i** **Write down** word and symbol equations for the reaction that occurred.

**ii** **Suggest** an explanation for the change in conductivity.

**b** When solid sodium ethanoate ($CH_3COONa(s)$) is added to an aqueous solution of hydrogen fluoride ($HF(aq)$), a reaction occurs in which the weak acid loses hydrogen ions ($H^+(aq)$).

**i** **Write down** word and symbol equations for the reaction that occurred.

**ii** **Suggest** the identity of the ion that is competing with the fluoride ion, $F^-(aq)$, for the proton.

**c** **Suggest** why, although the reaction of sodium with dilute hydrochloric acid is almost explosive, the reaction between sodium and ethanoic acid (at the same concentration and temperature) is only a little faster than that between sodium and water.

**9** Table 5.5 lists the strength of various acids, familiar and unfamiliar, and their dissociation in water. **Analyse** the information and make a scientifically supported judgment about acids that have more than one ionisable hydrogen atom in their molecules or ions.

| Acid | Strength | Reaction |
|---|---|---|
| Chloric(VII) acid | Very strong | $HClO_4(aq) \rightarrow H^+(aq) + ClO_4^-(aq)$ |
| Hydrochloric acid | | $HCl(aq) \rightarrow H^+(aq) + Cl^-(aq)$ |
| Nitric acid | | $HNO_3(aq) \rightarrow H^+(aq) + NO_3^-(aq)$ |
| Sulfuric acid | | $H_2SO_4(aq) \rightarrow H^+(aq) + HSO_4^-(aq)$ |
| Phosphoric acid | Strong | $H_3PO_4(aq) \rightarrow H^+(aq) + H_2PO_4^-(aq)$ |
| Hydrofluoric acid | Weak | $HF(aq) \rightarrow H^+(aq) + F^-(aq)$ |
| Nitrous acid | | $HNO_2(aq) \rightarrow H^+(aq) + NO_2^-(aq)$ |
| Ethanoic acid | | $CH_3COOH(aq) \rightarrow H^+(aq) + CH_3COO^-(aq)$ |
| Hydrosulfuric acid | | $H_2S(aq) \rightarrow H^+(aq) + HS^-(aq)$ |
| Hydrogen peroxide | Very weak | $H_2O_2(aq) \rightarrow H^+(aq) + HO_2^-(aq)$ |
| Water | | $H_2O(l) \rightarrow H^+(aq) + HO^-(aq)$ |

■ **Table 5.5** Relative strengths of acids in aqueous solution at room temperature. The dissociation reactions of weak to very weak acids are reversible.

## THESE PROBLEMS CAN BE USED TO EVALUATE YOUR LEARNING IN CRITERION A TO LEVEL 7–8

**10 a** **Use** the Brønsted–Lowry theory to **explain** (with examples) why water is amphoteric in acid–base reactions.

**b** **Explain** the distinction between strong and weak versus concentrated and dilute acids. Include diagrams to represent these concepts.

**11** The definitions below represent some of the emerging ideas by scientists reflecting on the chemistry of acids and bases.

| | | |
|---|---|---|
| 1661 | Robert Boyle | Acids taste sour; alkalis are slippery. They change the colour of certain vegetable dyes, such as litmus. Acids lose their acidity when they are combined with alkalis; alkalis consume, or neutralize, acids. |
| 1776 | Antoine Lavoisier | Acidity is caused by the presence of oxygen in a compound; an 'acidifiable base' was the other portion of the compound that combines with the oxygen and is responsible for the specific properties of the compound. |
| 1884 | Svante Arrhenius | An acid releases $H^+$ ions as the only positive ions when dissolved in water; a base releases $OH^-$ ions as the only negative ions when dissolved in water |
| 1923 | Brønsted–Lowry | An acid is a proton donor; a base is a proton acceptor. |

**a** **Analyse** and **evaluate** these definitions and make scientifically supported judgments about whether any parts of these definitions are satisfactory in the light of your present knowledge.

**b** **Use** your evaluations to **present** the relationship of the concepts in these four definitions as a Venn diagram. **Explain** why you have grouped the ideas the way you have.

**12** The $K_w$ is a constant for the extent that pure water molecules dissociate into its component ions, protons ($H^+(aq)$) and hydroxide ions ($OH^-(aq)$). The $K_w$ value is the product of the hydrogen ion and hydroxide ion concentrations (or alternatively the square of the hydrogen ion concentration).

Table 5.6 compares the extent that pure water molecules dissociate at different temperatures, and very precise measurements of pH values.

**a** **Describe** the trend in the extent that water molecules in a sample of water dissociate with an increase in temperature.

**b** **Explain** why the pH changes in response to the dissociation of water molecules. What does pH measure?

**c** **Use** the Brønsted–Lowry acid–base theory to write an equation showing how two water molecules react together and produce ions.

**d** As the numbers of ions present in the pure water changes with temperature, can the water still be considered neutral? **Explain** your reasoning.

| Temperature/°C | $K_w$ | pH |
|---|---|---|
| 15 | $0.453 \times 10^{-14}$ | 7.17 |
| 20 | $0.684 \times 10^{-14}$ | 7.08 |
| 25 | $1.00 \times 10^{-14}$ | 7.00 |
| 30 | $1.47 \times 10^{-14}$ | 6.92 |
| 35 | $2.09 \times 10^{-14}$ | 6.84 |

**Table 5.6** Hydrogen ion concentrations and pH values of pure water at different temperatures.

# Reflection

In this chapter you learnt to recognize how chemical reactions are symbolized as balanced, chemical equations, and investigated examples of precipitation reactions and the interactions between acids and bases. Because matter is fundamental and cannot be created or destroyed, some of the roles of chemists include analysing how to minimize harm and reporting the impact of chemical industry in communities.

| **Use this table to reflect on your own learning in this chapter** | | | | | | |
|---|---|---|---|---|---|---|
| Questions we asked | Answers we found | Any further questions now? | | | | |
| **Factual:** How can I distinguish acids and bases? What do the symbols of a chemical equation show? | | | | | | |
| **Conceptual:** Why must a chemical equation be balanced? How do atoms and their compounds persist in the environment? | | | | | | |
| **Debatable:** What is the fairest way to use our chemical resources? | | | | | | |
| Approaches to learning you used in this chapter: | Description – what new skills did you learn? | How well did you master the skills? | | | | |
| | | Novice | Learner | Practitioner | Expert | |
| **Communication skills** | | | | | | |
| **Collaboration skills** | | | | | | |
| **Organization skills** | | | | | | |
| **Affective skills** | | | | | | |
| **Critical-thinking skills** | | | | | | |
| **Transfer skills** | | | | | | |
| **Learner profile attribute(s)** | How did you demonstrate your principled skills in this chapter? | | | | | |
| **Principled** | | | | | | |

# 6 What determines chemical change?

Physical and chemical **change** requires the **transfer** of kinetic energy between particles of matter **over time and affects the space they occupy**.



**Figure 6.1** Do particles behave like colliding balls?

## CONSIDER AND ANSWER THESE QUESTIONS:

**Factual:** How can particle motion be described? How is the quantity of a substance measured consistently during change?

**Conceptual:** How do the conditions of the environment affect chemical reactivity? Why do changes in the total number of particles, but not necessarily the total number of atoms, determine the volume of a gas?

**Debatable:** To what extent are physical and chemical changes linked?

Now **share and compare** your thoughts and ideas with your partner, or with the whole class.

## IN THIS CHAPTER, WE WILL ...

- **Find out** about the conditions required for substances to change state or react.
- **Explore:**
  - physical conditions that affect rates of diffusion and particle motion;
  - tools and techniques of an experimental chemist;
  - quantitative chemistry;
  - factors that make reactions possible.
- **Take action** by interesting younger students in chemistry by demonstrating your geysers in their science class.

## These Approaches to Learning (ATL) skills will be useful …

- Communication skills
- Organization skills
- Media literacy skills
- Critical-thinking skills
- Transfer skills

## We will reflect on this learner profile attribute …

- Thinker – What transfer skills are needed to quantify chemistry? Can experiences of movement, including ball games, guide critical thinking in the physical sciences, including chemistry? Do physical models inspire creative thinking, or are they simplifications to guide our understanding?

## KEY WORDS

accuracy
energy
kinetic
precision
pressure
scale
vapour

## Assessment opportunities in this chapter …

- Criterion A: Knowing and understanding
- Criterion B: Inquiring and designing
- Criterion C: Processing and evaluating
- Criterion D: Reflecting on the impacts of science

## THINK–PUZZLE–EXPLORE

Can the movement of particles of matter in different states be described with the same words? Use **lab.concord.org/embeddable.html#interactives/samples/4-100-atoms-conceptual.json** to investigate how their movement changes at different temperatures and with changing intermolecular attractions.

What do you **think** you know about this topic? What questions or **puzzles** do you have? How can you **explore** this topic? Jot down your ideas and be ready to discuss them with your class.

Imagine a ball played during a sport, perhaps a tennis ball being hit across the court, a billiard ball rolling across a felt table, or a basketball being 'dribbled' from a very, very low height. A scientist might describe changes in the angle of the ball's movement as **translational** motion, rolling and spinning as **rotation**, and small quivering movements as **vibration**.

- In crystalline solids, molecules or ions cannot move through their lattice. What types of motion are possible in these positions?
- Liquids are usually only slightly less dense than solids. What evidence is there that these particles have some translational movement? What might cause this?
- In gases, particle motion is almost entirely translational, molecules moving rapidly from place to place in straight lines, like a tennis ball during a match. How can this type of motion explain why gases expand to fill the space that contains them or how the perfume of flowers diffuses through a still room?

# How can particle motion be described?

## PARTICLE PHENOMENA

The processes that we explore in science are all around us, every day. A learning strategy called Familiar Phenomena Probes aims to help you consider everyday events from a scientific perspective. As you reflect on the examples on these pages, imagine how the motion of the many, many tiny particles of matter might explain these events.



**Figure 6.2** Water that has been heated to boiling

### DISCUSS: Boiling water

1. **Is the composition of these bubbles in boiling water the same as the bubbles that appear when cold water heats up?**
2. **What is inside these bubbles?**
3. **Why do the bubbles change size as they move towards the surface?**
4. **What will happen if the heat is turned off?**

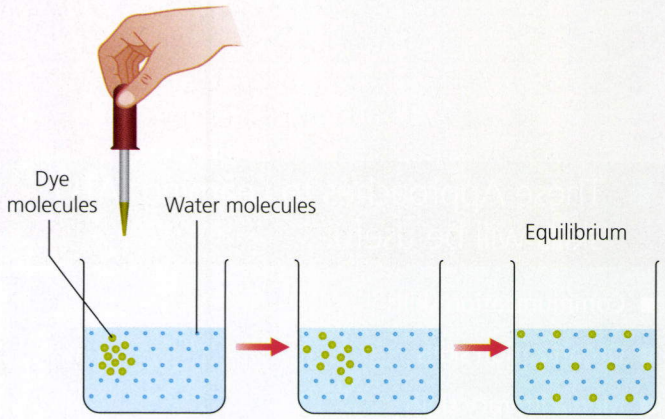
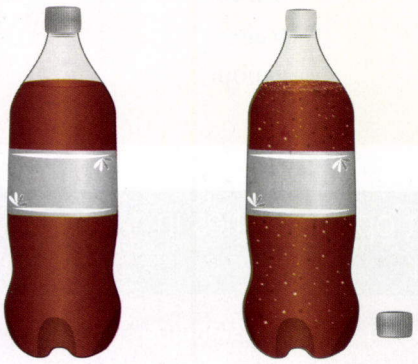



**Figure 6.3** Diffusion of a dye. Equilibrium is a steady state, in which there is a balance in competing changes, including movements of particles

### DISCUSS: Diffusion

1. **Why, without stirring, does the dye gradually spread through the liquid?**
2. **Do you expect the coloured dye molecules to spontaneously regroup together in one part of the beaker after they have reached equilibrium?**
3. **How might the dye become concentrated again?**
4. **How might changing the temperature of the liquid change the rate at which the phenomenon happens?**



Liquid in bottle at high pressure

Bubbles appear when the pressure is released

**Figure 6.4** Carbonated drink, also known as soft drink or soda drinks. The system in the bottle contains carbon dioxide in two forms, $CO_2(aq)$ and $CO_2(g)$



**Figure 6.5** Shape sorting toys require the shapes to be inserted into the corresponding hole at the correct angle

## DISCUSS: Orientation

To play this game successfully, the shapes need to pass through the correct hole. How would the chance of success change if ...

1. ... there were more shapes available to pick up?
2. ... the little girl's hands moved at twice her normal speed?
3. ... all the holes and the shapes were of the same type?
4. What does the model suggest about spatial conditions required for chemical change?

## DISCUSS: Bubbles in a soft drink

1. Why does soda only begin to fizz when the bottle is opened?
2. What prevented the bubbles fizzing from the liquid's surface while the bottle was closed?
3. Why does the liquid go 'flat' in bottles without a cap? Why doesn't it go flat all at once?
4. How can you change the rate the soda loses its bubbles?

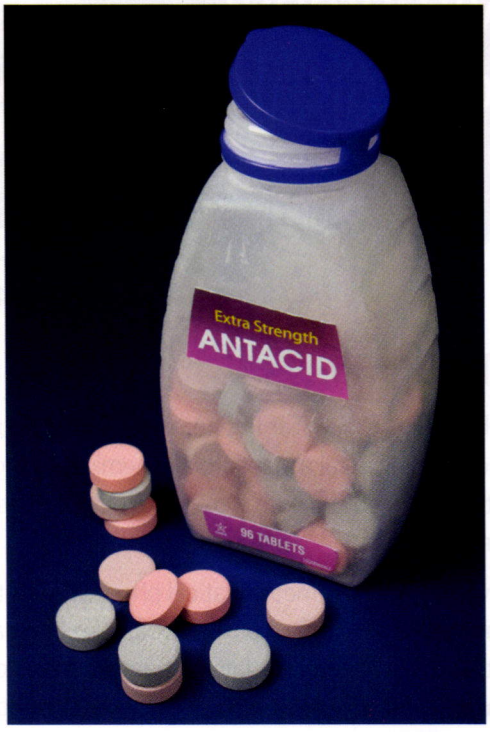



**Figure 6.6** Popular **antacids** come in powdered, tablet and liquid form

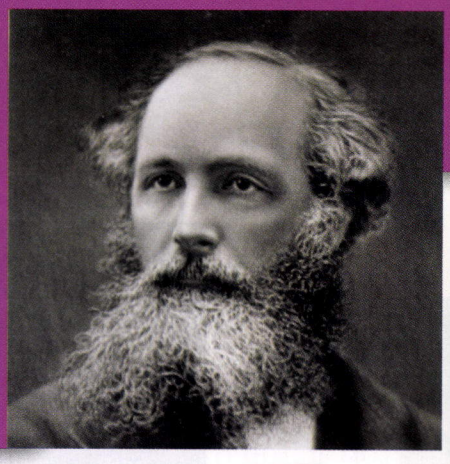
## DISCUSS: Medication

1. Why are 'rapid-acting' versions of remedies for headaches and indigestion usually taken as liquids or solutions?
2. Do all chemical reactions require collisions between particles? What effect does having a smaller particle size of a solid substance have on the relative surface area available for collisions?
3. Are there any advantages of having medication as tablets, powders or liquids?

### Links to: Physical education

Throughout this chapter, it may be helpful to consider analogies between sports and the movement of particles in space. How does the movement of a ball resemble the movement of particles in different states? Can our experience of kinetic energy in sports help us understand the motion of gas molecules of different mass and at different temperatures?

# How do the conditions of the environment affect chemical reactivity?



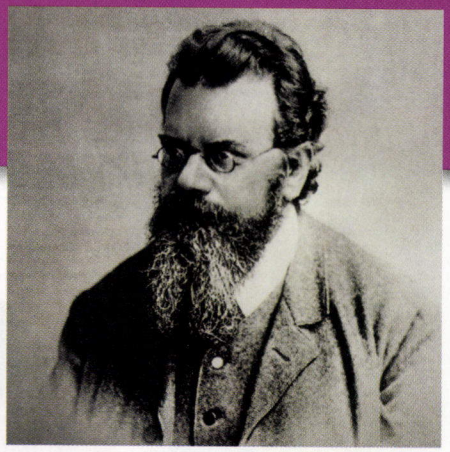


**Figure 6.7** *Left:* James Clerk Maxwell (1831–1879) and *right:* Ludwig Boltzmann (1844–1906)

## KINETIC THEORY

Perhaps your probing of the 'Familiar Phenomena' has helped you recognize that there are physical aspects to all chemical change. Kinetic theory began in the 18th century with Bernoulli's descriptions of gas pressure (Chapter 1).

James Clerk Maxwell, a Scottish mathematical physicist, was the first person to describe the distribution of particle velocities in a gas. An Austrian physicist, Ludwig Boltzmann, later expanded these ideas. The **Maxwell–Boltzmann distribution curve** (Figure 6.8) recognizes that the **kinetic energies** of individual particles in an 'ideal' gas are not all the same, but are grouped closely around an average. The average kinetic energy of the molecules in the 'ideal' gas represents the temperature.

Although details of the shape of the curve change with temperature, its shape has consequences for changes of state and for chemical reactions, including those involving catalysts (to be discussed further in Chapter 11).

Changes of state involve only the molecules at the interface between the states. For example, when a liquid evaporates, only molecules at the surface which have enough combined kinetic energy are able to escape from the attractive forces that hold them in the liquid. Because these molecules are at the extremes of the distribution, any molecule that changes state affects the average kinetic energy of all the remaining molecules. This observation explains why processes involving evaporation (like perspiring) have a cooling effect, because the loss of particles with higher kinetic energies removes thermal energy (**heat**) from the system and so lowers the average kinetic energy of the sample, which is measured by the temperature. The reverse change of state, condensation, has the opposite effect, adding heat to the system by increasing thermal energy as particles form bonds or intermolecular forces in the liquid state.

## ACTIVITY: Particle motion

### ATL

- Transfer skills: Inquire into different contexts to gain a different perspective

Brainstorm your ideas to identify common explanations relating to the movement and kinetic energy of particles in solids, liquids and gases.

1. **Identify** which of the observations involved changes of state and what happened to the movement and energy of the particles.
2. **Describe** what happened to the 'order' of the particles involved, in each of the changes of state.
3. **Explain** how the phenomena modelled conditions that affected the rates of chemical and physical reactions.

### Assessment opportunities

- In this activity you have practised skills that are assessed using Criterion A: Knowing and understanding.

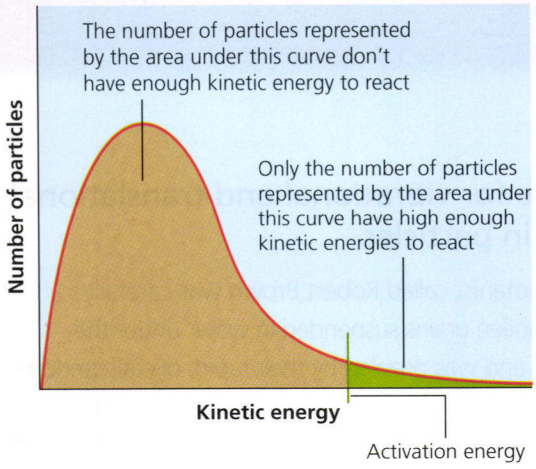



**Figure 6.8** A generic Maxwell–Boltzmann distribution curve describing the distribution of the kinetic energies of particles in a gas. The exact shape of this curve will vary depending on the gas, the mass of the molecules and the temperature it describes

The molecules in the gas state above a liquid exert a **vapour pressure**. Molecules will continue to evaporate from the liquid until the pressure reaches a maximum value for the temperature, called the **saturated vapour pressure**. At this pressure, some molecules will rejoin the liquid state, and others will not be able to evaporate. At equilibrium, the rates at which molecules evaporate from the liquid's surface and others condense back to the liquid's surface will be identical. This explains why liquids do not evaporate from closed bottles, which are **closed systems**. The observation that a soda bottle begins fizzing after its cap is removed can be explained by the sudden decrease in the pressure above the liquid. This low vapour pressure also explains why, water boils at less than 100 °C at high altitudes.

The concept of saturation also applies to molecules of solute dissolving into liquids. It represents the maximum concentration of the solution for the temperature of the conditions. At equilibrium, the solute molecules will be dissolving and precipitating at the same rate. An insoluble salt saturates at a much lower concentration than a soluble one.

The Maxwell–Boltzmann distribution curve also has implications for the chemical reactivity of particles. Chemical reactions can only proceed when the approaching particles have enough kinetic energy. The distribution means that sometimes, not all of the reactant molecules are able to participate in the reaction, and bounce off each other following a collision.

## ACTIVITY: How kinetic theory affects our world

### ATL

- Communication skills: Make inferences and draw conclusions

With reference to Figure 6.8:

1. **Suggest** why washing dries more quickly on
   a. dry days
   b. hot days
   c. windy days.
2. As the temperature of a gas increases, **describe** what will happen to the
   a. average kinetic energy of the particles
   b. pressure exerted by the particles on the walls of a rigid container
   c. volume of a gas in an elastic container, like a balloon.
3. **Describe** the relationship between pressure and volume of a fixed amount of gas at different temperatures.
4. **Describe** what limits the number of evaporated particles (gas) in an enclosed container, for example occupying the 'air' just below the lid in a bottle of soda water.
5. **Explain** why heat needs to be applied continually to keep a liquid boiling.
6. If a chemical reaction could only involve molecules with particular kinetic energies, **suggest** one approach that might change the rate of a reaction.

### Assessment opportunities

- In this activity you have practised skills that are assessed using Criterion A: Knowing and understanding.

## EXTENSION

Explore **kinetic theory** further and find out more about the **Maxwell–Boltzmann distribution curve**.

# To what extent are physical and chemical changes linked?

As you carry out the activities or observe the demonstration reactions, think about the kinetic energy of the particles involved. If the change depends on collisions, reflect on the conditions that might determine whether particles will collide, combine or repel each other.

## Evidence for vibrational and translational motion in particles

In 1827, a botanist called Robert Brown was carefully observing pollen grains suspended in water under the microscope and was puzzled by their rapid, overall random movements. He then measured the same movements in other small particles. Although he could not understand what he saw, he eliminated 'living' as a property that explained his observations. It was nearly 80 years before his observations were recognized as strong evidence for molecular motion.

## ACTIVITY: Brownian motion

### ATL

- Organization skills: Select and use technology effectively and productively
- Transfer skills: Apply skills and knowledge in unfamiliar situations

### Materials and equipment

- **a light transmission microscope, for magnifying 400×.**
- **microscope slides, cover slips, pipettes**
- **at least one of the following suspensions:**
  - **diluted full cream milk**
  - **water colour paint, or**
  - **soot (i.e. diluted Indian ink or smoke particles) dissolved in water.**

If your school owns a smoke cell, you may also be able to observe Brownian motion caused by collisions between the smoke and gas particles in the air.

### Method

1. **Prepare a microscope slide with a small droplet of the solution, covered with a cover slip.**
2. **Further examples may be observed here: https://youtu.be/2Vdjin734gE and https://youtu.be/cDcprgWiQEY**

### Analysis

1. **Suggest strategies for measuring the motion of the suspended particles.**
2. **Evaluate evidence for the relationship between particle size and the movement observed.**

### Reflection and extension

3. **Predict and explain what would happen to the Brownian motion if the suspensions were heated. Perhaps you were able to observe this as the microscope light heated the slide.**
4. **Explain the relationship between observations of Brownian motion and the familiar phenomenon of the rate at which substances like sugar or salt dissolve in water of different temperatures.**
5. **On a sunny day, you may see dust 'dancing' in the air. Is this movement an example of Brownian motion? Explain this observation in terms of particle (kinetic) theory.**

### Assessment opportunities

- In this activity you have practised skills that are assessed using Criterion A: Knowing and understanding.

In a theoretical paper discussing a quantitative model for particle motion, the physicist Albert Einstein calculated that suspended particles in solutions could provide visible evidence of being jostled in collisions with highly energetic water molecules that were too small to be seen. Incredibly, at the time this famous paper was published in 1905, Einstein had apparently been unaware that the phenomenon was familiar to most biologists!

**Brownian motion** can be observed in any suspension of tiny particles.

### Links to: Language and Literature

Read a **translation of Lucretius' poem *The Nature of Things***. What analogies, similes or metaphors does the poem use that might also be used to describe Brownian motion?

## ACTIVITY: When gas molecules collide!

### ATL

- Critical-thinking skills: Practise observing carefully in order to recognize problems; draw reasonable conclusions and generalizations

**Safety:** The following reaction between two corrosive gases needs to be demonstrated by your teacher, in a fume cupboard. Eye protection and gloves must be worn.

### Materials and equipment

- eye protection
- concentrated ammonia solution
- concentrated hydrochloric acid solution
- cotton wool
- large bore (2–3 cm diameter) glass tube
- corks or bungs to fit the glass tube.
- retort stand and clamps
- timer

### Method

1. Put on eye protection.
2. Add a few drops of each solution to plugs of cotton wool.
3. Secure the plugs inside each end of the glass tubing with the corks or bungs. Immediately, start timing until evidence of a chemical reaction is observed.
4. Clamp the tubing in a horizontal position.
5. **Measure** the distance between the reaction product, and the cotton wool at the ends of the tube.

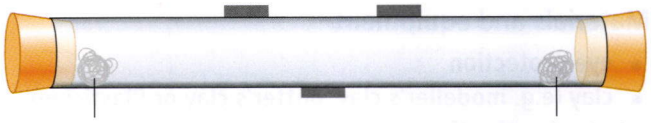



**Figure 6.9** Example of the arrangement for observing the reaction between two gases

### Analysis

1. **List** evidence that the two gases reacted.
2. **Suggest** why the tube was placed horizontally and not vertically.
3. **Identify** where the precipitate, $NH_4Cl(s)$, formed in relation to the ends of the tube.
4. **Formulate** a balanced equation for the reaction between $HCl(g)$ and $NH_3(g)$.
5. **Analyse** how the location of the product can be used to **calculate** the rate of diffusion of each gas, using the formula, distance/time ($m\,s^{-1}$).
6. The formula for calculating the kinetic energy (KE) is $\frac{1}{2}mv^2$, where $m$ is mass and $v$ is velocity. **Suggest** one reason the molecules in different vapours might diffuse at different velocities at the same temperature.
7. **Suggest** why your teacher demonstrated this reaction in a fume hood. Where do the extracted gases go?

### Assessment opportunities

- In this activity you have practised skills that are assessed using Criterion C: Processing and evaluating.

# ACTIVITY: How does temperature affect chemical change?

## ATL

- Critical-thinking skills: Practise observing carefully in order to recognize problems

**Safety:** The following reaction needs to be demonstrated by your teacher, in a fume cupboard, because sulfur can easily ignite. Eye protection and gloves must be worn.

### Materials and equipment

- eye protection
- clay (e.g. modeller's clay, potter's clay or Plasticine)
- powdered sulfur
- powdered iron
- spatulas
- tongs
- a clean, dry tin or other disposable container
- stirring rod
- a coin, with a surrounding barrier of clay
- heat-proof safety mats
- Bunsen burner, tripod, gauze
- matches
- magnet
- (optional) dissecting microscope

### Method

1. Put on eye protection.
2. Roll a barrier of clay and arrange it around the coin. This will act as a mould.
3. In the tin, mix a total volume of about 1 tablespoon of the powdered solids in a ratio of approximately 7 iron : 4 sulfur.
4. Light the Bunsen burner.
5. Heat the mixture, until a reaction is evident.
6. Quickly pour the contents onto the coin.
7. When cooled to a solid, students can handle the result.
8. Test both the cast and the unreacted iron with a magnet.
9. (Optional) If a dissecting microscope is available, observe the surface of the cast. The texture of the reacted product is so fine that it can record details such as scratches on the metal coin.

### Analysis

1. **Describe** the role of the following conditions for this reaction:
   a. the application of heat (thermal energy)
   b. the powder form of the reactants.
2. **Formulate** a balanced equation for the reaction between iron and sulfur to form iron(II) sulfide, FeS (s). **State** why this is an example of a synthesis reaction.

### Reflection and extension

3. In forensic investigations, the product of this reaction is applied to metal surfaces to record evidence. **State** useful physical properties of the reaction product.

## Assessment opportunities

- In this activity you have practised skills that are assessed using Criterion C: Processing and evaluating.

# Why does the total number of particles determine the volume of a gas?

## A CHEMICAL CONUNDRUM

At this stage of our inquiries into matter, nearly all our observations of chemical and physical changes have been **qualitative**, relying on comparisons of similarity or difference. Yet chemistry is a quantitative practice.

A Frenchman, Joseph Gay-Lussac (1778–1850), was a contemporary of the Englishman John Dalton (Chapter 1). At the beginning of the 19th century, both scientists published papers investigating the relationship between gas pressure and volume. Soon afterwards, Gay-Lussac discovered that when two different gases (at the same temperature and pressure) reacted, they did so in small whole-number volume ratios. However, his proposed 'law of combining gases' disagreed with the Dalton's atomic theory, which predicted that the volumes of the gases should simply add up.



■ **Figure 6.10** Count Amedeo Avogadro trained as a lawyer, and his passion for mathematics and physics led him to change careers later in life. Unfortunately, the significance of his ideas was not well understood during his lifetime

Gay-Lussac's experimental evidence showed:

- two volumes of hydrogen gas reacted with one volume of oxygen gas to form two volumes of gaseous water, and
- one volume of nitrogen gas reacted with three volumes of hydrogen gas to form two volumes of gaseous ammonia.

In 1811 Count Amedeo Avogadro (1776–1856) suggested a solution. He proposed gases could exist as molecules, which divided into atoms or combined into new molecules during chemical reactions. He also proposed that volumes of all gases, no matter what their chemical composition, contained the same number of molecules at the same temperature and pressure. Avogadro demonstrated oxygen and hydrogen were diatomic gases, and correctly determined the formulas for many others.

In 1865, an Austrian physicist, Josef Loschmidt (1821–1895) used an estimation of the size of an atom and kinetic theory to estimate the number of molecules in a cubic centimetre of gas under standard conditions. The number of particles in a cubic centimetre of ideal gas is now called Loschmidt's number. Subsequent work by others, including a French physicist, Jean Perrin (winner of the 1926 Nobel Prize in Physics), helped to establish more accurately the relationship between the mass of a substance and that of its individual particles (molecules or atoms).

### Avogadro's constant

**Avogadro's constant** (symbol $L$ or $N_A$), or **$6.02 \times 10^{23}$**, is defined as the number of particles in 12 g of the most commonly occurring type of carbon atoms, with six neutrons. That number, $6.02 \times 10^{23}$ is also known as a **mole**. The symbol for the SI unit representing this quantity is **mol**.

The mole is the quantity used for calculations involving mass, solute concentrations and gas volumes, and represents a fixed number of particles, $6.02 \times 10^{23}$.

- The **molar mass** of a substance at standard temperature and pressure (STP, 273 K and 100 kPa) contains a mole of (or $6.02 \times 10^{23}$ particles of) the substance. The molar mass is calculated using the chemical formula and relative atomic masses in grams of its component elements as shown in the periodic table. Its units are grams per mole, $g\,mol^{-1}$.
- Solute concentration is expressed as a **molarity** (abbreviated M), standardized as moles per cubic decimetre. A one molar concentration (**$1\,mol\,dm^{-3}$**) at Standard Ambient Temperature and Pressure (SATP, 298 K and 100 kPa) represents a solution in which the molar mass of a substance is made up to exactly 1 $dm^3$ (1 litre) of aqueous solution.
- A **molar volume** of an 'ideal' gas at STP is 22.7 $dm^3$. This is a good approximation for most gases. The mole is a measurement of the number of gas molecules, not the number of atoms.

## Example calculations

### Molar mass conversions

**Find** the mass of 0.50 mol cobalt(II) chloride(s).

Solution: formula: $CoCl_2$

molar mass ($g\,mol^{-1}$):

$1 \times 58.9 + 2 \times 35.5 = 129.9\,g\,mol^{-1}$

$0.50\,mol = 129.9\,g\,mol^{-1} \times 0.50\,mol = 65\,g$

How many moles are there in 900 g of iron(III) oxide?

Solution: formula $Fe_2O_3$

molar mass ($g\,mol^{-1}$):

$2 \times 55.8 + 3 \times 16 = 159.6\,g\,mol^{-1}$

$900\,g/159.6\,g\,mol^{-1} = 5.64\,mol\ Fe_2O_3$

### Molar volume conversions

**Determine** the volume of 0.800 mol $SO_2$(g) at STP

Solution: Assume the gas is 'ideal'

The volume of 1 mole of gas = $22.7\,dm^3$

$0.800\,mol \times 22.7\,dm^3\,mol^{-1} = 18.2\,dm^3$

Given the density of a particular gas is $1.25\,g\,dm^{-3}$, **calculate** its molar mass, and **suggest** its possible identity.

Solution: molar mass of the gas:

$m_{(gas)} = density_{(gas)} \times$ molar gas volume

$m_{(gas)} = 1.25\,g\,dm^{-3} \times 22.7\,dm^3\,mol^{-1} = 28.4\,g\,mol^{-1}$

The gas could be $N_2$ (2 × 14 g).

## Relative velocities of oxygen and hydrogen molecules

The average kinetic energy of all gas particles is equal at any temperature. Therefore, the kinetic energy ($KE_{H_2}$) of hydrogen gas molecules must on average be equal to the kinetic energy of oxygen molecules ($KE_{O_2}$) at any temperature: $KE_{H_2} = KE_{O_2}$

$$\tfrac{1}{2}m_{H_2}(v_{H_2})^2 = \tfrac{1}{2}m_{O_2}(v_{O_2})^2$$

$$\frac{(v_{O_2})^2}{(v_{H_2})^2} = \frac{m_{H_2}}{m_{O_2}} = \frac{2}{32} = \frac{1}{16}$$

Solving for the square root of $v_{H_2}$, this means that on average, the velocity of hydrogen gas molecules must be four times as fast as the velocity of oxygen molecules, in a gas of the same temperature.

## ACTIVITY: The mole concept

### ATL

- Transfer skills: Use effective learning strategies in subject groups and disciplines; apply skills and knowledge in unfamiliar situations

1. **Calculate**, with reference to the periodic table, the molar masses of carbon (C), table salt, sodium chloride (NaCl), sand (silicon dioxide, $SiO_2$), and sugar (sucrose, $C_{12}H_{22}O_{11}$).

   Weigh a mole of each of these familiar substances. Note the differences between the masses and the volumes.

   Use a 1 litre volumetric flask to make up a 1.0 M solution of one of the two soluble substances.
2. **Calculate**, assuming that the gases in air are 'ideal'
   a. the amount (in moles) of gas in a cardboard box 1.0 m × 0.6 m × 2.0 m
   b. the amount (in moles) of gas in your classroom.
3. **Comment** on the relative kinetic energies of HCl(g) and $NH_3$(g) in the demonstration of their diffusion through air inside a glass tube.
4. **Suggest** why the standard conditions for determining a molar solution are SATP and not STP.
5. An 'ideal' gas is a theoretical concept consisting of point particles (which have mass but no volume) which interact perfectly elastically. **Suggest** how intermolecular forces (see Chapter 4) between gas molecules may cause an actual gas to depart from this model.

### Assessment opportunities

- In this activity you have practised skills that are assessed using Criterion A: Knowing and understanding.

## EXTENSION

**International Mole Day.** Suggest how you could celebrate Avogadro's number at your school on October 23 from 6.02 a.m. to 6.02 p.m.

Gas pressure is caused by the collisions of molecules with the sides of their container. If two different gases have the same temperature, the average kinetic energies of their molecules must be identical. As $KE = \tfrac{1}{2}mv^2$, this means that at the same temperature, particles of gas which have less mass will move at greater speeds.

## Estimation and measurement: vital skills for quantitative chemists

Estimation is a life skill. We transfer our numeracy skills constantly to anticipate our savings potential, predict travel times or identify value for money when shopping. Estimation uses rough calculations based on rounded numbers, to provide approximate figures to guide our decisions.

In chemistry, we use estimation to understand scale, duration, frequency and the variability of reactions. With experience, all chemists develop familiarity with relevant constants and are able to make realistic predictions about reaction products and uncertainties. Estimation is also a consideration for planning how data should be measured in practical investigations.

Measurement should be appropriate to the context. **Evaluate** the suitability of a measurement by considering the following three aspects.

- **Scale** is about considering the level of detail needed, but also restricts the type, quantity and quality of data. For example, would you measure the distance across the school sporting ground in mm? Enlarging a small-scale map or adding significant figures to the results of a calculation does not increase its level of accuracy or detail.
- **Precision** refers to the closeness of agreement between independent measurements. Replicate (repeat, duplicate) measurements provide evidence for precision by the level of agreement between results (see Chapter 1). Highly precise data can be very difficult, time consuming and (in a commercial environment) costly to collect.
- **Accuracy** refers to the closeness of agreement between a test result and its accepted value. The level of accuracy required for particular applications varies greatly. As an example, consider the difference between preparing mixtures of ingredients for 'sherbet' and weighing magnesium ribbon to calculate molar ratios. Highly accurate data can also be difficult and costly to produce and compile.

## ACTIVITY: How important is quality assurance in 'everyday' chemistry?

### ATL

- Media literacy skills: Understand the impact of media representations and modes of presentation; seek a range of perspectives from multiple and varied sources

Imagine suffering from a minor illness. You remember seeing an advisement about a medication that might help. Your pharmacist suggests an 'anti-acid' medication. Faced with a range of tablets, powdered and liquid medications, you notice that all contain chemical ingredients that counter stomach acid, and some also claim to 'fizz' when mixed with water. How will you select a product? Would you consider the image (marketing), sensual effects or evaluate the dosage?

In a formal essay of 700–1200 words, reflect on the importance of quantitative analytical chemistry for the quality assurance of a consumer product, and aspects of the substance that are intended to provide the product with a commercial advantage. You could consider any product, including cleaning agents, insecticides, cosmetics, fertilizers or fuels. Before refining your research, check with your teacher whether the chemical (or category of product) that you have chosen enables you to meet the requirements of this task.

**Explain** the problem or issue the product solves, and scientific details such as the quantities recommended for use, a description of how kinetic theory is involved in the product's reactivity, and details of chemical equation(s) involved.

Science does not work in isolation. Moral, ethical, social, economic, political, cultural or environmental considerations affect research, applications and choices available to citizens. **Discuss** how one of these factors interacts with your chosen product.

Be sure to use scientific terminology accurately and **document** all your sources using a recognized referencing and citation standard.

### Assessment opportunities

- This activity can be assessed using Criterion D: Reflecting on the impacts of science.

# How is the quantity of a substance measured consistently during change?

## QUANTITATIVE CHEMISTRY

The following examples of chemical reactions all require accurate, precise measurements to enable you to apply your skills in analytical quantitative chemistry to practical contexts when you analyse the results.

### The decomposition of water by electrolysis

Pure water is a poor conductor, consisting mostly of covalent molecules and a very small number of ions due to the self-ionization of water:

$$H_2O(l) \rightarrow H^+(aq) + OH^-(aq)$$

However, adding a little sulfuric acid significantly increases the number of ions in solution. The sulfuric acid ionizes to release hydrogen ions and sulfate ions:

$H_2SO_4(aq) \rightarrow 2H^+(aq) + SO_4^{2-}(aq)$, increasing the total number of charged particles in the solution. During electrolysis, these ions will migrate to the oppositely charged electrode.

At the anode (the positive electrode), water molecules are preferentially oxidized because sulfate ions (the predominant anion in solution) are very stable, so do not oxidize as readily. In this reaction, water molecules decompose to molecules of oxygen gas and hydrogen ions, giving up electrons ($e^-$) to the anode:

$$2H_2O(l) \rightarrow O_2(g) + 4H^+(aq) + 4e^-$$

At the cathode (the negative electrode), water molecules are reduced to molecules of hydrogen gas and hydroxide ions:

$$4e^- + 4H_2O(l) \rightarrow 2H_2(g) + 4OH^-(aq)$$

Notice each of these '**half-equations**' used to describe parts of the reaction at the electrodes involves the same number of electrons. The reactants and the products can be grouped and common ions can be cancelled to derive a balanced equation for the overall reaction.

## ACTIVITY: The electrolysis of water into component gases

**ATL**

- Critical-thinking skills: Practise observing carefully in order to recognize problems; interpret data

### Materials and equipment

- **Hofmann voltameter**
- **small amount of 0.1 M sulfuric acid**
- **DC power supply (10 V)**
- **phenolphthalein (optional)**
- **plastic aquarium tubing**
- **dishwashing detergent**
- **matches**

### Method

1. **Add a small amount of sulfuric acid to improve the conductivity of water, which is normally a poor conductor.**
2. **Add a few drops of phenolphthalein.**
3. **Connect the power supply as shown in Figure 6.11.**
4. **(Optional demonstration) Use the aquarium tubing to bubble the gases produced gently through a solution of dishwashing detergent in a beaker.**
5. **Use a match to ignite the bubbles to observe a synthesis reaction.**

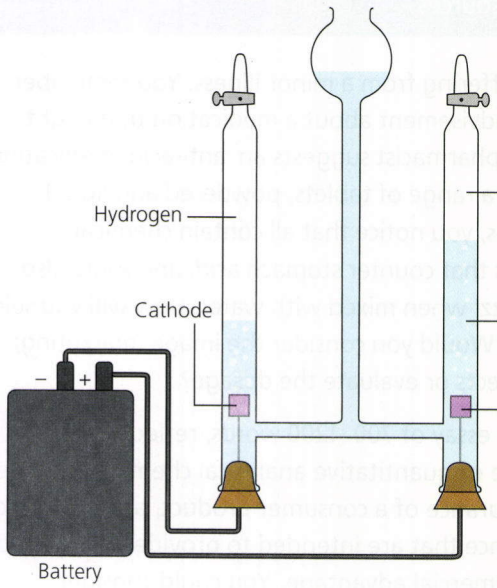



**Figure 6.11** The electrolysis of water in a Hofmann voltameter

## Analysis

1 **State** evidence that water has been decomposed. **State** evidence that excess hydroxide ions, $OH^-$, are produced at one of the electrodes. **Formulate** a balanced equation for the overall reaction.
2 **Compare** this overall equation with the chemical equation obtained when the reactants of both half-equations are grouped, the products of the two half-reactions are grouped, and the common ions cancelled out.
3 **Define** the reactions occurring at the anode and the cathode as oxidation and reduction reactions.
4 **Calculate** the volume of hydrogen gas, measured at standard temperature and pressure, produced at the cathode in the electrolysis of acidified water by 18 moles of electrons.
5 As the concentration of hydrogen ions and hydroxide ions builds up at their electrodes, they will diffuse away from these sources. **Suggest** what happens to them. **Identify** the location where this is likely to occur.
6 **Comment** on the sizes of the gas bubbles produced at each electrode, and suggest a reason for the difference in size.
7 **Estimate** the predicted ratio of the volumes of the two gases produced.
8 **Measure** the volumes and **calculate** the number of moles of the gases produced.
9 **Suggest** scientifically supported reasons for only *approximately* twice as much hydrogen gas being produced at the cathode as oxygen gas at the anode in the electrolysis of water.
10 John Dalton, a contemporary of Avogadro, believed the formula for water was OH. **State** whether the results of your experiment support or refute Dalton's 'rule of greatest simplicity'.
11 **Suggest** examples of other compounds that could have been added, to increase the conductivity of water in this reaction.
12 A **fuel cell** (Chapter 10) is a device that converts the chemical energy from a fuel, for example oxygen and hydrogen gases, into electricity. In a hydrogen fuel cell,
   - at the anode, hydrogen gas loses electrons to form hydrogen ions. The hydrogen ions diffuse towards the cathode through a polymer-based membrane called a proton exchange membrane
   - at the cathode, hydrogen ions accept electrons, and react with oxygen to form water.

   a **Formulate** half-equations for the two reactions.
   b **Suggest** why the synthesis of water in a fuel cell from the hydrogen and oxygen gases results in an electric current.

### Assessment opportunities

- This activity can be assessed using Criterion A: Knowing and understanding.

## ACTIVITY: Determine the empirical formula for solid iron(II) oxide

### ATL

- Critical-thinking skills: Practise observing carefully in order to recognize problems; interpret data

**Safety:** Wear safety goggles. Take great care when handling hot objects. Allow hot objects to cool before placing them on a balance.

### Materials and equipment

- eye protection
- 2 g very fine steel wool
- porcelain evaporating dish
- heat mat
- tongs
- electronic balance (sensitive to 0.01 g)
- DC power source (6 V recommended), leads

### Method

1. Put on eye protection.
2. Weigh the evaporating dish.
3. Tease out the iron wool and reweigh the evaporating dish with the iron wool.
4. Ignite the iron wool by briefly touching it on opposite sides with the leads, attached to the power source.
5. When the reaction ceases, reweigh the crucible and contents to determine the mass of the reaction product.

### Analysis

1. **Suggest** why electrical energy was needed to start this reaction, and why the wool needed to be teased out.
2. As the product began to form, heat and light were generated. **Suggest** where this energy comes from.
3. **Calculate** the number of moles of iron atoms, Fe(s) used in the reaction and predict the mass of iron(II) oxide, FeO(s) that was produced.
4. Weigh the iron(II) oxide FeO(s) produced and **explain** any anomalies compared to the calculation.

**Hint**

Is FeO(s) the only possible product? **Calculate** the percentage increase predicted if the oxide produced was purely FeO, $Fe_2O_3$ or $Fe_3O_4$.

5. **Suggest** the location where the reaction/s occur/s and how the method could be improved.
6. Iron(II) oxide is an ionic compound. You may recall that iron is in group 8 and oxygen is in group 16 of the periodic table.
   - a **Formulate** half-equations to show:
     - i oxidation of two iron atoms to two iron(II) ions
     - ii reduction of an oxygen gas molecule to two oxide ions.
   - b **Describe** the relationship between the valency of the ions and their location in the periodic table. Why do you think valency is also sometimes called '**oxidation state**'?
   - c **Compare** a balanced equation for the reaction, and the two, combined half-equations.

### Assessment opportunities

- In this activity you have practised skills that are assessed using Criterion C: Processing and evaluating.

# TITRATION – MAKING NEUTRALIZATION VISIBLE

Imagine you had HCl with a concentration of exactly 0.10 M. If 0.023 $dm^3$ of a sodium hydroxide solution, NaOH(aq), could exactly neutralize 0.040 $dm^3$ of the HCl solution, what is the concentration of the NaOH(aq)?

Solution: The reaction between the acid and the base is:

$$HCl(aq) + NaOH(aq) \rightarrow NaCl(aq) + H_2O(l)$$

Therefore, one hydroxide ion, $OH^-$, is required to neutralize each hydrogen ion, $H^+$.

How many moles of HCl are present in 0.040 $dm^3$ of 0.10 M HCl? Solution:

$$0.040\,dm^3 \times 0.10\,mol\,dm^{-3} = 4.0 \times 10^{-3}\,moles.$$

Therefore, 0.023 $dm^3$ of the NaOH(aq) contains $4.0 \times 10^{-3}$ mol NaOH.

The concentration of the NaOH(aq) must be $0.040/0.023 \times 0.1 = 0.17\,mol\,dm^{-3}$.

The advantage of using a burette in an acid–base titration is that you can measure and control the rate the unknown solution is added to the substance being neutralized. The 'end point' of the **titration** occurs when the indicator just shows a permanent change of colour.



**Figure 6.12** Make sure you read the meniscus of the burette carefully during titrations

## ACTIVITY: Titration

### ATL

- Organization skills: Select and use technology effectively and productively

In this activity, you will 'standardize an acid' by reacting hydrochloric acid solution with a weak base.

### Materials and equipment

- burette, 25.0 $cm^3$ pipette, pipette filler
- 0.10 M HCl solution (approximate concentration)
- standardized 0.10 M $Na_2CO_3$
- 0.25 $dm^3$ conical flasks
- phenolphthalein indicator

### Method

1. Rinse the burette with water (if you need to practise controlling the tap).
2. Rinse the burette with the standard 0.1 M $Na_2CO_3$ solution, and then discard it.
3. Refill the burette with the standard 0.1 M $Na_2CO_3$ solution.
4. **Measure** exactly 0.025 $dm^3$ of 0.1 M HCl into the conical flask.
5. Add a drop of indicator.

Rough standardization

1. The purpose of this step is to provide guidance for the location of the '**end point**' of the reaction.
2. Carefully add the $Na_2CO_3$ solution in 1 $cm^3$ amounts, swirling the liquid in the flask after each addition. Note the volume of $Na_2CO_3$ solution used at the time the indicator changes.

Fine standardization

3. Prepare a fresh sample of 0.025 $dm^3$ of 0.1 M HCl and indicator.
4. Carefully add the $Na_2CO_3$ solution to within 2 $cm^3$ of the end point. Now reduce the rate of additions to a drop at a time, to find the exact end point.
5. Repeat this process at least three times.

### Analysis

1. Suggest why you
   - a rinsed the burette with the carbonate solution before starting the first titration
   - b carried out a rough standardization
   - c performed the titration four times.
2. **Formulate** a balanced equation for the reaction between hydrochloric acid and sodium carbonate solutions.
3. **State** the ratio of moles of hydrogen ions ($H^+$) to carbonate ions ($CO_3^{2-}$).
4. **Calculate** the amount in moles, on average, of sodium carbonate, $Na_2CO_3$(aq), titrated. How certain are you of this value?
5. **Calculate** the concentration of the acid solution in mol $dm^{-3}$ and g $dm^{-3}$.
6. **Identify** examples where your measurement could have affected the accuracy of the result.

### Reflection and extension

1. **Suggest** how you might adapt this technique for the following situations:
   - a to standardize a base
   - b to determine the acidity of
     - i vinegar
     - ii carbonated drinks
     - iii acids in orange juice.
2. Titration can be used in precipitation reactions. **Suggest** how you could determine the end point.
3. Titration can be used in redox reactions. **Suggest** how you could determine the end point.

### Assessment opportunities

- In this activity you have practised skills that are assessed Criterion A: Knowing and understanding.

# To what extent are physical and chemical changes linked?

## WHY SHOULD A REACTION HAPPEN AT ALL?

All the reactions you have observed in this chapter, both physical and chemical, were spontaneous processes, and some became fast enough to be noticeable after the reactants were heated or dissolved in water.

The kinetic theory of particle collisions is one explanation for these changes. Heating helped chemical reactions by increasing the average kinetic energy of the particles, increasing the probability, and therefore the frequency, of collisions that would result in a chemical change. The change in the type of motion of particles is part of the explanation for the temperature plateaux seen during state changes (Chapter 1), when the average kinetic energies of these particles remained constant.

Whenever new compounds form, there will always be energy differences between bonds of the reactants and the products, causing differences between the temperature of the substances involved and their surroundings. The intrinsic potential energy within the bonds and intermolecular forces of chemical substances is called **enthalpy**, and changes in this form of energy are used to define **exothermic** and **endothermic** reactions (Figure 6.13). Spontaneous exothermic reactions release energy, for example light, heat or sound, and spontaneous endothermic reactions result in products that feel cold compared to their surroundings.

Enthalpy changes may apply also to bond changes caused as a result of changes in phase, where there is a change from one homogeneous system to another but no chemical reaction. For example, when 1 mole of NaCl(s) dissolves in excess water, a very small amount of heat is released because the sodium and chloride ions dissociate from their ionic lattice and ion-dipole forces form new interactions

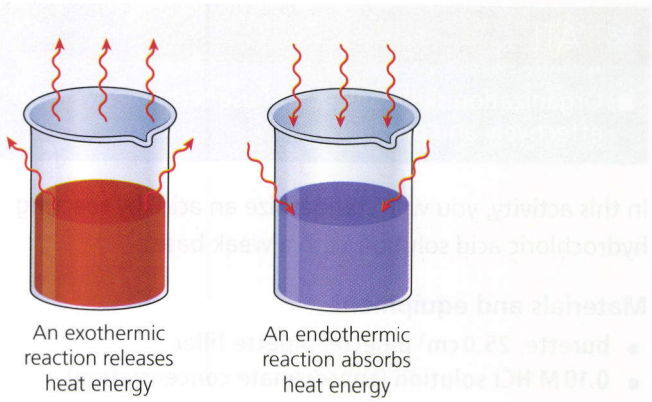



**Figure 6.13** A simple definition of exothermic and endothermic reactions

with water molecules. The overall energy or enthalpy change ($\Delta H$) is called the enthalpy of solution and is very small, with only 3.9 kJ mol$^{-1}$ released. In a chemical equation, this value is given a negative sign to indicate the reaction is exothermic, because heat has been removed from the system. In this example:

(aq) + NaCl(s) → NaCl(aq); $\Delta H$ = –ve

Physical changes that do not involve changes in enthalpy can also be spontaneous. The diffusion of dye through liquid, even without stirring (Figure 6.3) is an example, as is mixing of two gases (that do not react with each other) by diffusion. Although no energy change accompanied the change, when the dye particles mixed through the water they became more disorderly, and a property called **entropy** increases. The spontaneous melting of an ice cube in a glass of water as it absorbs heat from its surroundings is another example of a positive **entropy change ($\Delta S$)**, or one in which a system becomes more disordered.

The combined effects of changes in enthalpy and entropy on the spontaneity of a chemical reaction will be explored in more detail in Chapter 10.

## THINK–PAIR–SHARE

### ATL

- Critical thinking skills: Evaluate evidence and arguments

1. **Identify** whether the change in entropy is positive or negative, in these situations:
   a. when a solid precipitates or crystallizes from a solution
   b. when a room becomes untidy.
2. **Discuss** whether decreases in entropy can ever be reversed spontaneously, without the input of energy.
3. **State**, based on the evidence provided, whether the following reactions are *endothermic* or *exothermic*:
   a. a burning candle producing light and heat
   b. the cooling effect in the reaction between vinegar (ethanoic acid) and sodium carbonate
   c. the loud implosion as the result of the reaction between hydrogen and oxygen gases to produce water
   d. the electrolysis of water to produce hydrogen and oxygen gases.
4. **Synthesize** your ideas by completing the table below, by stating the sign (positive or negative) of changes in enthalpy and entropy. Assume the changes of state are happening in a closed system at constant temperature.

| | State change at constant temperature | Change in enthalpy ($\Delta H$) | Change in entropy ($\Delta S$) |
|---|---|---|---|
| a | Ice melts to water | Positive | Positive |
| b | Water boils to steam | | |
| c | Water freezes to ice | Negative | |
| d | Steam condenses to water | | |
| e | Sublimation of iodine $I_2(s) \rightarrow I_2(g)$ | | |

### Assessment opportunities

- In this activity you have practised skills that are assessed using Criterion A: Knowing and understanding.

## ACTIVITY: Observing endothermic and exothermic reactions

### ATL

- Organization skills: Select and use technology effectively and productively

**Safety:** Wear safety goggles.

### Materials and equipment

- 10 g solid citric acid and 10 g sodium hydrogencarbonate, and water
- 10 $cm^3$ vinegar (ethanoic acid) with 10 g calcium carbonate
- 2–3 g zinc(s) and 10 $cm^3$ of 0.2 M HCl
- 2 cm magnesium ribbon and 10 $cm^3$ of vinegar (ethanoic acid)
- 10 $cm^3$ of 0.2 M HCl and 0.2 M NaOH
- test tubes or Styrofoam cups
- a way of measuring temperature changes, perhaps using a thermometer or temperature probe

### Method

1. Assume the solid materials are at room temperature, and **measure** the temperature of the liquids, drying the thermometer or probe after rinsing with water.
2. Mix the pairs of substances together, and **measure** changes in temperature.

### Analysing results

1. **Formulate** balanced equations for the chemical reactions.
2. **Identify** whether the reaction is exothermic or endothermic using the format in which changes in enthalpy are shown as $\Delta H$.

### Assessment opportunities

- In this activity you have practised skills that are assessed with Criterion C: Processing and evaluating.

# How are changes of state affected by the conditions of the environment?

## ! Take Action: Explosive fizz!

### ATL

- Organization skills: Set goals that are challenging and realistic; use appropriate strategies for organizing information; select and use technology effectively and productively
- Critical-thinking skills: Practise observing carefully in order to recognize problems

**Safety:** This reaction is not dangerous, but it is very messy. Attempt it only in an area that can be cleaned easily, for example by hosing.

! The effect of adding a Mentos® (a brand of peppermint sweet) or an alternative such as powdered sugar to a carbonated drink is a physical change. The rough surface of the added substance provides 'nucleation' sites where the dissolved carbon dioxide gas begins to accumulate and quickly forms bubbles of gas. Both soft drinks and sweets come in many forms; for example, 'diet' versions of soft drinks usually contain phenylalanine (aspartame) or potassium benzoate, as well as other additives such as caffeine and flavourings. Sweets come in a range of textures. Finally, the effects of adding other substances or environmental conditions might be considered. The range of possible variables provides ample scope for you to design an open-ended experimental investigation and evaluate your results!

! In this activity, you will investigate how gas formed in a reaction can be used to make an exciting display for younger chemists.

### Planning, recording and evaluating

! Once again, you may want to review the investigation inquiry cycle introduced in Chapter 1 (Figure 1.11).

! When developing your hypothesis, be sure to include an explanation based on scientific reasoning, for example by discussing the intermolecular interactions (refer to Chapter 4).

! To reduce costs, you may want to develop a method that does not require a full bottle of soda for each replicate trial. The Risk Management checklist (see Chapter 5) may be helpful, and could be appended to your report.



**Figure 6.14** A dramatic coloured line of 'soda fountains' with added fluorescent dyes and illuminated with UV (365 nm) radiation. In each case two Mentos® were added to the bottle of carbonated drink via an optional Geyser Tube

! **Explain** your results with reference to the **collision theory** of particle motion and physical changes in bonding and intermolecular forces caused by the variables, and include an evaluation of your hypothesis and method.

! Suggest how your investigation could be used in an educational campaign to interest younger chemists. Why not try it out by demonstrating your geysers to a younger science class?

### ◆ Assessment opportunities

◆ This activity can be assessed with Criterion B: Inquiring and designing and Criterion C: Processing and evaluating.

# SOME SUMMATIVE PROBLEMS TO TRY

Use these problems to apply and extend your learning in this chapter. The problems are designed so that you can evaluate your learning at different levels of achievement in Criterion A: Knowing and understanding.

A copy of a periodic table should be available for reference.

## THESE PROBLEMS CAN BE USED TO EVALUATE YOUR LEARNING IN CRITERION A TO LEVEL 1–2

1 **State** in your own words what these terms mean:
   - **a** diffusion
   - **b** exothermic
   - **c** endothermic
   - **d** enthalpy
   - **e** entropy

2 **Identify** each of the reactions below as synthesis, decomposition, neutralization or double displacement:
   - **a** $2Mg(s) + O_2(g) \rightarrow 2MgO(s)$
   - **b** $2H_2(g) + O_2(g) \rightarrow 2H_2O(l)$
   - **c** $2H_2O(l) \rightarrow 2H_2(g) + O_2(g)$
   - **d** $2HCl(aq) + Na_2CO_3(aq) \rightarrow 2NaCl(aq) + H_2O(l) + CO_2(g)$
   - **e** $HCl(g)$ and $NH_3(g) \rightarrow NH_4Cl(s)$
   - **f** $AgNO_3(aq) + HCl(aq) \rightarrow HNO_3(aq) + AgCl(s)$

3 **Interpret** each of the examples below and use collision theory to make a judgment about the causes.
   - **a** It is difficult to light coal, but coal dust in mines can cause explosions. Similarly, although all foods burn, in sweet factories that use corn flour, special precautions have to be taken to filter the fine powder from the air as it is a fire hazard.
   - **b** A biology student prepared a 'wet mount' with a suspension of fine grey dust collected from a vacuum cleaner. At very high magnification, she saw small specks jerking about.

## THESE PROBLEMS CAN BE USED TO EVALUATE YOUR LEARNING IN CRITERION A TO LEVEL 3–4

4 **Outline**
   - **a** in gas particles, the qualitative relationship between the
     - **i** average kinetic energy and the temperature
     - **ii** pressure and volume, at constant temperature
   - **b** how the electrolysis of acidified water can provide experimental evidence for the empirical formula of water.

5 In a reaction similar to that in which you oxidized iron, magnesium metal was reacted with a number of other elements. Refer to the periodic table to work out their empirical formulas.

| Compound | Mass of magnesium/g | Mass of other element/g | Calculations and empirical formula |
|---|---|---|---|
| magnesium chloride | 5.34 | 15.78 | |
| magnesium bromide | 3.43 | 22.86 | |
| magnesium nitride | 12.69 | 4.95 | |
| magnesium sulfide | 1.60 | 2.14 | |
| magnesium iodide | 1.14 | 12.09 | |

6 In 1799 a French chemist, Joseph Louis Proust described what is now known as the Law of constant composition:

'... a compound is a privileged product to which nature has assigned a fixed composition. ... Between pole and pole compounds are identical in composition. Their appearance may vary according to their mode of aggregation but their properties never. No differences have yet been observed between oxides of iron from the South and those from the North; the cinnabar of Japan has the same composition as the cinnabar from Spain; silver chloride is identically the same whether obtained from Peru or from Siberia; in all the world there is but one sodium chloride; one saltpetre [now known as sodium nitrate]; one calcium sulfate, and one barium sulfate. Analysis confirms these facts at every step.'

**Interpret** the information to judge whether the results of analyses of sodium chloride and sodium fluoride samples below support Proust's claim that elements chemically combine in constant proportions by mass.

| Element, mass | Sodium, g | Chlorine, g | Fluorine, g |
|---|---|---|---|
| NaCl (sample 1) | 0.55 | 0.85 | |
| NaCl (sample 2) | 1.38 | 2.14 | |
| NaF (sample 1) | 0.55 | | 0.46 |
| NaF (sample 2) | 1.61 | | 1.35 |

## THESE PROBLEMS CAN BE USED TO EVALUATE YOUR LEARNING IN CRITERION A TO LEVEL 5–6

7 **Describe**

a the differences between translational, rotational and vibrational motion, and how each type of motion relates to particles in solids, liquids and gases

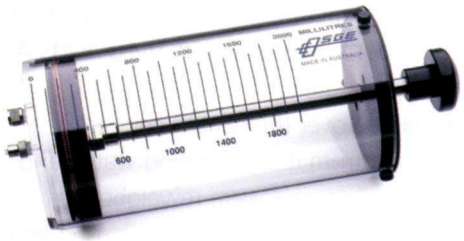
b the three states matter in order, from the state which has the least to the state which has the greatest entropy.

8 Consider a cube with a side length of 3 nm ($3 \times 10^{-9}$ m). If this cube is occupied by a solid, it can contain exactly 3000 molecules.

**Estimate**, from the numbers provided, how many molecules would occupy the same volume in the situations described in the table, describing the reasoning for your answer.

Suggested numbers of molecules: 1, 3, 10, 30, 100, 280, 320, 1000, 2800, 3200

| | | Number of molecules | Reasoning |
|---|---|---|---|
| a | The cube was heated until it melted | | |
| b | The cube was heated further, until it became a gas contained at normal atmospheric pressure | | |
| c | The cube was heated further, until it became a gas contained at 10 times atmospheric pressure | | |



■ **Figure 6.15** A special syringe for studying large volumes of gas

**9** The equipment in Figure 6.15 is a special kind of syringe that is used to investigate gases.

- **a** **Explain** what would happen to the pressure of the gas, relative to air pressure in each of these situations:
  - **i** The plunger is drawn up, collecting air from the room. The opening is left unsealed.
  - **ii** The opening is sealed, and the cylinder is heated up.
  - **iii** The opening is sealed, but now the plunger is pushed down from 2000 $cm^3$ to the 1000 $cm^3$ position (2000 $cm^3$ = 2.0 $dm^3$).
- **b** **Explain** what would happen to the gas in the following situation (assume the equipment does not break).

  The syringe is opened, 1000 $cm^3$ of air collected, the opening is lowered into a bucket and 1000 $cm^3$ of water is collected.

  The syringe is sealed, and the plunger pushed down as far as it can go.
- **c** **Calculate** the amount of gas in moles contained in the syringe in each of these circumstances:
  - **i** 1.0 $dm^3$ of $O_2(g)$
  - **ii** 0.8 $dm^3$ of $N_2(g)$ and 0.2 $dm^3$ of $O_2(g)$
  - **iii** 2.95 g of $CO_2(g)$.

**10** The stomach contains gastric juice, which contains hydrochloric acid with a pH between 1 and 2. A normal person has about 1 $dm^3$ of 0.10 mol $dm^{-3}$ hydrochloric acid in the stomach. Acid indigestion is caused by excess hydrochloric acid and can be relieved by taking antacid tablets.

Details of two brands of antacid tablets are shown below.

| **Brand A** | **Brand B** |
|---|---|
| Sodium hydrogencarbonate ($NaHCO_3$) | Magnesium hydroxide ($Mg(OH)_2$) |
| 250 mg | 250 mg |
| Each pack contains 10 tablets | Each packet contains 10 tablets |
| Price: $2.40 | Price: $5.20 |

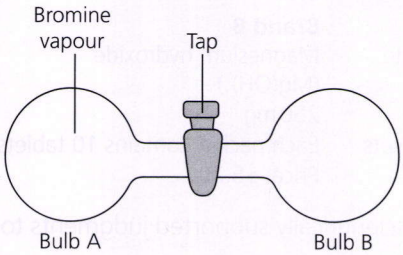
**Analyse** and make scientifically supported judgments to **identify**

- **a** which of these antacid tablets would be most effective for relieving acid indigestion
- **b** which brand is 'better value for money'
- **c** why strong bases, such as potassium hydroxide, are not used as antacids.

**THESE PROBLEMS CAN BE USED TO EVALUATE YOUR LEARNING IN CRITERION A TO LEVEL 7–8**

**11** Use kinetic theory to **explain** why

- **a** liquids cool when they evaporate
- **b** some chemical reactions need to have their reactants heated before they can begin
- **c** the rate of a reaction increases when the solid reagents have been ground up finely
- **d** the cells of active living organisms contain a high percentage of water
- **e** when two gases are brought together, they mix more quickly than two liquids
- **f** gas molecules with low mass move at greater average velocities than molecules with high mass, at the same temperature.




■ **Figure 6.16** Equipment for investigating the mixing of gases

**12** The apparatus shown in Figure 6.16 was used to investigate the diffusion of bromine.

In the first experiment, bulb B was filled with air and when the tap was opened the bromine molecules slowly diffused to fill both bulbs.

In the second experiment, the air was pumped out of bulb B and this time when the tap was opened, the bromine molecules diffused at a very rapid speed.

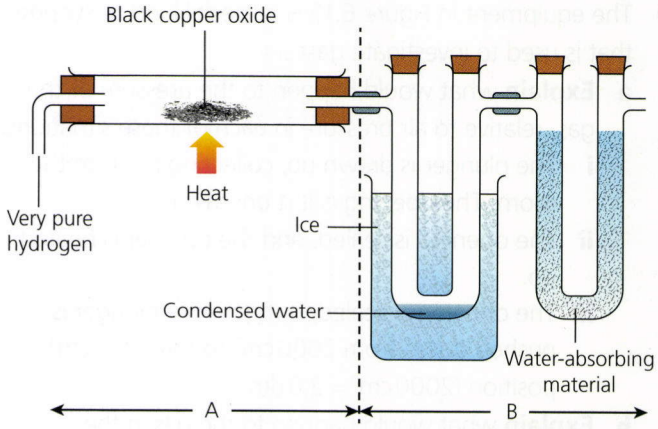
**a** **Explain** the difference in the results using the particle or kinetic theory of matter.

**b** **Predict** and **explain** the results if bulb B was filled with air and the bromine gas was replaced with fluorine gas maintained at the same temperature. Your answer should refer to the relative molecular masses of $Br_2$ and $F_2$ molecules.

**13** In 1842 Dumas used the apparatus shown in Figure 6.17 to determine the composition of water by mass. Parts A and B were weighed separately.

Hydrogen was passed over the heated copper(II) oxide, removing oxygen from it and forming water, and then both parts of the apparatus were reweighed.

The loss in mass of A is the mass of oxygen used and the gain in the mass of B is the mass of water formed. The difference is the mass of hydrogen used.




■ **Figure 6.17** A simplified version of Dumas' apparatus

The results of Dumas' experiment showed:

Initial mass of copper(II) oxide = 61.31 g
Final mass of copper = 27.84 g
Initial mass of B = 87.02 g
Final mass of B = 124.67 g

**Analyse and evaluate** this information to make scientifically supported judgments.

**a** **Formulate** a balanced symbol equation for the reaction.

**b** **Calculate** the mass of

- **i** oxygen used to produce the water
- **ii** hydrogen used to produce the water
- **iii** hydrogen that combines with 16.00 g of oxygen.

**c** **Deduce**

- **i** the percentage composition of each element in water by mass
- **ii** the formula of water
- **iii** whether Dumas' experiment is only evidence for the *empirical* formula of water, i.e. the ratio of hydrogen and oxygen in the molecular formula.

# Reflection

In this chapter you developed your understanding of why chemical reactions proceed, and how chemistry is quantified, in solids, liquids and gases. Because matter is subject to physical and chemical change, the molar volume of a gas is standardized at STP, and the molar concentration of an aqueous solution is standardized to mol $dm^{-3}$. You were introduced to the important skill of titration, which can be used to calculate the concentrations of unknown reactants, in acid–base reactions in particular.

| **Reflect on your own learning in this chapter** | | | | | |
|---|---|---|---|---|---|
| Questions we asked | Answers we found | Any further questions now? | | | |
| **Factual:** How can particle motion be described? How is the quantity of a substance measured consistently during change? | | | | | |
| **Conceptual:** How do the conditions of the environment affect chemical reactivity? Why do changes in the total number of particles, but not necessarily the total number of atoms, determine the volume of a gas? | | | | | |
| **Debatable:** To what extent are physical and chemical changes linked? | | | | | |
| Approaches to learning you used in this chapter: | Description – what new skills did you learn? | How well did you master the skills? | | | |
| | | Novice | Learner | Practitioner | Expert |
| **Communication skills** | | | | | |
| **Organization skills** | | | | | |
| **Media literacy skills** | | | | | |
| **Critical-thinking skills** | | | | | |
| **Transfer skills** | | | | | |
| **Learner profile attribute(s)** | How did you demonstrate your skills as a thinker in this chapter? | | | | |
| **Thinker** | | | | | |

# 7 What's inside the nucleus?

**Evidence** from physical properties such as masses of nuclei has helped to elaborate our **systems** for classifying matter and explained the **distribution of elements on Earth and elsewhere in the universe**.



**Figure 7.1** Hair grows at about 1 cm each month. How does its composition provide a record of where you have been, and what you have consumed?

## CONSIDER AND ANSWER THESE QUESTIONS:

**Factual:** What differences are there between the isotopes of an element? What can we learn from the isotope ratio? How often do we find different isotopes in a sample of an element?

**Conceptual:** How did the elements on Earth originate? How do models of atomic structure help us understand their physical chemistry?

**Debatable:** Should humans continue to use radioactive isotopes in our technologies despite the dangers of ionizing radiation?

Now **share and compare** your thoughts and ideas with your partner, or with the whole class.

## IN THIS CHAPTER, WE WILL ...

- **Find out** how radioactive elements can be used.
- **Explore**
  - how models can inform us about what we cannot see;
  - models that explain nuclear chemistry.
- **Take action** by encouraging the safe recycling of radioactive waste.

## These Approaches to Learning (ATL) skills will be useful ...

- Communication skills
- Collaboration skills
- Organization skills
- Critical-thinking skills
- Creative-thinking skills

## Assessment opportunities in this chapter ...

- Criterion A: Knowing and understanding
- Criterion D: Reflecting on the impacts of science

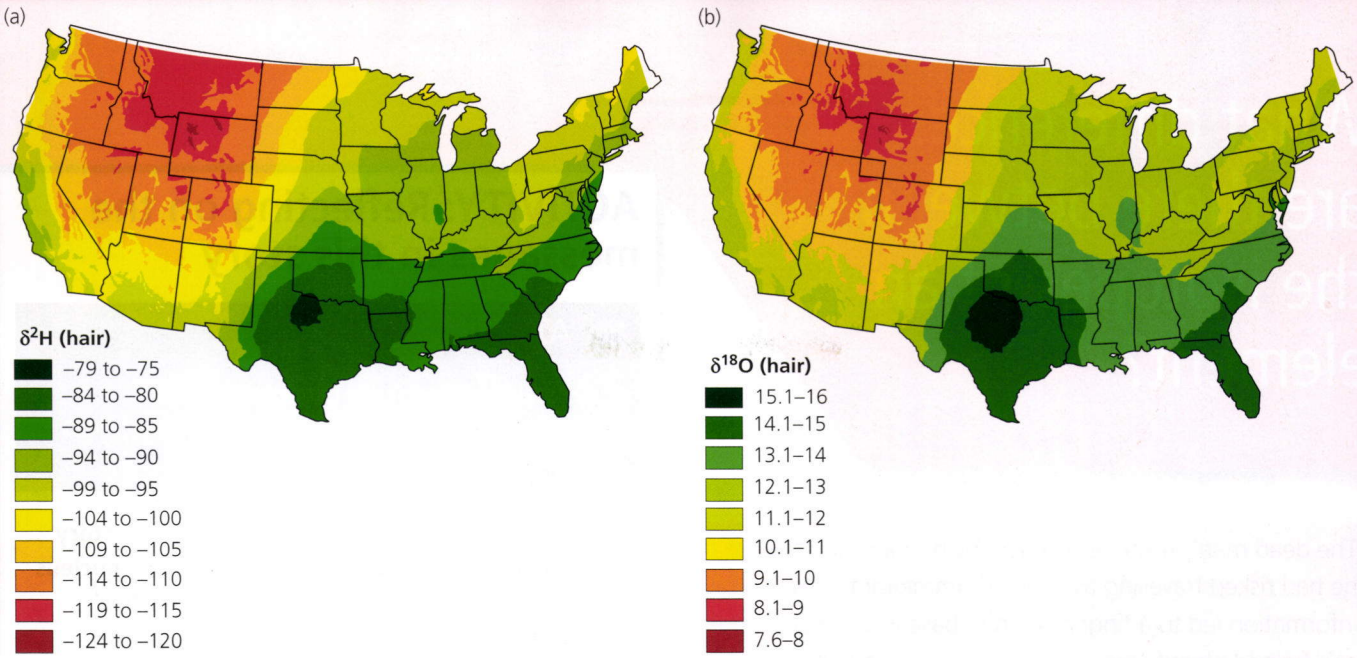



**Figure 7.2** Maps showing the distribution of the abundance of (a) $^2$H and (b) $^{18}$O in human hair in the USA. The higher isotope fractions are represented by the higher $\delta^2$H and $\delta^{18}$O values

## We will reflect on this learner profile attribute …

- Risk taker – In science, are you willing to risk testing and applying new ideas, even though you may be wrong? Do you recognize asking questions as a sign of strength and confidence? How can we decide if the benefits gained from nuclear power outweigh the environmental risks it brings? How well are you able to use science to defend your ideas?

## HEADLINES

Read the story below, about the mystery man, silently without discussing it. Then write a headline that in your opinion captures the most important aspect that should be remembered.

In 2006, a badly beaten, dying man was dropped off at a hospital emergency department in Wales, United Kingdom. Who was he, and how did he come to be there? His hair had not been cut for more than a year, and it would provide vital clues.

Every month, our hair grows about 1 cm in length. The mixture of isotopes in the emerging strand is determined by our diet, and provides a record of our geographical location. Even a few days of international travel will leave its trace in your hair. The dead man's hair revealed he had been in the UK for about 10 weeks, after six or seven months in Germany. Before that, he had lived in Ukraine.

## KEY WORDS

decay radiation

In the past few decades, the Earth has been mapped in an entirely new way (Figure 7.2). Atoms of many elements, including oxygen and hydrogen, differ by the numbers of neutrons found in their nuclei. Although all of these **isotopes** are chemically identical, the mass contributed by the additional neutrons changes the kinetic properties of molecules that contain heavy forms of the elements. For example, raindrops containing water molecules with heavy oxygen atoms tend to fall slightly earlier than drops with molecules with the more common, lighter form of oxygen atoms. Across continents, the ratio of heavy to light forms of water declines in a pattern that follows the direction of prevailing winds. Water moves through the ecosystem via the food chain, ultimately leaving its signature in our tissues, including our bones, nails and hair. Isotope analyses of bone have also long been used by anthropologists to track migration routes of prehistoric peoples.

# What differences are there between the isotopes of an element?

The dead man's route as revealed by his hair suggested he had risked travelling as an illegal immigrant. This information led to a fingerprint database in Germany, and helped identify him as Tran Nyugen, originally from Vietnam. A person's identity reveals his connections. Nyugen had been forced to pay off his debt to his people-smugglers by working for a drug syndicate, and this caused him to become a casualty of gang warfare. Within two years of his murder all these crimes had been uncovered, ultimately by using isoforensics, a new application in the science of law that analyses evidence for subtle differences in the ratios of chemical isotopes.

## HOW DOES THE NUCLEUS ADD UP?

You will recall from Chapter 3 that the mass of an atom's electrons is almost insignificant compared with that of its neutrons and protons. The identity of an element comes from its number of protons and is identical to its **atomic number** ($Z$). Since isotopes have the same number of protons, the number of neutrons ($N$) they have must vary.

The concept of 'relative atomic mass' ($A_r$) that is displayed with each symbol in a standard periodic table (Figure 7.3) is more correctly expressed as the 'weighted average atomic mass', because it incorporates the ratios (relative amounts) of all the element's isotopes. The **nucleon number** ($A$) is the actual number of protons and neutrons (**nucleons**) in a particular nucleus. Most elements contain a mixture of isotopes which explains why their relative atomic masses are not whole numbers.

## ACTIVITY: Reflecting on the messages in this story

### ATL

- Critical-thinking skills: Draw reasonable conclusions and generalizations; consider ideas from different perspectives

1. **State** what an isotope is, according to this story.
2. **Suggest** how the number of neutrons in a nucleus makes a difference to the 'kinetic properties' of molecules with these atoms. **Suggest** how molecules with different isotopes of elements may 'fractionate' or separate into different mixtures.
3. **Identify** two branches of learning that use isotopes to track a person's geographical location.
4. **Comment** on how the observation that your geographic location is constantly being recorded in your body makes you feel.
5. **Evaluate** whether drinking carbonated drinks (soft drinks or soda drinks) all the time, would disguise your geographic location. Where are the carbonated drinks that are on sale at your local shops bottled?
6. Share your original headline with your peers and **reflect** on it. How would you change it, based on your discussion? **Evaluate** how its message differs from what you would have said initially.

### Assessment opportunities

- In this activity you have practised skills that are assessed using Criterion A: Knowing and understanding.

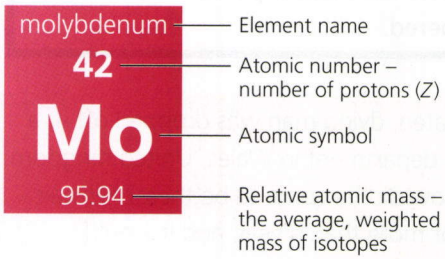



**Figure 7.3** The relative atomic mass ($A_r$) of an element as shown in the periodic table is an average based on the relative amounts of all its isotopes

# How often do we find different isotopes in a sample of an element?

Individual isotopes are described using the notation ${}^{A}_{Z}X$, where $A$ refers to the mass number (protons and neutrons) of the isotope and $Z$ to the atomic number of an element, X. In written references to isotopes, the name of an element is followed by the mass number of its isotope. For example, the isotopes of carbon, ${}^{12}_{6}C$, ${}^{13}_{6}C$ and ${}^{14}_{6}C$ are referred to as carbon-12, carbon-13 and carbon-14.

Because the number of electrons in an atom is the same as the number of protons, all the isotopes of an element enter into the same chemical reactions. For example, either **deuterium** (hydrogen atoms with a mass number of 2) or **protium** (hydrogen atoms with a mass number of 1) will react with oxygen gas to form water molecules, $H_2O$.

However, additional neutrons give isotopes different physical properties because their atoms have different masses. For example, the three isotopes of neon (${}^{20}_{10}Ne$, ${}^{21}_{10}Ne$, ${}^{22}_{10}Ne$) all have different densities, melting points, boiling points and rates of diffusion. These similarities and differences between isotopes of the same element are summarized in Table 7.1.

| Similarities | Differences |
|---|---|
| Number of protons (atomic number $Z$) | Number of neutrons ($N$), which affects the mass of the atom |
| Number of electrons | Physical properties: |
| Chemical properties | rate of diffusion |
| | density |
| | boiling point |
| | melting point |

■ **Table 7.1** The similarities and differences between isotopes of the same element

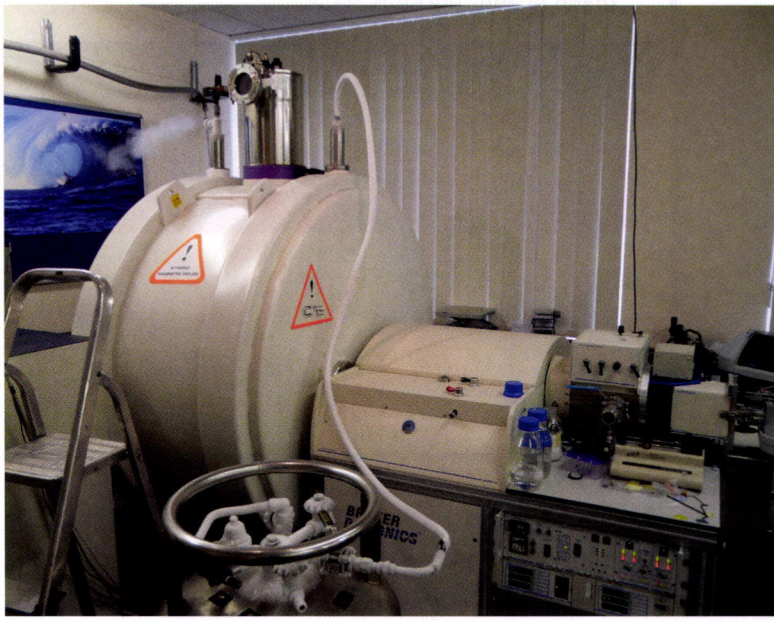
## EXTENSION

Nuclear **fission** reactors use uranium that contains 3–4 per cent of the uranium-235 isotope. However, this isotope is very rare in natural uranium, in which 99.3 per cent of the atoms are the heavier uranium-238 isotope. Find how differences in physical properties of uranium hexafluoride are used in **uranium enrichment**.

## How do we detect isotopes?

If you've ever played a ball sport you will have an intuitive understanding that the degree that the ball changes its speed and direction is determined by its mass and the force you apply (an example of Newton's second law, $F = ma$).

This is the principle used in a **mass spectrometer** (Figure 7.4). In a vacuum, a sample of atoms or molecules is ionized, and the positive ions streamed past a strong magnet as a vapour. As you might expect, the magnetic force field interacts with the charged particles and deflects them according to their mass/charge ratio. The output trace (chart) from the mass spectrometer provides a series of peaks corresponding to the relative frequency of ions of each type of isotope.



■ **Figure 7.4** A mass spectrometer. Ionized particles stream in a vacuum through a powerful magnetic field (which is inside the cylindrical structure) and are separated depending on their mass-to-charge ratio

## ACTIVITY: Comparing isotope composition

### ATL

- Critical-thinking skills: Interpret data

1. **Copy and complete the table, to practise thinking about the relative contributions of protons, neutrons and electrons to the identity of an atom or ion.**
2. **Naturally occurring magnesium consists of three isotopes: 78.70 per cent magnesium-24 (amu 23.99), 10.13 per cent magnesium-25 (amu 24.99) and 11.17 per cent magnesium-26 (amu 25.98). Calculate its relative atomic mass and compare it with the value given in your periodic table.**

### Assessment opportunities

- In this activity you have practised skills that are assessed using criterion A: Knowing and understanding.

| Symbol | Atomic number (Z) | Mass number (A) | Number of protons | Number of neutrons | Number of electrons | Particle type: (neutral isotope/ positive ion/ negative ion) |
|---|---|---|---|---|---|---|
| $^{1}H$ | 1 | 1 | | | 1 | |
| $^{2}H^{+}$ | 1 | 2 | | | 0 | |
| $^{3}H$ | 1 | 3 | | | 1 | |
| $^{4}He$ | | | | | | |
| $^{6}He$ | | | | 4 | | |
| $^{8}Li^{+}$ | 3 | | | | | |
| $^{12}C$ | | | 6 | 6 | | |
| $^{13}C$ | | | 6 | 7 | | |
| $^{14}C$ | | | 6 | 8 | | |
| $^{16}O^{2-}$ | 8 | | | 8 | | |
| $^{18}O$ | 8 | | | 10 | | |
| $^{35}Cl$ | | 35 | 17 | | | |
| $^{37}Cl$ | | 37 | | | | |
| $^{37}Cl^{-}$ | | 37 | 17 | | | |
| $^{235}U$ | 92 | | | | 92 | |
| $^{238}U$ | 92 | | | | 92 | |

For example, a mass spectrometer trace shows that chlorine consists of two isotopes with mass numbers of 35 and 37 (Figure 7.5). If chlorine contained only $^{35}_{17}Cl$ atoms, then its relative atomic mass would be 35. If it contained only $^{37}_{17}Cl$ atoms, then its relative atomic mass would be 37. A balanced 50 : 50 mixture of $^{35}Cl$ and $^{37}Cl$ would have a relative atomic mass of 36. The relative size of the peaks shows that naturally occurring chlorine has about three times as much $^{35}Cl$ as $^{37}Cl$.

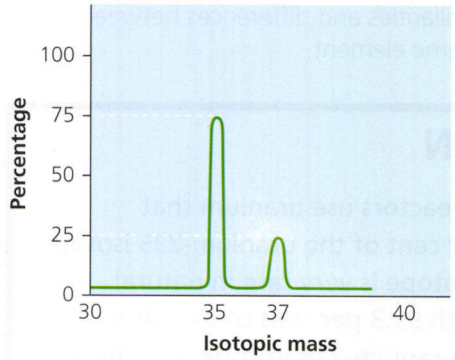



**Figure 7.5** Naturally occurring chlorine contains about three times as much $^{35}Cl$ as $^{37}Cl$

# What can we learn from the isotope ratio?

## THE STABILITY OF ISOTOPES

The stability of an element's nucleus is related to the ratio of its protons and neutrons and to its size. It also seems to depend on whether the number of protons or neutrons is even or odd. Only atoms of five elements have odd numbers of both neutrons and protons. Natural isotopes with similar numbers of neutrons and protons tend to be stable (Figure 7.6). Natural elements with greater numbers of neutrons in their ratios, and elements with an atomic number greater than 83, are unstable. These unstable elements will 'decay' by releasing various types of particles or energy in the form of gamma radiation, until their nuclei become stable.

Most naturally occurring elements have stable nuclei and are not **radioactive**. There are a small number of examples of light elements that have naturally occurring radioactive isotopes, such as potassium-40 and carbon-14, but it is much more common for radioactivity to be shown by the very heavy elements from lead (atomic number 82) to uranium (atomic number 92).

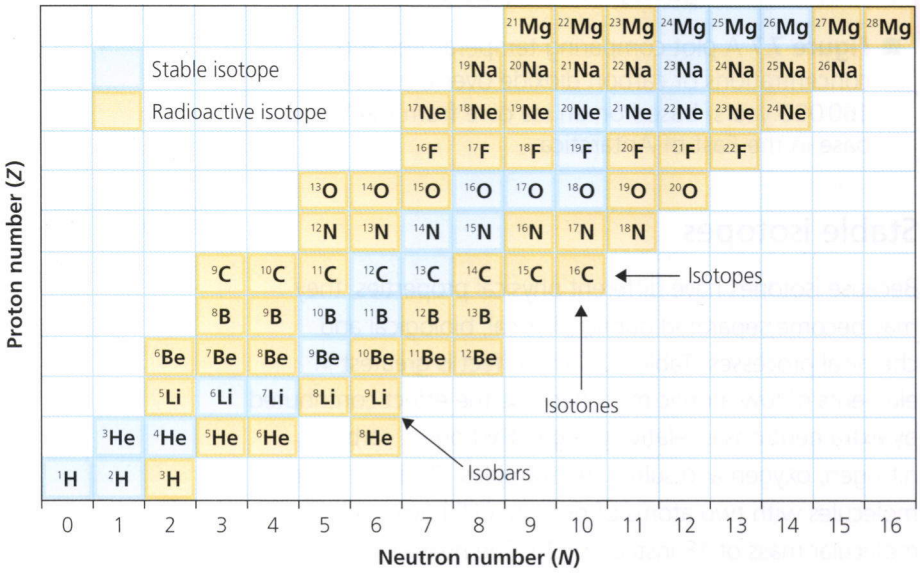



**Figure 7.6** A 'diagram of **nuclides**' describing the number of protons (Z) against the number of neutrons (*N*) in nuclei. Each horizontal line of atoms therefore lists all of the element's isotopes. Plotting isotopes this way also introduces two other patterns: 'isotones' which are isotopes that have the same number of neutrons in the vertical arrangement, and 'isobars' or isotopes that have the same mass in the diagonal arrangement from the lower right to upper left

### Sample calculation of relative atomic mass

**Question: Calculate** the relative atomic mass of chlorine. Its two naturally occurring isotopes occur in the ratio 75.53 per cent chlorine-35 (mass = 34.97 amu) to 24.47 per cent chlorine-37 (mass = 36.97 amu).

**Solution:** Relative atomic mass

$$= \frac{(\%\ \text{chlorine-35})(\text{mass chlorine-35}) + (\%\ \text{chlorine-37})(\text{mass chlorine-37})}{100}$$

$$= \frac{(75.53)(34.97\ \text{amu}) + (24.47)\ (36.97\ \text{amu})}{100}$$

$$= \frac{2641.28\ \text{amu} + 904.66\ \text{amu}}{100} = \frac{3545.94\ \text{amu}}{100} = 35.46\ \text{amu (rounded to 4 significant figures)}$$

The slight difference in this result from the relative atomic mass value of 35.45 in the periodic table is due to the rounding error.

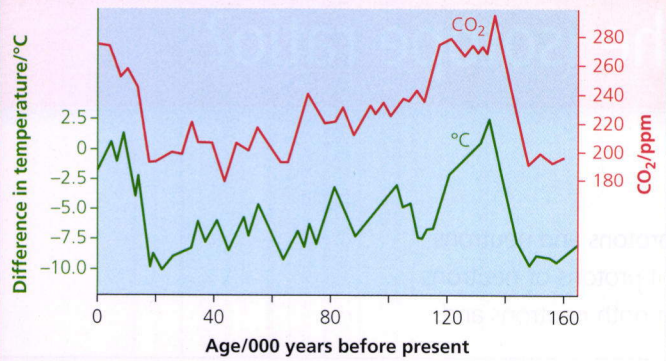



**Figure 7.7** A plot comparing temperatures and concentrations of carbon dioxide over the past 160 000 years, based on an ice core from the Vostok base in the East of Antarctica

## Stable isotopes

Because isotopes have different physical properties, they may become separated during physical, biological and chemical processes (Table 7.2). This effect is greatest in elements of low atomic mass because the effect contributed by extra neutrons is relatively larger. Hydrogen, carbon, nitrogen, oxygen and sulfur are examples. Ordinary water molecules with two atoms of protium ($^1_1H$) have a relative molecular mass of 18 instead of 20. The heavier molecules can be expected to move around and react more slowly, but take part in the same chemical reactions.

A natural landscape contains many elements, and therefore the combination of isotope ratios of several different elements provides a unique 'signature'. This may apply to the past as much as to geography. For example, one of the most important pieces of evidence for global warming (Chapter 9) is from Antarctic ice cores (Figure 7.7). Polar ice caps contain ice that has been laid down over hundreds of thousands of years, and ice cores up to 2 kilometres deep have been drilled. When the snow falls and becomes compacted into ice, air is trapped, and the carbon dioxide content of this 'time capsule' can be determined. The $^{18}O/^{16}O$ ratios of the ice surrounding the bubbles can be used to calculate the Earth's temperature at that time.

The difference in mass of very small atoms means that chemical bonds require more energy to break. For example, the bond between atoms of hydrogen-2 and carbon is 6.5 times slower to break than the bond between atoms of hydrogen-1 and carbon. In materials of organic compounds, such as living organisms, this difference can be very significant.

| Isotopes affected | Process | Example/ application |
|---|---|---|
| $^{18}O/^{16}O$ | Physical<br>Precipitation (rain) | Rainwater enriched in oxygen of isotope $^{18}O$, $H_2{}^{18}O$ tends to fall earlier than rainwater with the lighter $H_2{}^{16}O$.<br>This results in geographical patterns of 'isotopic signatures' (Figure 7.2) that can help identify the origin of foods and the movement history of individuals through their hair. |
| $^{18}O/^{16}O$ | Physical<br>Evaporation | This is the reverse effect of precipitation. Because $H_2{}^{18}O$ is a more massive particle than $H_2{}^{16}O$, it takes more energy to evaporate it from the surface of the oceans. In other words, evaporation discriminates against $H_2{}^{18}O$.<br>As a result, past global temperatures can be calculated from Antarctic ice cores. Ice from precipitation during cold, glacial periods will be enriched with lighter $H_2{}^{16}O$. |
| $^{13}C/^{12}C$ | Biological<br>Photosynthesis pathways | For reasons related to the kinetic energy of the isotopes, plant stomata discriminate against the heavier $^{13}CO_2$ compared to $^{12}CO_2$.<br>Subsequently, differences in enzyme pathways between two major groups of plants results in differences in the $^{13}C$ content of their sucrose. Sugar from sugar cane (a C4 plant) has more $^{13}C$ compared to sugar from sugar beet (a C3 plant). This distinction is used to identify the adulteration of food, for example food that has been sweetened by adding extra sugars. |
| $^{13}C/^{12}C$ | Chemical<br>$^{12}C$ bonds are slightly weaker than $^{13}C$ bonds; $^1H$ bonds are slightly weaker than $^2H$ bonds | Any natural processes involving carbon chemistry will tend to separate the different isotopes.<br>The effect depends on the reactions involved. |

**Table 7.2** Sorting the stable isotopes of elements

# Should we continue to use radioactive isotopes despite the dangers?

## RADIOACTIVE DECAY

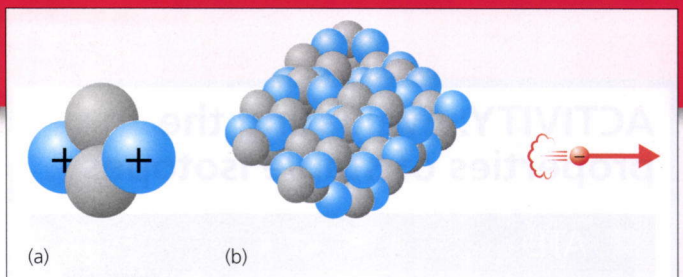
A **radioactive** atom emits particles and radiation from its nucleus because the nucleus is unstable. This is called radioactive decay and isotopes which undergo this process are called radioisotopes or radionuclides. Nearly all radionuclides have a relatively high ratio of neutrons to protons, for example, uranium with 143 neutrons to 92 protons (in the isotope of mass number 235). Elements with atomic numbers greater than 92 do not occur naturally but may be prepared artificially by bombardment with neutrons or protons. These elements are all radioactive and many are important in a wide variety of uses. Some elements lighter than 92 also do not occur naturally, because all their isotopes are radioactive and have therefore long since decayed. Examples are technetium and astatine.

Because these changes affect the nucleus and can change the number of protons, unlike chemical reactions, the products of nuclear reactions can be new elements. Radioactive decay can involve a series of decay steps called a **decay series**. The first, unstable radionucleotide is called the 'parent' isotope and all the stable isotopes that eventually result are called '**daughters**'. Important types of radioactive **decay** are described below.

**Alpha (α) decay** occurs when an **alpha particle** or helium-4 nucleus ($^{4}_{2}He^{2+}$) is emitted. Therefore, alpha particles carry a positive charge. Alpha particles are the largest **decay product**, and their loss decreases an atom's atomic number by 2 and its mass by 4. As an example, the balanced nuclear equation below shows uranium-234 undergoing alpha decay to thorium-230:

$$^{234}_{92}U \rightarrow {}^{4}_{2}He + {}^{230}_{90}Th$$

**Beta (β) decay** occurs when a beta minus particle, the equivalent of a high speed electron ($^{0}_{-1}e$ or $^{0}_{-1}\beta$) is emitted. A neutron transforms into a proton, an electron and a third particle with no charge (an antineutrino) to ensure conservation of energy and momentum. In beta decay, the proton remains behind in the nucleus. The **beta particle** carries a negative charge, while the proton increases the atomic number by 1. The overall mass of the atom is approximately unchanged. As an example, the equation below represents carbon-14 undergoing beta decay into nitrogen-14:



(a) (b)

**Figure 7.8** Examples of particles emitted by radionuclides. (a) **alpha (α) particles** are two protons and two neutrons combined together (helium-4 nuclei), (b) **beta (β) particles** are high energy electrons (not to scale) formed and released from the nucleus when a neutron transforms into a proton, electron and a third particle (an antineutrino). The proton remains behind in the atom's nucleus

$$^{14}_{6}C \rightarrow {}^{0}_{-1}\beta + {}^{14}_{7}N$$

**Positron emission** (also called beta positive or beta plus decay) occurs when the nucleus emits a positron ($^{0}_{1}e$ or $\beta^{+}$), a particle that has the same size and mass as an electron but has a positive charge. A positron is therefore the antimatter equivalent of an electron. This process occurs when the neutron-to-proton ratio is too small for stability. A proton transforms into a neutron ($p \rightarrow {}^{1}_{0}n + {}^{0}_{+1}e$, decreasing the atomic number by 1), a positron and a third particle of no mass or charge (a neutrino) to ensure conservation of energy and momentum. After the positron is emitted, the neutron remains behind in the nucleus, so the overall mass of the nucleus is unchanged.

**Gamma (γ) decay** consists of the emission of electromagnetic radiation of very high frequency (short wavelength) and energy. Its symbol, $^{0}_{0}\gamma$, indicates its emission does not affect charge or mass, and for this reason, **gamma radiation** is often not included in nuclear equations. Gamma radiation is emitted from excited nuclei of elements that have formed as a result of radioactive decay by emitting alpha or beta particles, and removes further energy from their nucleus. Gamma ray photons have energies of about $1 \times 10^{-12}$ joules.

## ACTIVITY: Evaluating the properties of stable isotopes

### ATL

- Critical-thinking skills: Interpret data; evaluate evidence and arguments; draw reasonable conclusions and generalizations

1. **In the table you completed in the Activity: *Comparing isotope composition*, identify examples of isobars and isotones.**
2. **Suggest why stable isotope fractionation (separation) is most evident in**
   a. **molecules with low molecular mass elements**
   b. **molecules with covalent bonding.**
3. **Describe the correlation between the two variables in the Vostok ice cores (Figure 7.7).**

### Assessment opportunities

- In this activity you have practised skills that are assessed using Criterion A: Knowing and understanding.

## Transuranium elements

Elements with atomic numbers greater than 93 do not occur naturally. They have to be prepared by nuclear reactions. They are known as the **transuranium elements**. The first two were prepared in 1940 by bombarding uranium-238 nuclei with neutrons:

$$^{238}_{92}U + {}^{1}_{0}n \rightarrow {}^{239}_{92}U$$

Uranium-239 decays by beta emission:

$$^{239}_{92}U \rightarrow {}^{239}_{93}Np + {}^{0}_{-1}e$$

Neptunium also decays by beta emission, forming plutonium (Pu):

$$^{239}_{93}Np \rightarrow {}^{239}_{94}Pu + {}^{0}_{-1}e$$

Other transuranic elements have been prepared using nuclei such as $^{12}_{6}C$ or $^{14}_{7}N$ as bombarding projectiles.

The larger an atomic nucleus, the more its protons repel one another with their positive charges, making it, in general, less stable, or more radioactive. Element 117, for example, has a **half-life** of about 50-thousandths of a second.

## ACTIVITY: Evaluating changes in unstable isotopes

### ATL

- Critical-thinking skills: Interpret data; evaluate evidence and arguments; draw reasonable conclusions and generalizations

1. **List examples of radioactive decay products and their formulas.**
2. **Formulate balanced nuclear equations to describe these examples of radioactive decay:**
   a. **$^{14}C$ is used for carbon-dating and undergoes beta decay.**
   b. **Radium-221 is used in industrial radiography and undergoes alpha decay.**
   c. **Iodine-131 and astatine-211 have medical uses in the treatment of cancer, particularly in the thyroid. Each undergoes beta negative decay.**
   d. **$^{60}Co$ is used in external beam radiation therapy for treating cancer. It undergoes beta negative decay which is accompanied by the emission of gamma rays.**
   e. **$^{210}Po$ is used as a power source in unmanned spacecraft, including New Horizons (the probe that visited Pluto in 2015). It undergoes alpha decay.**
3. **Formulate the radioactive decay series (in which $-\alpha$ and $-\beta$ indicate the type of decay) to identify the nuclides X, Y and Z.**

$$^{232}_{90}Th - \alpha \rightarrow \mathbf{X} - \beta \rightarrow \mathbf{Y} - \beta \rightarrow \mathbf{Z} - \alpha \rightarrow {}^{224}_{88}Ra$$

### Assessment opportunities

- In this activity you have practised skills that are assessed using Criterion A: Knowing and understanding.

## EXTENSION: EXPLORE FURTHER!

Theoretical predictions suggest the existence of stable super heavy elements called **islands of stability**. Their existence, if confirmed, would be due to the presence of stable **magic numbers** of protons and neutrons.

### Links to: Language and Literature

Novels carry broad messages about our human condition, and dilemmas and resolutions faced by their characters transfer beyond the immediate story. In medicine and in law, case studies are an important part of instruction. In the Activity: *Reflecting on the uses of isotopes, stable or unstable*, apply the techniques discussed in Language and Literature to science journalism.

## ACTIVITY: Reflecting on the uses of isotopes, stable or unstable

### ATL

- Communication skills: Use appropriate writing for different purposes and audiences; use a variety of media to communicate with a range of audiences; write for different purposes; structure information in summaries, essays and reports
- Creative-thinking skills: Combine knowledge, understanding and skills to create products or solutions

Explaining science to the public is always more effective when you 'start with a story'. There are stories about the application of stable isotopes in anthropological, forensic and environmental contexts, or the use of unstable isotopes in geological dating and medicine. Science journalism often uses a short case study to make the science relevant.

Here are some tips for presenting scientific information effectively through case studies:

- **Explain the problem or issue the product solves using a case study. It is recommended, but not essential, that you use a fairly recent example. Your story should *have generality*. Therefore, you need to explain the science involving the isotopes. Depending on your interest, this can be either stable isotope fractionation or the process of radioactive decay of an unstable isotope.**
- **Science does not work in isolation. To discuss moral, ethical, social, economic, political, cultural or environmental considerations in your case study, consider creating empathy. Mystery or true crime stories are popular approaches. Provoke controversy (feelings of conflict). For example, Tran Nyugen (page 147) was both a tragic victim of his circumstances and a person who acted illegally.**
- **Naturally, your use of scientific terminology should be appropriate and correct. This may apply to the notation for describing the fractionation process of stable isotopes, or for describing radioactive decay, depending on your case study.**
- **Consider including quotations. Direct speech captures the protagonists' emotions and adds immediacy. However, recognize that inventing dialogue will shift your case study from a documentary focus into the creative territory of the playwright. How should you navigate this territory with integrity?**
- **All primary and secondary sources of information should be documented.**

### Assessment opportunities

- In this activity you have practised skills that are assessed using Criterion D: Reflecting on the impacts of science.

## OBSERVING NUCLEAR DECAY

A **Geiger counter** is an instrument used for measuring ionizing radiation. The 'counts' (clicks) you hear are caused when radiation (and in some detectors, alpha and beta particles) ionizes gas molecules inside a tube.

No matter where we live, there will be sources of natural radiation near us. For example, if you live in an environment that has granite rocks, you will naturally be exposed to low levels of the radioactive noble gas radon.

Every potassium atom in your environment (including the salts in your food and in your blood plasma) will include some atoms of the isotope potassium-40. Although potassium-40 is very rare, representing only 0.012 per cent (120 ppm) of all potassium atoms, and decays very slowly, its radioactivity will be detectable using a Geiger counter.

# ACTIVITY: Observing nuclear decay

## ATL

- Organization skills: Select and use technology effectively and productively; use appropriate technologies for organizing complex information
- Critical-thinking skills: Interpret data

**Safety:** Only your teacher is qualified to demonstrate the use of the following salts: potassium carbonate $K_2CO_3$; potassium dichromate(VI), $K_2Cr_2O_7$; potassium fluoride, KF, and potassium nitrate, $KNO_3$. In solid form, these salts are irritants or extremely toxic. Eye protection and gloves should be worn at all times.

The remaining salts are safe for students to handle.

### Materials and equipment

- eye protection, gloves
- a Geiger counter
- oven
- glass Petri dishes with lids
- crucibles
- desiccating jar
- Bunsen burner
- a range of standard potassium salts (laboratory reagent). Suggested examples are listed below.

  For use by students:

  i potassium bromide, KBr
  ii potassium chloride, KCl
  iii potassium hydrogen phthalate, $C_8H_5KO_4$
  iv potassium iodide, KI

  For teacher demonstration only (for further data):

  v potassium nitrate, $KNO_3$
  vi potassium dichromate(VI), $K_2Cr_2O_7$
  vii potassium fluoride, KF
  viii potassium carbonate, $K_2CO_3$



**Figure 7.9** A Geiger counter

### Method

1. Put on eye protection and gloves.
2. Dehydrate each of the salts.

   Salts **i–vi** can be dehydrated in a 150 °C oven for 24 h.

   Salts **vii–viii** should be heated to 'constant mass' using a Bunsen burner.
3. Store these salts in a Petri dish inside a desiccating jar, between measurements.
4. Spread 5 g of the salt in a Petri dish, and cover until ready to measure.
5. Hold the Geiger counter tube 1.5 cm above the sample in an open Petri dish.
6. **Measure** counts for 10 minutes. Repeat each measurement five times.
7. Suggest a control for this investigation. **Measure** this **background radiation** for 10 minutes, five times.

### Analysis

1. **Calculate** the percentage by mass of potassium in each of the test compounds.
2. **Calculate** the average number of counts over a 10 minute interval, and the range of counts.
3. **Plot** the relationship between percentage by mass of potassium and the average count from your samples. **Explain** this result.
4. **Evaluate** the use of this method to assay the amount of potassium in an unknown substance, for example 'low-sodium' dietary alternatives. What assumptions will you make?
5. **Evaluate** the effect on your data if your counts were conducted for longer than 10 minutes.
6. Potassium-40 decays in three different ways:
   a. about 90 per cent of $^{40}_{19}K$ decays to $^{40}_{20}Ca$ by $\beta^-$ emission
   b. a *very, very small amount* (0.001 per cent) decays directly to $^{40}_{18}Ar$ by $\beta^+$ emission
   c. about 10 per cent decays to $^{40}_{18}Ar$ by 'electron capture'.

   **Suggest** how each of these processes might be described using a nuclear equation.
7. In 1803, John Dalton (Chapter 1) wrote, '*Thou knowest no man can split the atom.*' **Outline** arguments for how the evidence in this activity supports or rejects his claim.

## Assessment opportunities

- In this activity you have practised skills that are assessed using Criterion C: Processing and evaluating.

# How do models of atomic structure help us understand their physical chemistry?

## UNDERSTANDING THE NUCLEUS THROUGH MODELLING

### ACTIVITY: Modelling radioactive half-lives

**ATL**

- Organization skills: Use appropriate strategies for organizing complex information
- Collaboration skills: Delegate and share responsibility in decision making; negotiate effectively

The tendency of a radioactive atom to decay into stable elements is not affected by natural conditions such as temperature or pressure, but is determined by the forces within its nucleus. Because we cannot predict when any given atom will decay, radioactive decay is an example of a random event. The half-life of an isotope is the time for half its radioactive particles to decay. The concept of a half-life in nuclear physics is an example of how random events involving very large numbers can produce a predictable result.

#### Materials and equipment

You need about 500 'atoms' for this activity. Suggestions are:

- **500 dice or cubes on which one side is marked (or one number selected), sweets that have one face marked (e.g. M&Ms®) or coins. Alternatively you may want to consider one of the simulations from the Extension box on page 158**
- **a container, such as a box or cup**
- **a flat surface**

#### Method

The cubes, dice, sweets or coins represent atoms, and if they fall with the marked side up they have 'decayed' to the stable isotope (symbolized *N*). In the proposed model, a cube-based set of isotopes will have a different half-life from a two-dimensional model.

1. **Design** a table on which to tally the results of marked ($N$) and unmarked particles ($N_0$) for each time interval (or half-life). Aim to collect 6–10 sets of data, using the following method.
2. **Put all the 'particles' in the container and shake them up. Pour them onto a flat surface. Pick out all the cubes or sweets that have fallen marked-side up and put them on one side and count them (in the column headed *N*). Also count the remaining radioactive, undecayed 'particles' (in the column headed $N_0$).**
3. **Repeat the previous stage, each time using only the remaining undecayed cubes ($N_0$) until you have completed between six to ten 'counts', representing half-lives.**

#### Analysis

1. **Plot the number of decayed particles ($N$) produced in each round. What does the shape of the curve suggest?**
2. **Evaluate whether there will ever be a time when there is no 'radioactivity' left.**
3. **Evaluate the accuracy of this 'simulation' of radioactive decay and a half-life cube. Outline how the accuracy could be improved.**
4. **Polonium-218 has a half-life of only 3 minutes. Deduce**
   a. **if you start with a 24 g sample, how much will be left after 9 minutes?**
   b. **if you started with a 48 g sample, how much longer would it take to reduce to the level reached by the 24 g sample?**
5. **Use this information to estimate a value for the decay constant $\lambda$ for each simulation.**

**Assessment opportunities**

- In this activity you have practised skills that are assessed using Criterion C: Processing and evaluating.

## Modelling

Modelling is used by scientists when experiments are (i) expensive, (ii) time consuming, (iii) impractical or (iv) dangerous. Many of these limitations extend to school contexts.

A model provides a way of explaining complex data simply or may be a method for presenting a hypothesis when limited data is available, and therefore used for making predictions. Models may be physical, or they may be virtual, for example a computer simulation.

A model can become more and more sophisticated but it can never be the real thing. For example, John Dalton (Chapter 1) explained the constant composition of compounds by suggesting that matter was composed of atoms and that compounds consisted of chemical combinations of atoms of elements in certain fixed ratios. He was proposing the atom as a model, and his model was extremely simple. Dalton suggested atoms were small, hard, indivisible particles. Atoms of the same element were all alike. Eventually, of course, experimental evidence led to the replacement, in stages, of Dalton's simple model by more sophisticated models that are in general use today. A scientific model simply explains observations.

The activities on these pages model real events to improve your understanding of nuclear chemistry.

## EXTENSION

**Explore further:** There are many **virtual radioactive decay simulators** online. Here are two examples:

**www.glencoe.com/sites/common_assets/science/virtual_labs/E18/E18.html**

**astro.unl.edu/classaction/questions/solar/ca_solar_halflifetwo.html**

Perhaps you can write a similar simulation to model radioactive decay. You will need to find out how to generate random numbers in your chosen programming language or spreadsheet.

## Links to: Mathematics

A half-life is a time. The half-life of carbon-14 is 5700 years, but the half-life of polonium-218 is only 3 minutes, representing the time in which half the atoms of the radioactive isotopes decay. The decay depends on the number of atoms left, and declines at a constant rate, therefore decreasing exponentially. The **decay constant** (given by the symbol $\lambda$) is the chance that an atom will decay in a unit of time. It is constant for a given isotope. It is related to the 'half-life' ($T_{½}$), in that an isotope with a higher probability of decaying will lead to the substance having a shorter half-life.

If you enjoy mathematics, you may like the explanation.

Over a period of time, the exponential decay is expressed using the formula:

$N = N_0 e^{-\lambda t}$ **(equation 1)**

The symbol e (Euler's number) = 2.718... and represents the natural (Napier) log, ln or logarithm to base e. $\lambda$ is the decay constant ($s^{-1}$). By taking the logarithm to the base e of both sides of the equation, equation 1 can be expressed as:

$\ln N = \ln N_0 - \lambda t$

Notice how this equation has the form $y = mx + c$, a form that identifies $\lambda$ as a constant rate.

Every half-life ($t = T_{½}$), the number of particles that are still radioactive is half of the number left, $N_0$. Therefore,

$N = ½N_0$ **when** $t = T_{½}$ **(equation 2)**

Now there are two equations for $N$, and they can be combined and solved to find the half-life, $T_{½}$.

$½N_0 = N_0 e^{-\lambda T_{½}}$

$\ln ½ = -\lambda T_{½}$ **(divide both sides by** $N_0$ **and take the natural log of both sides)**

$\ln 2 = \lambda T_{½}$ **(since** $\ln x^{-1} = -\ln x$**)**

$T_{½} = 0.693/\lambda$ **(because** $\ln 2 = 0.693...$**)**

This equation gives the half-life, the time taken for half the remaining atoms to decay.

The half-life of the two-dimensional model (coins, sweets) is one toss. The half-life of the three-dimensional model (dice, cubes) is almost four tosses, because one toss should leave about 5/6 radioactive isotopes, and so on. Half will have decayed between three $(5/6)^3 = 125/216 = 0.58$ and four $(5/6)^4 = 625/1296$ (0.48) tosses.

# ACTIVITY: Modelling radiation

## ATL

- Organization skills: Use appropriate strategies for organizing complex information
- Communication skills: Understand and use mathematical notation; organize and depict information logically

Radioisotopes have potentially harmful effects. The most penetrating ionizing radiation is gamma radiation. But alpha and beta sources can also be harmful if they get inside the body. All radioactive sources must be handled with care since radiation kills or damages living cells. The benefits of any deliberate exposure must always outweigh the risk. Table 7.3 compares the properties of different types of radiation.

### Materials and equipment

- **a light source (to simulate gamma radiation): if the light source is not an actual 'point source', assume the intensity of the beam is representative of what it would be if it were a point source**
- **a light meter or a solar cell connected to an ammeter**
- **a ruler (to measure the radius *r* from the light source)**
- **spreadsheet software**

### Method

1. **In a darkened room, set up the light source so that its radiation falls perpendicular to the detector.**
2. **Measure the intensity of the light (*I*) using the light meter set at different distances (*r*).**
3. **Enter the results of the relationship into a spreadsheet.**

### Analysing results

1. **Construct a graph that reveals a direct relationship between the distance from the light source and energy. Investigate your data by manipulating the values using a spreadsheet, until a straight line relationship appears.**
2. **State what the mathematical correlation reveals about the relationship between radiation intensity and distance from the source.**
3. **Evaluate whether**
   a. **light is a valid model for gamma radiation**
   b. **there is a distance at which the radiation will actually 'vanish', or be completely absorbed**
   c. **whether the surrounding air affected your model.**
4. **Describe, with reference to Table 7.3,**
   a. **how gamma ($\gamma$) radiation differs from the other types of nuclear emissions ($\alpha$ or $\beta$ particles)**
   b. **how you could model the effect of (i) particle size and (ii) particle charge, if you were investigating these types of emissions instead of gamma (Figure 7.10).**
5. **Based on your modelling, create a protocol for the safe handling of potential sources of radiation.**

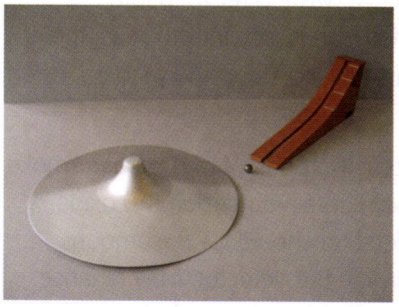


**Figure 7.10** How might equipment simulate the effect of an alpha particle approaching a nucleus?

## Assessment opportunities

- In this activity you have practised skills that are assessed using Criterion C: Processing and evaluating.

| Name (symbol) | Nature and composition | Charge | (Depending on the energy of the radiation) it can be stopped by | Relative ionizing 'power' |
|---|---|---|---|---|
| Alpha ($\alpha$) | Particle<br>$^4_2$He nucleus | +2 | Approximately 5 cm air<br>A sheet of paper | Relatively strong |
| Beta ($\beta$) | Particle<br>Very high kinetic energy electron | −1 | Approximately 5 cm aluminium | Medium |
| Gamma ($\gamma$) | Wave<br>High energy electromagnetic radiation | 0 | At least 10 cm lead<br>A greater thickness of steel or concrete<br>Several metres of water | Relatively poor |

**Table 7.3** Properties of types of radiation

## EXTENSION

**Explore further:** Measure alpha, beta and gamma radiation using an online model Geiger counter, for example, www.scootle.edu.au/ec/viewing/L45/index.html

# SMOKE ALARMS

One of the problems associated with radioactive materials is the disposal of radioactive waste. Some radioisotopes have very long half-lives and therefore can emit radiation for many years. Some radioactive waste is recycled into useful materials, but most is buried or released into the sea, if low level waste. High level waste has to be specially stored, often underground.

In our homes, the radioactive isotope $^{241}_{95}Am$ is used in smoke detectors (Figure 7.11). They contain americium(IV) oxide, $AmO_2$. The label on the detector should list the amount of americium-241 that is inside the detector. Maintenance advice for these types of smoke detectors includes:

- replacing batteries annually
- replacing the device after a service life of 10 years.

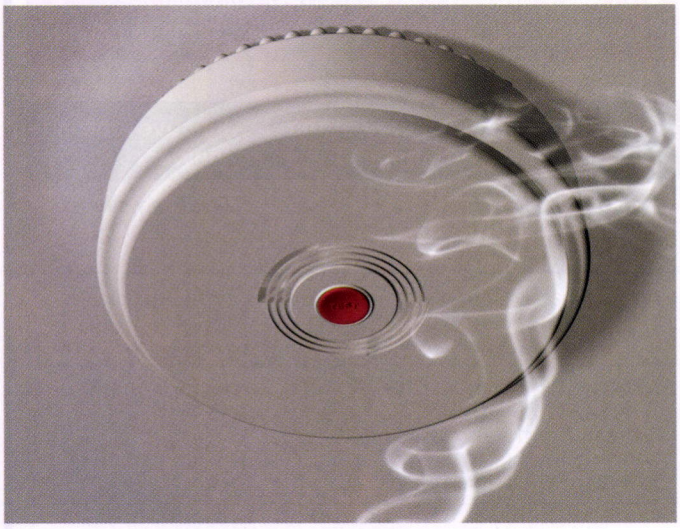


**Figure 7.11** An example of a domestic smoke detector

## ! Activity: Smoke alarms

### ATL

- Communication skills: Negotiate ideas and knowledge with peers and teachers; write for different purposes; use a variety of media to communicate with a range of audiences

! Smoke alarms are everywhere, and they save lives. But what are the pros and cons of their use?

! How can we benefit even further, in the way we use smoke alarms?

1 **Formulate** the nuclide symbol for the americium(IV) ion, $Am^{4+}$.
2 **Identify** the type of radiation emitted by $^{241}_{95}Am$.
3 **Suggest** why
   a smoke detectors are powered by batteries
   b every house should be equipped with smoke detectors
   c you should never disassemble or take apart an ionization smoke detector.
4 **Evaluate**, after using the Internet to find out how ionization smoke detectors work, whether their normal use and disposal could pose a health risk.
5 **Construct** posters or virtual reminders (e.g. with Outlook messages) to remind people of the importance of regular maintenance of their smoke detector.
6 **Evaluate** how sustainable actions to 'reduce, reuse' apply to smoke detectors, and what you can do to contribute. For example:
   a It is probable that the 9 V 'heavy duty' batteries used in smoke detectors will still have functionality after 1 year. Could these batteries be safely used in another, less critical context before their disposal? Organize a collection.
   b Recycling is the preferred option for disposal of all fire alarm components. In many countries, it is legal to dispose of up to two devices in domestic waste during any period of seven days. In other countries, the detector must be returned, intact, to the manufacturer. Find out how smoke detectors are disposed of or recycled in your country, and make your community aware of what it should do.

### ◆ Assessment opportunities

◆ In this activity you have practised skills that are assessed using Criterion D: Reflecting on the impacts of science.

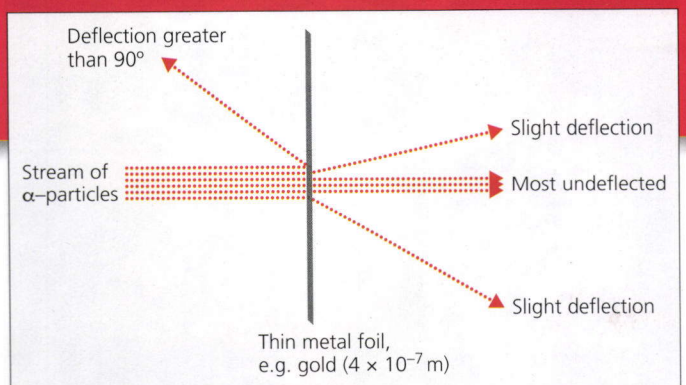



**Figure 7.12** The deflection of alpha particles in the famous 'gold foil' experiment

# A 'BLACK-BOX' EXPERIMENT: THE DISCOVERY OF THE NUCLEUS

In 1909 the New Zealand-born British physicist Ernest Rutherford (1871–1937) and his graduate research students, Hans Geiger and Ernest Marsden, carried out a famous experiment on the atomic scale.

They directed a stream of alpha particles at a very thin gold foil, approximately 400 atoms in thickness. At the time, atoms were considered to be positively charged solids with a scattering of mobile negative changes (the 'plum pudding' model, Figure 8.2). Alpha particles are positively charged, so they predicted the positive charges in the gold atoms would repel them. However, the majority passed through the gold foil unimpeded. Some alpha particles indeed suffered small deflections. Incredibility, a very small number (approximately 1 in 10000) showed a large deflection of more than 90 degrees (Figure 7.12). Rutherford summarized this surprising result in a famous analogy, that it was 'as if you had fired a 15-inch [0.38m] shell at a piece of tissue paper and it came back and hit you'.

Gradually, they inferred that most of the mass of an atom must be located in a tiny, dense core. This they named the nucleus (Figure 7.13).

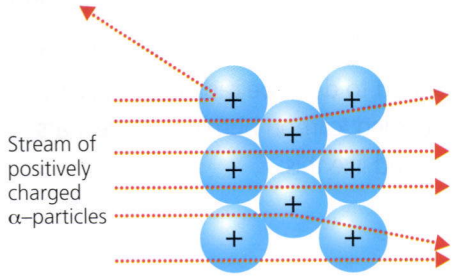



**Figure 7.13** The structure of the atom as revealed by the 'gold-foil' experiment

## ACTIVITY: Black-box experiments

### ATL

- Critical thinking skills: Recognize unstated assumptions and bias; recognize and evaluate propositions; use models and simulations to explore complex systems and issues
- Creative-thinking skills: Make unexpected and unusual connections between objects and/or ideas

### Investigating the validity of 'black-box' modelling

What made the interpretation of the results of gold foil experiment so challenging? In this task, you need to develop models that allow you to investigate the relationship between the numbers of 'deflected bullets' and 'dense, positively charged nuclei', and extrapolate the relationship shown by your data to that obtained by Rutherford's team.

### Planning

- **Your experimental models may be physical or virtual. You need to make at least two models to enable you to compare suitable variables. Both a risk analysis and completed environmental impact analysis must be included in your plan.**
- **What is the best control, and why?**

### Analyses

- **How can your results be transformed to show trends effectively? Suggestions include calculating averages, ranges or percentage change, multiplying by a constant, or translating the results of a two-dimensional spatial pattern to a three-dimensional pattern.**

### Reporting your investigation: interpreting the science

- **Reflect on the validity of your hypothesis, and whether the model you develop was a valid method to compare to Rutherford's approach.**

### Assessment opportunities

- In this activity you have practised skills that are assessed using Criterion B: Inquiring and designing and Criterion C: Processing and evaluating.

# How did the elements on Earth originate?

## WE ARE ALL STAR DUST

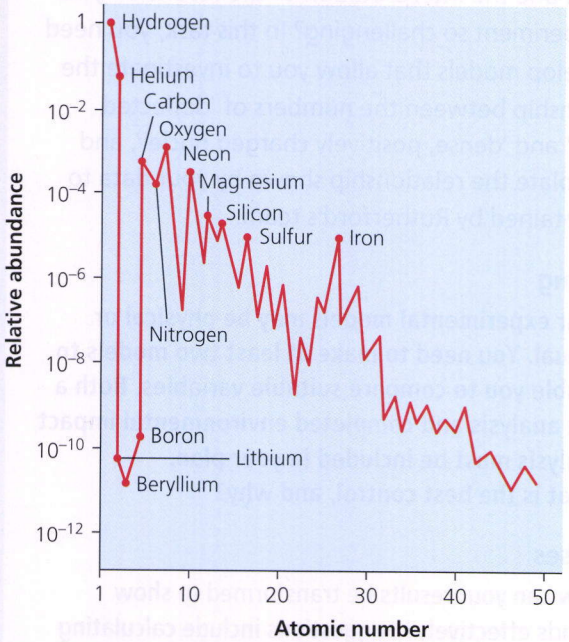



**Figure 7.14** Frequency of elements in the universe. Hydrogen (75 per cent) and helium (23 per cent) are the most abundant

In chemistry, you have investigated reactions involving many different elements. However, compared to the frequency of all the elements in the universe (Figure 7.14), the proportions of elements found on Earth are very different.

Earth is composed of about 35 per cent iron, 30 per cent oxygen, 15 per cent silicon and 10 per cent magnesium. It has even been suggested that most of Earth's elements that are heavier than iron are 'impurities' in the universe. How did the special composition of the Earth come about?

The chemical elements which make up the Earth and all the living organisms on the planet formed in a star. The changes in stars which release energy are the **fusion** reactions of

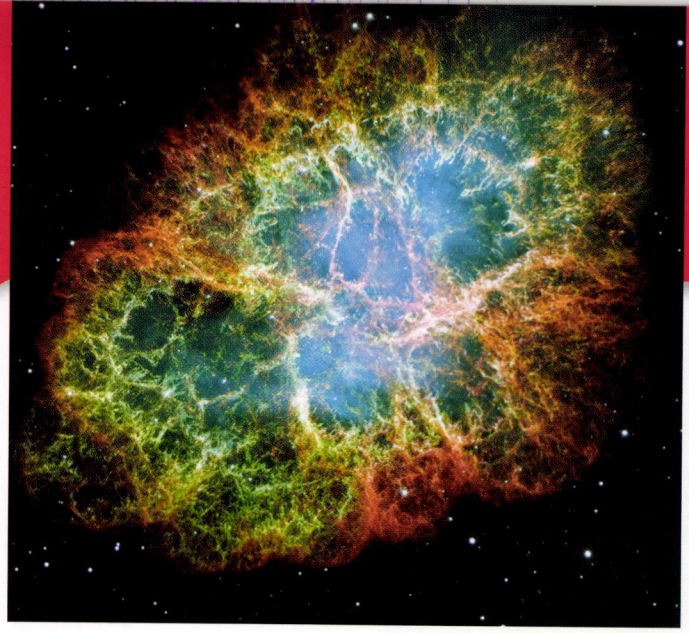


**Figure 7.15** The Crab nebula – a supernova remnant

atomic nuclei. At the enormously high temperatures in stars the electrons are removed from atoms to form highly charged ions. Most stars consist mainly of hydrogen. At temperatures of 10 million °C or higher, the inside of a star is hot enough for the nuclei of hydrogen atoms ($^{1}_{1}H$) to combine (fuse) with deuterium ($^{2}_{1}H$) to form helium ($^{3}_{2}He$). Next, helium nuclei fuse to form beryllium ($^{6}_{4}Be$). Other nuclear fusion reactions result in heavier elements, such as carbon and oxygen. Fusion reactions of these light elements release huge amounts of energy that make the star hot and release radiation.

Eventually all the hydrogen atoms in a star are used up. When this happens to small stars (like the Sun) they expand to become red giants. They gradually then fade away as the nuclear fusion reactions stop.

Chemical elements as heavy as iron ($^{61}Fe$) can be synthesized in the cores of more massive stars. Nuclear fusion reactions are endothermic and stop when the dying star collapses inwards under gravity, causing it to become very hot. Then the star explodes, and its matter bounces back into space as a spectacular supernova explosion (Figure 7.15). The collapsed core of the star becomes a very dense mass of neutrons or even a black hole, where gravity is so strong that even light rays cannot escape. Meanwhile the outer layers become so hot that the heaviest elements (beyond iron) are able to form.

The equations for fusion reactions are described with the same symbolism as is used to describe radioactive decay. Examples of a process called 'carbon burning' inside stars can therefore be described like this:

$$^{12}_{6}C + {}^{4}_{2}He \rightarrow {}^{16}_{8}O + {}^{0}_{0}\gamma$$

$$^{12}_{6}C + {}^{12}_{6}C \rightarrow {}^{24}_{12}Mg + {}^{0}_{0}\gamma$$

## ACTIVITY: Chemical elements from the stars

### ATL

- Critical-thinking skills: Gather and organize relevant information to formulate an argument; test generalizations and conclusions
- Communication skills: Negotiate ideas and knowledge with peers and teachers; read critically and for comprehension

Interpret the claims of 'We are all star dust' using the three-level guide below. (See Chapter 1, page 7.) Be prepared to justify your opinion!

### Level 1: Literal statements

Tick the box if you think the text actually says this.

1 ☐ **Fusion is the exact opposite of radioactive decay.**
2 ☐ **New elements are created when carbon burns.**
3 ☐ **Earth lost most of its light elements after it was formed.**
4 ☐ **New elements can only be made through fusion and radioactive decay.**

### Level 2: Interpretative statements

Tick the box if you think the text supports this opinion.

5 ☐ **Hydrogen is the building block for all the elements.**
6 ☐ **Earth once had a composition of elements similar to the rest of the universe.**
7 ☐ **Fusion and radioactive decay generate starlight.**
8 ☐ **$^{4}_{2}$Helium forms from the alpha decay of $^{6}_{4}$Be.**

### Level 3: Applied statements

Tick the box if you think this is a 'take home' message from the text. Be prepared to justify your opinion with your peers.

9 ☐ **Without black holes, we wouldn't be here.**
10 ☐ **Heavy elements are rarer because there are more steps involved in their creation.**
11 ☐ **The composition of elements found on a planet is continually changing.**
12 ☐ **Don't take the elements around you for granted!**

### Assessment opportunities

- In this activity you have practised skills that are assessed using Criterion A: Knowing and understanding and Criterion D: Reflecting on the impacts of science.

In the very high temperature, and very high pressure, conditions of the other regions of a supernova, neutrons collide with iron atoms, building up large, unstable radioactive isotopes. When these undergo beta decay, a proton is added to the nucleus. Through continual cycles of this process, elements with larger and larger nuclei are created (Figure 7.16).

$$^{61}_{26}\text{Fe} \rightarrow {}^{61}_{27}\text{Co} + {}^{0}_{-1}\text{e} + {}^{0}_{0}\gamma$$

When the Earth accreted from particles swirling at the edges of the same rotating cloud of interstellar dust and gas as the Sun, it may have collected a higher fraction of the heavy elements. Most of the lighter elements, hydrogen and the noble gases were subsequently lost when they were blown away by the 'solar wind', the stream of high energy electrons, protons and alpha particles pouring from the developing Sun. Meanwhile, the naturally occurring radioactive elements decayed. Each planetary body has a different composition, reflecting its unique evolution.

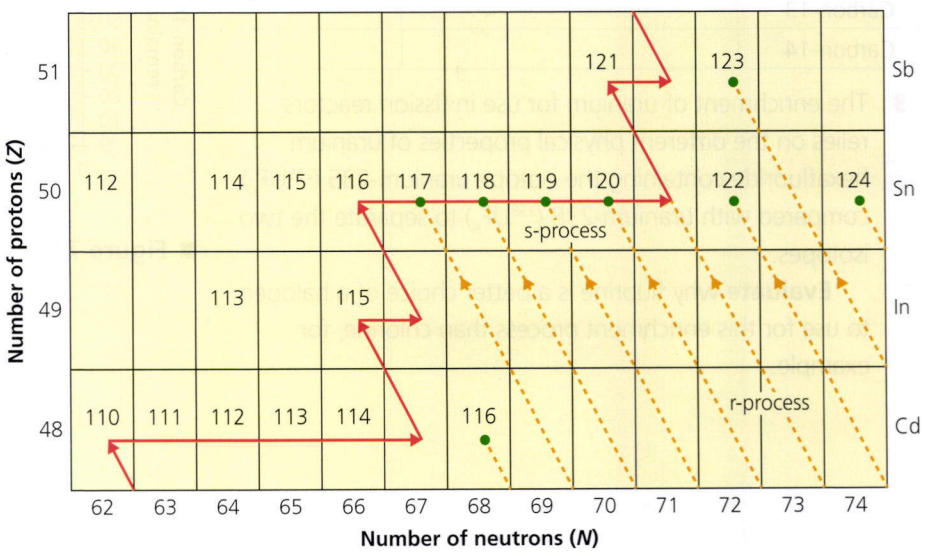



**Figure 7.16** A chart showing repeated cycles of neutron capture and beta decay, to create elements with large nuclei (r- and s-processes refer to *rapid* and *slow* neutron capture)

# SOME SUMMATIVE PROBLEMS TO TRY

Use these problems to apply and extend your learning in this chapter. The problems are designed so that you can evaluate your learning at different levels of achievement in Criterion A: Knowing and understanding.

A copy of a periodic table should be available for reference

### THESE PROBLEMS CAN BE USED TO EVALUATE YOUR LEARNING IN CRITERION A TO LEVEL 1–2

1 **State** the meaning of the symbols *A*, *N* and *Z*.

2 **Deduce** the composition of the nucleus in these three isotopes of carbon:

| Isotope | Atomic number | Proton number | Neutron number |
|---|---|---|---|
| Carbon-12 | | | |
| Carbon-13 | | | |
| Carbon-14 | | | |

3 The enrichment of uranium for use in fission reactors relies on the different physical properties of uranium hexafluoride containing the isotope uranium-235 ($^{235}UF_6$), compared with uranium-238 ($^{238}UF_6$) to separate the two isotopes.

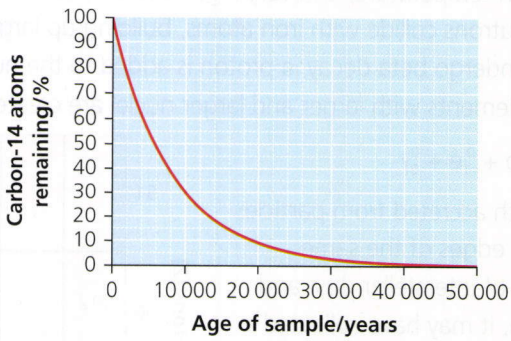
**Evaluate** why fluorine is a better choice of a halogen to use for this enrichment process than chlorine, for example.

### THESE PROBLEMS CAN BE USED TO EVALUATE YOUR LEARNING IN CRITERION A TO LEVEL 3–4

4 **Outline,** in a table,
- **a** the differences in the subatomic particles of hydrogen-1, hydrogen-2 and hydrogen-3 atoms
- **b** the similarities and differences of the chemical and physical properties of isotopes.

5 **Calculate** the relative atomic mass of each of the following elements:
- **a** lithium, consisting of 7.42% lithium-6 (6.0151 amu) and 92.58% lithium-7 (7.0160 amu)
- **b** copper, consisting of 69.09% copper-63 (62.9298 amu) and 30.91% copper-65 (64.9278 amu)
- **c** boron, consisting of 19.78% boron-10 (10.0129 amu) and 80.22% boron-11 (11.0093 amu).

6 With reference to Figure 7.17,
- **a** **estimate** the half-life of carbon-14
- **b** **evaluate** the suitability of this isotope to date artefacts linked to the arrival of Australian Aboriginal peoples, who definitely reached the continent more than 40 000 years ago.




■ **Figure 7.17** The **decay curve** of carbon-14

## THESE PROBLEMS CAN BE USED TO EVALUATE YOUR LEARNING IN CRITERION A TO LEVEL 5–6

**7** **Describe,** using a nuclear equation, the

- **a** α decay of polonium-218 to lead-214
- **b** β decay of neptunium-239 to plutonium-239
- **c** fusion of lithium-6 with hydrogen-2 to produce helium-4 and an α particle (in a star)
- **d** U-238 absorbing a neutron to form Pu-239 accompanied by the emission of a beta particle
- **e** beta decay of iron-61 to cobalt-60, a positron and gamma radiation.

**8** **Evaluate** the following information to make scientifically supported responses to the questions below.

The ratio of oxygen and hydrogen isotopes in water varies slightly with location. A certain region of a city will have a definite pattern of hydrogen and oxygen isotopes in their local water supply. This pattern is called an 'iso-signature' and drinks made in that area will also have the same 'iso-signature'.

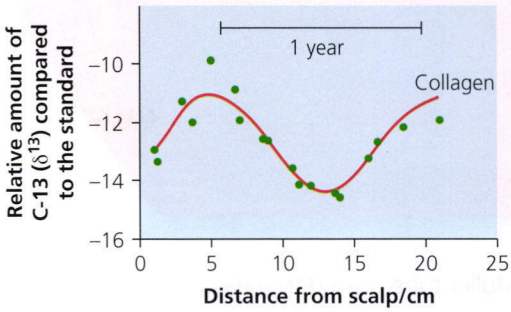
Listed in order of frequency that they are found in nature, the stable isotope for these elements are:

- hydrogen-1, hydrogen-2 and hydrogen-3
- oxygen-16, oxygen-18 and oxygen-17.

- **a** **List** all the possible forms of water molecules, using this format: $^{2}H^{17}O^{1}H^{1}$.
- **b** **Determine** the order, from the most common to the rarest natural form of the water, of the molecules you listed above.

**9** A gold atom has a radius of $0.1441 \times 10^{-9}$ m and a gold nucleus has a radius of $1.07 \times 10^{-15}$ m. The formula for the volume of a sphere is $4/3\ \pi r^3$. The mass of the gold atom is $3.27 \times 10^{-25}$ kg.

- **a** **Calculate** the
  - **i** volume of the gold atom
  - **ii** volume of the gold nucleus
  - **iii** percentage of the volume of the atom that is occupied by the nucleus
  - **iv** density of a gold atom (density = mass/volume)
  - **v** density of the gold nucleus. Ignore the mass of the electrons.
- **b** **Describe** how your results relate to Rutherford's gold foil experiment.




■ **Figure 7.18** Isotopic values from the hair of an Inca mummy

**10** Figure 7.18 shows the carbon-13/carbon-12 isotope signature analysis of the collagen (a kind of protein) in the very long hair of an ancient Inca mummy, from Peru. Diets that are high in foods like corn will have higher levels of carbon-13 than diets that are high in foods like beans. Corn is a grain crop that is usually harvested in autumn and can be stored for many years. Beans can be eaten fresh from spring and throughout summer, and can also be stored as dry food.

**Analyse** and **evaluate** the information in the graph to suggest

- **a** the time interval that would equate to a hair of length 21 cm
- **b** the reason for the variation of isotope frequency in different parts of the hair
- **c** the season when the Inca died.

## THESE PROBLEMS CAN BE USED TO EVALUATE YOUR LEARNING IN CRITERION A TO LEVEL 7–8

**11** **Explain** your answers for each of the situations below.

- **a** Bromine consists of two isotopes, $^{79}$Br (50.5%) and $^{81}$Br (49.5%). Data booklets usually give the approximate value for the relative atomic mass of bromine as 80. Is the accurate value just above or just below 80?
- **b** Copper consists of two isotopes, $^{63}$Cu and $^{65}$Cu. The relative atomic mass of copper is 63.5. Which of these isotopes is present in the greater abundance?

**12** A Geiger–Müller tube is used to measure the radiation at different distances from a source emitting alpha and gamma radiation. As the Geiger–Müller tube was gradually moved away from the source, it was found that the level of radiation fell very rapidly over the first few centimetres. However, after that the radiation fell more slowly. **Explain** these observations.

**13** In 1930 the physicist Paul Dirac proposed that all the fundamental particles have antiparticles whose electrical properties are opposite to the familiar particles.

**a** **Predict** the charge on the 'anti-electron' and write its nuclide symbol.

In 1932 the American physicist Carl Anderson (1905–1991) discovered the 'anti-electron' (now called a positron) by allowing cosmic rays to pass through a cloud chamber.

When particles and antiparticles collide they annihilate each other and are converted to energy.

**b** **Calculate**, using Einstein's equation $E = mc^2$, the energy produced by an 'electron–positron annihilation'. Assume the mass of the electron to be $9.1091 \times 10^{-31}$ kg and the speed of light ($c$) to be 299 792 458 m s$^{-1}$. Your answer should be in joules.

**14** The table below summarizes the numbers of stable isotopes and the combinations of odd and even numbers of protons.

| Proton number ($Z$) | Neutron number ($N$) | Number of stable isotopes | Percentage of total (254) |
|---|---|---|---|
| Even | Even | 148 | 58 |
| Even | Odd | 53 | 21 |
| Odd | Even | 48 | 19 |
| Odd | Odd | 5 | 2 |

Isotopes that appeared to have particularly stable arrangements of nucleons were identified. Further analyses revealed these isotopes were likely to meet one or more of these conditions:

- The total number of (protons and neutrons) in the nuclide of the isotope is **even**.
- The ratio $N/Z$ is close to 1.
- They have **2**, **8**, **20**, **28**, **50**, **82**, **114 protons** or **2**, **8**, **20**, **28**, **50**, **82**, **126**, **184 neutrons** (note the similarity of these two series of numbers; they have been described as 'magic').

**Analyse** the isotopes listed in the table below and make a scientifically supported judgment about their stability based on the information provided.

| | Isotope | Judgment | Reason |
|---|---|---|---|
| **a** | $^{14}_{7}N$ | | |
| **b** | $^{10}_{5}B$ | | |
| **c** | $^{16}_{8}O$ | | |
| **d** | $^{40}_{19}K$ | | |
| **e** | $^{23}_{11}Na$ | | |
| **f** | $^{28}_{56}Ni$ | | |
| **g** | $^{98}_{43}Tc$ | | |
| **h** | $^{208}_{82}Pb$ | | |

# Reflection

In this chapter you were introduced to nuclear chemistry, and explored the features and uses of stable and unstable isotopes. Like chemical equations, nuclear equations used to describe radioactive decay or fusion need to be balanced. Isotopes provide deep insight into the history of the universe and past climates of the Earth, and have a range of immediate applications in medicine, and forensic science, usually based on their radioactivity of kinetic properties.

| **Use this table to reflect on your own learning in this chapter.** | | | | | |
|---|---|---|---|---|---|
| Questions we asked | Answers we found | Any further questions now? | | | |
| **Factual:** What differences are there between the isotopes of an element? What can we learn from the isotope ratio? How often do we find different isotopes in a sample of an element? | | | | | |
| **Conceptual:** How did the elements on Earth originate? How do models of atomic structure help us understand their physical chemistry? | | | | | |
| **Debatable:** Should humans continue to use radioactive isotopes in our technologies despite the dangers of ionizing radiation? | | | | | |
| Approaches to learning you used in this chapter: | Description – what new skills did you learn? | How well did you master the skills? | | | |
| | | Novice | Learner | Practitioner | Expert |
| **Communication skills** | | | | | |
| **Collaboration skills** | | | | | |
| **Organization skills** | | | | | |
| **Critical-thinking skills** | | | | | |
| **Creative-thinking skills** | | | | | |
| **Learner profile attribute(s)** | Reflect on the importance of risk-taking for your learning in this chapter. | | | | |
| **Risk taker** | | | | | |

# 8 Why do electrons matter?

Protons define the **identity of an element**, but its **relationship** and **interaction** with other elements is a **function** of its outer electrons.

## IN THIS CHAPTER, WE WILL …

- **Find out** about redox reactions and the activity series.
- **Explore**
  - methods of representing patterns of electrons;
  - trends in the periodic table.
- **Take action** by suggesting how your school can recycle metals.

## CONSIDER AND ANSWER THESE QUESTIONS:

**Factual:** How does the main energy level affect an atom's chemical reactivity? How can we represent the organization of electrons in an atom?

**Conceptual:** How does the organization of electrons in shells contribute to an atom's oxidation state?

**Debatable:** To what extent could human progress be defined by its ability to control the reduction and oxidation of metals?

Now **share and compare** your thoughts and ideas with your partner, or with the whole class.

## These Approaches to Learning (ATL) skills will be useful …

- Communication skills
- Collaboration skills
- Organization skills
- Affective skills
- Reflection skills
- Critical-thinking skills
- Creative-thinking skills
- Transfer skills
- Information literacy skills

## Assessment opportunities in this chapter …

- Criterion A: Knowing and understanding
- Criterion B: Inquiring and designing
- Criterion C: Processing and evaluating
- Criterion D: Reflecting on the impacts of science



**Figure 8.1** What causes the colours of exploding fireworks?

## We will reflect on this learner profile attribute …

- Thinker – What thinking skills do we use in science? How can we interpret trends in reactivity (activity) to provide evidence about the arrangement of electrons in atoms? How do spreadsheets and similar technologies improve our ability to find patterns? Can these skills be used elsewhere? Is science creative?

## KEY WORDS

corrosion patina rusting

## THINK–PUZZLE–EXPLORE

What can we learn about chemistry from firework displays in the air (Figure 8.1)?

What do you **think** about how the chemistry you already know gives fireworks their properties?

What questions or **puzzles** do you have about how

1. **the rate of the reaction is controlled**
2. **different visual effects are determined**
3. **risk management factors are managed?**

How you can **explore** this topic?

# How does the main energy level affect an atom's chemical reactivity?

## ACTIVITY: A chemical rainbow!

### ATL

- Reflection skills: Consider content: What did I learn about today? What don't I yet understand? What questions do I have now?

### Materials and equipment

- Bunsen burner
- 0.1 M NaCl (aq)
- 0.1 M KCl (aq)
- 0.1 M LiCl (aq)
- 0.1 M $CsCl_2$ (aq)
- 0.1 M $CaCl_2$ (aq)
- 0.08 M $BaCl_2$ (aq)
- 0.1 M $CuCl_2$ (aq)
- matches or lighter
- safety mat
- nichrome wire loop
- beaker of dilute (0.1 M) HCl, to rinse
- if available, hand-held spectroscope

### Method

1. Light the Bunsen burner in a darkened room.
2. Dip the nichrome wire loop into one of the ionic solutions and hold it in the hot part of the roaring Bunsen burner flame.
3. If available, repeat this step, this time observing the results through a hand-held spectroscope.
4. Rinse the loop in the beaker of acid and flame it several times to clean away the residual salt solution.
5. Continue testing the remaining solutions.

### Discussing your observations

1. **State** how long the effect was sustained in the Bunsen burner flame.
2. **Identify** whether the non-metal or the metal in the solution is responsible for the effect.
3. **Suggest** whether the effect is the result of a physical change or a chemical reaction caused by atoms or ions. How could you test this idea?
4. Table 8.1 describes the wavelength and frequency of visible light in a rainbow. **Identify** the wavelength range of the radiation emitted when the solutions were heated and vaporized.
5. **Suggest** a relationship between your observations of exploding fireworks and Table 8.1.
6. How has this activity helped you explore electronic structure?

| Colour | Wavelength interval/nm | Frequency interval/THz |
|---|---|---|
| Violet | 430–380 | 700–790 |
| Blue | 500–430 | 600–700 |
| Cyan | 520–500 | 580–600 |
| Green | 565–520 | 530–580 |
| Yellow | 590–565 | 510–530 |
| Orange | 625–590 | 480–510 |
| Red | 740–625 | 405–480 |

**Table 8.1** Wavelength (nm) and frequency in terahertz (THz) of visible light of different colours

### Assessment opportunities

- In this activity you practised skills that are assessed using Criterion C: Processing and evaluating.

## What can we learn from emission spectra?

If you have studied waves in physics, you may be familiar with two equations that express the relationships (1) between **wavelength** and **frequency** (measured in **hertz**) and (2) between energy and frequency. They are summarized below, with a sample calculation to show how they can be applied.

1 $c = f\lambda$
where $\lambda$ is the symbol for wavelength (m), $f$ is the frequency (Hz) in cycles per second ($s^{-1}$) and $c$ is a constant, the speed of light, $3.00 \times 10^8\,m\,s^{-1}$. Notice that in this equation, wavelength and frequency are inversely proportional.

2 $E = hf$
where $E$ is the symbol for energy (J), $h$ is **Planck's constant**, $6.63 \times 10^{-34}\,J\,s$ (joule second) and $f$ is the frequency (Hz). Notice that in this equation, there is a directly proportional relationship between the energy and the frequency of radiation.

**Sample problem:** A source emits cyan light of wavelength 500.0 nm. Calculate the energy in kJ of one mole of photons of this radiation. Photons are light 'particles'. Light behaves both as a wave and a particle.

**Solution:**

1 Convert units to standard form:

**500.0** nm = $500.0 \times 10^{-9}$ m = $5.000 \times 10^{-7}$ m

2 Determine the frequency, from $c = \lambda f$

$3.00 \times 10^8\,m\,s^{-1} = (5.000 \times 10^{-7}\,m) \times f$

$f = 6.00 \times 10^{14}\,s^{-1}$ (this value is also in Table 8.1 as 600 THz, or $600 \times 10^{12}\,s^{-1}$)

3 Determine the energy, $E = hf$

$E = (6.63 \times 10^{-34}\,J\,s) \times (6.00 \times 10^{14}\,s^{-1})$

$E = 3.98 \times 10^{-19}$ J (this is the value for one photon emitted)

4 Notice the question requires a response for a mole, therefore the answer needs to be multiplied by Avogadro's constant, ($6.02 \times 10^{23}\,mol^{-1}$, Chapter 6)

$E\,mol^{-1} = 3.98 \times 10^{-19}\,J \times (6.02 \times 10^{23}\,mol^{-1})$

$E\,mol^{-1} = 240\,kJ\,mol^{-1}$

## ACTIVITY: Exploring the amounts of energy emitted by coloured light

### ATL

- Transfer skills: Apply skills and knowledge in unfamiliar situations; make connections between subject groups and disciplines

1 **Calculate** the energy of the radiation emitted by a mole of each of the substances tested. (If your school has hand-held spectroscopes, do this for one of the spectral frequencies that matches the colour of the flame.)
2 **Use** the average frequencies in Table 8.1 to **list** the compounds used in the **flame tests** in order, from the least to the most visible light energy released.
3 **Suggest** how this activity helped you understand the chemistry of fireworks in the think–puzzle–explore routine with which you started.

### Assessment opportunities

- In this activity you practised skills that are assessed using Criterion C: Processing and evaluating.

# DISCOVERING ATOMIC STRUCTURE: AN OUTLINE

The flame test activity reveals that dividing science into branches creates somewhat artificial divisions. For example, we know elements are the simplest pure substances, from which all other substances (matter) are made. The smallest particles of an element that can exist are atoms. Dalton (Chapter 1), who based his inferences on the evidence from chemical reactions, pictured atoms as solid, hard balls of matter.

Much of the later development of our modern understanding of atoms came from physicists.

- Joseph John Thomson (1856–1940) used cathode ray tubes (the same technology that was also used in old-fashioned television screens) to show that strong electric fields could break down atoms into positively and negatively charged particles. He modified Dalton's model by suggesting that atoms consisted of mobile negatively charged electrons within a cloud of positive charge, like 'plums' within a 'pudding' (Figure 8.2).

A demonstration of a cathode ray tube (Crook's tube) can be seen here: **https://youtu.be/XU8nMKkzbT8**

- Ernest Rutherford demonstrated that atoms were not solid, but contained large empty spaces with the positive charge concentrated in a small, very dense nucleus (see Chapter 7).
- Niels Bohr (1885–1962) suggested electrons occupied **orbits** around the nucleus, and that the volume of the space occupied by electrons around the nucleus depended on the energy of the electrons. These possible locations for electrons at different distances from the nucleus are also called shells or main energy levels. When an electron absorbs a specific, fixed amount of energy (called a 'quantum') it is promoted to a different orbit. The same amount of energy is re-emitted as electromagnetic radiation when the electron drops back to its lower energy level (Figure 8.3).

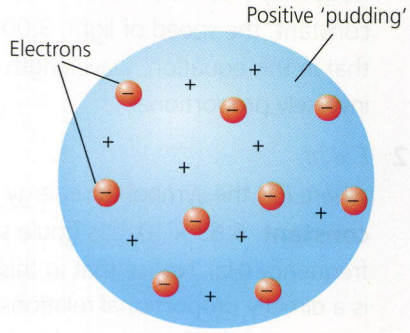



**Figure 8.2** J.J. Thomson described an atom as a 'plum pudding' in which the negatively charged electrons (the plums) are surrounded by a cloud of positive charge (the pudding)

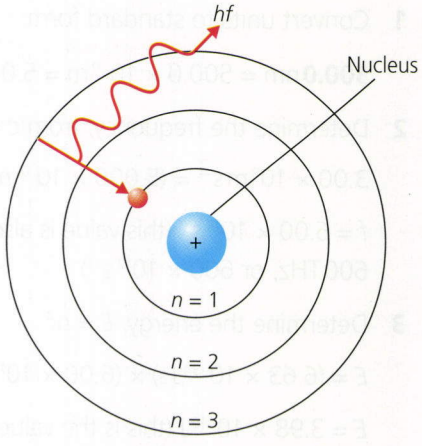



**Figure 8.3 Bohr's model** of atomic structure used a hydrogen atom, but his theories apply generally to the arrangement of electrons of atoms of all elements

# ACTIVITY: Exploring data sheets

## ATL

- Organization skills: Use appropriate strategies for organizing complex information
- Critical-thinking skills: Interpret data

Investigating spreadsheets may reveal patterns and provide deeper insight into the relationships between electrons and the nucleus of the elements in the periodic table.

In this activity you will extract data from spreadsheets, to discover examples of trends across periods and down groups of the periodic table. It is suggested you select the relevant information and represent it either as a scatter graph or as a line graph, using the atomic number of the element as the independent variable (on the *x*-axis). It may be helpful to work with a partner, or select different parts of the activity to cover all the tasks collectively as a class. It may also be helpful to focus on the first 20 elements only.

Download a spreadsheet representation of the periodic table. Examples to consider include

www.mrbigler.com/documents/Periodic-Table.xls

www.dbooth.net/mhs/common/p-tables.xls

You will notice that some of these examples include images showing a periodic table as well as tabular information (separate pages are listed as tabs at the bottom of the spreadsheet). Explore the tabs to find the data required for the following graphs.

1 **Plot** the relationship between the following dependent variables and the atomic number (Z):
   - **a** atomic radius
   - **b** first ionization energy
   - **c** electronegativity
   - **d** melting point
   - **e** density
   - **f** oxidation state/s
2 **Describe** the trends shown in each graph, and relate these to the location of the elements in the periodic table, for groups and periods.

An American chemist, Gilbert N. Lewis (1875–1946), first suggested bond formation required pairs of electrons, initially modelling atoms as cubes in which any vertex represented an electron. Although this early model could not explain the formation of triple bonds, it did suggest there was something special about the number eight. The set of eight outer electrons (an '**octet**') of the 'cubic atom' matched patterns seen in groups of the periodic table. He suggested that the non-reactivity of a noble gas resulted from its complete outer electron shell, and that the reactivity and bonding behaviour of other elements could be explained by the loss and gain of electrons to attain the electron arrangement of the nearest noble gas.

3 **Evaluate** whether the patterns and trends of your graphs provide evidence to support Lewis's idea.
4 **Present** your graph/s to the class, and share your thinking about the reasons for the trends. Can you reach any general conclusions linking your patterns?

## Assessment opportunities

- In this activity you have practised skills that are assessed using Criterion C: Processing and evaluating.

## Using spreadsheets

You will already be aware of how spreadsheet software improves the efficiency of routine operational calculations, such as determining the composition of nuclides, or discovering proportional relationships between variables or graphing data. They are also a very efficient way to store and extract data.

# EXTENSION

There are many examples of **interactive periodic tables** available online.

**Royal Society of Chemistry:** www.rsc.org/periodic-table (includes tabs to information describing trends)

**Dynamic periodic table:** www.ptable.com (includes pop-out details for individual isotopes)

**Chemical elements:** www.chemicalelements.com (includes details of electron arrangement)

**Chemicool:** www.chemicool.com (quotes from scientists connected with the history of the periodic table)

**University of Nottingham:** ed.ted.com/periodic-videos (videos of experiments)

Use data in some of these sources to explore trends in the periodic table, such as ionic radius, atomic volume and boiling point.

# How can we represent the organization of electrons in an atom?

## THE OCTET RULE

As atoms increase in size, adding electrons, they fill the orbits nearest to the nucleus first.

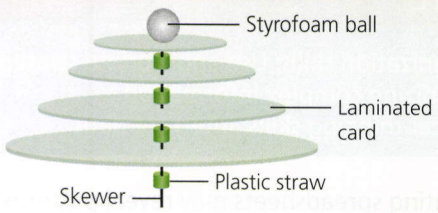
Figure 8.4 shows a simple model to help you visualize how this happens. The circular discs represent shells of increasing main **energy levels**, and the Styrofoam ball represents the nucleus. The first, small disc or innermost 'shell' can hold up to two electrons. These can be indicated using tacks or paper clips around the rim of the disc. The second, larger, 'shell' below may hold up to eight electrons. Looking down on the model from above provides an image of an atom's electron shell arrangement.

As shells fill from the lower levels outwards from the nucleus, a simple way for showing the electron arrangement is to group numbers of electrons together by shell, separated by a comma. For example, the **electron arrangement** for sodium atom ($Z = 11$) would be expressed as Na: 2, 8, 1. Therefore, the electron arrangement of a sodium ion is $Na^+$: 2, 8. Table 8.2 lists the electron arrangements of the noble gas elements.

| $Z$ | Shell number* | Element | Electron arrangement, by shell | Valence electrons |
|---|---|---|---|---|
| 2 | 1 | Helium | He: **2** | 2 |
| 10 | 2 | Neon | Ne: 2, **8** | 8 |
| 18 | 3 | Argon | Ar: 2, 8, **8** | 8 |
| 36 | 4 | Krypton | Kr: 2, 8, 18, **8** | 8 |
| 54 | 5 | Xenon | Xe: 2, 8, 18, 18, **8** | 8 |
| 86 | 6 | Radon | Ra: 2, 8, 18, 32, 18, **8** | 8 |

*Some resources number these shells as the K, L, M, N ... shells

■ **Table 8.2** Electron arrangements of noble gas elements, and their main energy levels




■ **Figure 8.4** A model to visualize the electron shells and main energy levels of the electrons they contain

This approach reveals several patterns:

1. Atoms of all noble gas elements (except helium) have just eight electrons in their outer shells. This outer shell is called the **valence shell** and the electrons in it are called the **valence electrons**. Elements in the other groups of the periodic table have unfilled shells and will lose, gain or share electrons so the arrangement of their outer shell also has eight electrons.
2. The expression $2n^2$, where $n$ refers to the period of the periodic table, describes the mathematical sequence for the maximum number of electrons in any shell (2, 8, 18, 32 ...).
3. Shells are not always immediately filled to the maximum number of electrons. For example, although the fourth (N) shell can contain up to 32 electrons, xenon has only 18 electrons in this shell. The inner-shell electrons are referred to as **core electrons** and usually have little to do with chemical reactions.

This idea of shells also helps explain some of the trends you discovered graphically in the previous activity.

### Atomic radius

The radius of the atoms tends to decrease across each period because there is a rapid increase in the nuclear charge, attracting all of the electrons towards the nucleus. For this reason, in Period 3 sodium atoms have a larger atomic radius than chlorine atoms.

The atomic and ionic radius increases down each group because atoms of each period of the table have an additional shell. This effect is stronger than the effect of adding to the nuclear charge. The inner-shell electrons also shield the valence electrons from the attraction of protons in the nucleus. For example, potassium's valence electrons are in the fourth shell (N) rather than sodium's third shell (M), and therefore the radius of a potassium atom is larger than the radius of a sodium atom.

## Ionization energies

The first ionization energy is the amount of energy required to remove one mole of electrons from a mole of gaseous atoms, resulting in a mole of gaseous cations (positive ions). It is expressed in units of $kJ\,mol^{-1}$. As you would predict, less energy is required to remove an electron from atoms of elements on the left-hand side of the periodic table, which have larger radii and small numbers of valence electrons, compared to removing electrons from elements on the right-hand side.

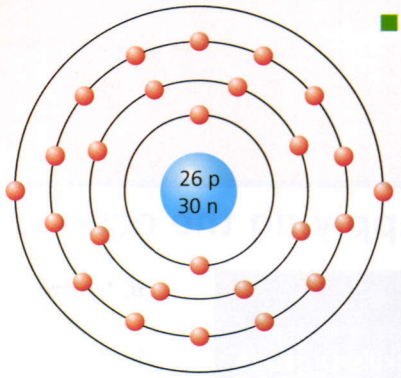
For similar reasons, radii increase down each group of the periodic table and less energy is required to remove electrons from atoms of elements with increasing numbers of electron shells.

## Electronegativity

Electronegativity is a calculated measure of the force of attraction of the nucleus for a pair of electrons in a covalent bond. As a trend across periods and down groups of the periodic table it is therefore related to an atom's valence electrons and its nuclear charge. On the Pauling scale, the least electronegative element is francium (0.7) and the most electronegative element is fluorine (4.0).

## Valency

The elements of each periodic table group share the same number of valence electrons. The 18 groups of the periodic table are sometimes shown in a contracted version (Table 8.3) that excludes the transition elements. You will recall elements with fewer than four valence electrons tend to lose electrons to form cations (positive ions), and those with more than four electrons tend to gain electrons and form anions (negative ions). Elements with four electrons, like carbon and silicon usually form covalent bonds with other atoms (Chapter 4).




■ **Figure 8.5** The removal of the outer two electrons lead to the formation of the iron(II) ion, $Fe^{2+}$. The third shell is very close in energy to the fourth shell so another electron can be removed, leading to the formation of the iron(III) ion, $Fe^{3+}$

The valency of a monoatomic ion is a number, corresponding to the number of electrons involved in creating bonds. The **oxidation number (or state)** can be positive or negative, because it describes the number of electrons that are lost or gained to achieve noble gas electron shell arrangement. For example, both aluminium (Al) and nitrogen (N) have a valency of 3, but the oxidation state of aluminium is +3 and nitrogen is –3.

Normally metal atoms lose electrons from their valence shell. For example, the alkali metals in group 1 always lose their outer electron to form an ion with a charge of +1.

However, many of the transition metals lose electrons from the shell next to the valence shell. The transition metal is then said to show variable valency. For example, copper forms copper(I) ions $Cu^{+}$ and copper(II) ions, $Cu^{2+}$; and iron can form iron(II) ions, $Fe^{2+}$ and iron(III) ions, $Fe^{3+}$. Iron atoms have the electron arrangement 2, 8, 14, 2 (Figure 8.5). The third shell can hold up to a maximum of 18 electrons. The third shell is not filled in iron and the fourth shell holds two electrons. This means the notation that describes electron shells using numbers only works effectively for the first 20 elements.

The spatial model shown in Figure 8.4 suggests a method for showing the location of electrons diagrammatically (Figure 8.5). In these diagrams, 'electrons' are shown as symbols on the edges of concentric circles, each representing an electron shell expanding out from the nucleus.

| Group | 1 | 2 | 13 | 14 | 15 | 16 | 17 | 18 |
|---|---|---|---|---|---|---|---|---|
| Contracted form | 1A | 2A | 3A | 4A | 5A | 6A | 7A | 8A |
| Charge | +1 | +2 | +3 | | –3 | –2 | –1 | 0 |
| Name | Alkali metals | Alkaline earth metals | Triels or icosagens | Tetrals or crystallogens | Pnictogens | Chalcogens | Halogens | Noble gases |
| Examples | Li, Na, K ... | Be, Mg, Ca... | B, Al, Ga... | C, Si, Ge... | N, P, As... | O, S, Se... | F, Cl, Br... | He, Ne, Ar... |

■ **Table 8.3** Common charges of elements of groups in the periodic table

# ACTIVITY: Applying the octet rule to periodicity

## ATL

- Communication skills: Organize and depict information logically

1 **Describe** the following atoms and ions using electron shell notation:
   a Ca
   b Cl
   c $Cl^-$
   d $Li^+$
   e $Ca^{2+}$
   f Si

2 The first ionization energy refers to the energy required to remove a mole of electrons from a mole of gaseous atoms. The table below shows the first ionization energy for the elements across period 2 of the periodic table.

The relative sizes of the values of ionization energy can be explained in terms of simple electrostatics: the charge on the nucleus, the amount of electron–electron repulsion and the distance of electrons from the nucleus.

| Element | First ionization energy/kJ mol$^{-1}$ |
|---|---|
| Lithium | 520 |
| Beryllium | 900 |
| Boron | 801 |
| Carbon | 1086 |
| Nitrogen | 1402 |
| Oxygen | |
| Fluorine | 1681 |
| Neon | 2081 |

   a **Formulate** an equation showing the first ionization of boron. Include state symbols.
   b **State** the general trend in ionization energy across period 2.
   c **Identify** the two elements which have lower than expected ionization energy.
   d **Explain** this general trend in terms of simple electrostatics involving the charges on electrons, protons and number of electron shells.
   e **Predict** the value for the first ionization energy of oxygen.
   f **Evaluate** and **explain** in electrostatic terms the following claim made by a student:

'Neon has the highest ionization energy because the electron being removed is from a filled outer shell'.

3 Figure 8.6 shows a section of the periodic table, but it is drawn in an unfamiliar format. The noble gases (group 18) are shown in the middle. These elements are unreactive and do not usually form compounds.

**Describe** and **explain** what this representation reveals about the relationship between the valency of elements and their distance from the noble gases on the periodic table.

| Group number | | | | | | | |
|---|---|---|---|---|---|---|---|
| 14 | 15 | 16 | 17 | 18 | 1 | 2 | 3 |
| | | | | | H Hydrogen | | |
| C Carbon | N Nitrogen | O Oxygen | F Fluorine | He Helium | Li Lithium | Be Beryllium | B Boron |
| | P Phosphorus | S Sulfur | Cl Chlorine | Ne Neon | Na Sodium | Mg Magnesium | Al Aluminium |
| | | | Br Bromine | Ar Argon | K Potassium | Ca Calcium | |
| | | | I Iodine | Kr Krypton | Rb Rubidium | | |
| | | | | Xe Xenon | Cs Caesium | | |
| 4 | 3 | 2 | 1 | 0 | 1 | 2 | 3 |
| Combining power (valency) | | | | | | | |

Figure 8.6

## Assessment opportunities

- In this activity you have practised skills that are assessed using Criterion A: Knowing and understanding.

# DOT-AND-CROSS DIAGRAMS

**Dot-and-cross diagrams** are an expansion of the electron shell diagram shown in Figure 8.5, to show how atoms of different valencies are involved in forming compounds to reach the stable electron arrangement of the nearest noble gas.

Figure 8.7 represents sodium becoming oxidized and chlorine reduced to form sodium chloride, $2Na(s) + Cl_2(g) \rightarrow 2\,NaCl(s)$. This representation shows how electrons are lost and gained in the formation of ions, which need to be written with a square bracket around them, with the charge shown outside of the brackets. These brackets are an important distinction between an ionic compound and a covalently bonded compound. Figure 8.8 extends this representation to a more complex ionic substance, lithium oxide.

Multiple covalent bonds may also be represented. In Figure 8.9, notice how the paired electrons are shown using different symbols, dots and crosses for each element, and how the double bond is represented as four closely grouped electrons, not just a pair of electrons as in a single bond. In this model, do the total numbers of electrons in the outer shells of carbon and oxygen satisfy the '**octet rule**'?

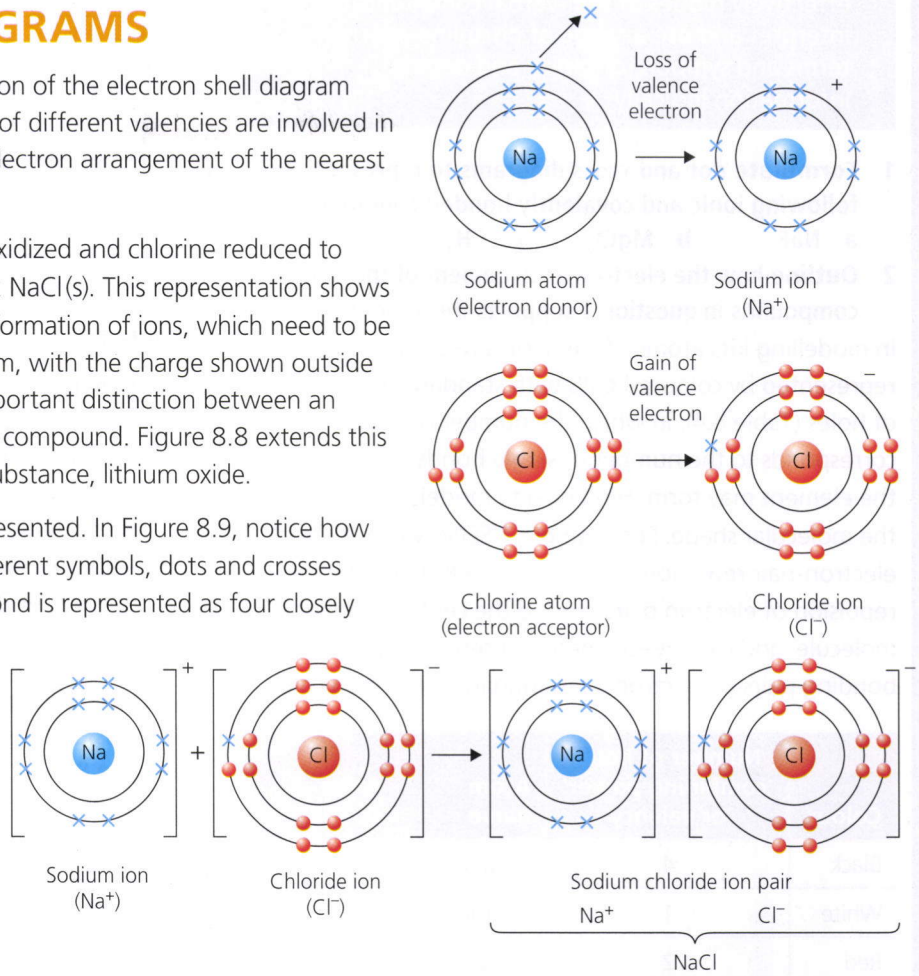



**Figure 8.7** Circles represent the electron shells of sodium and chlorine, which combine to form the ionic compound, sodium chloride. Square brackets are used to indicate each ion

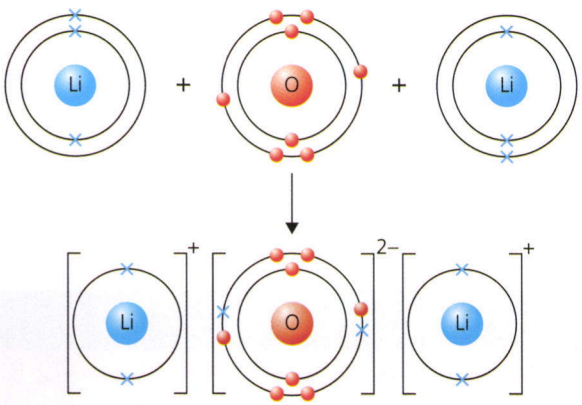



**Figure 8.8** Circles represent the electron shells of oxygen and lithium atoms, which combine to form the ionic compound lithium oxide

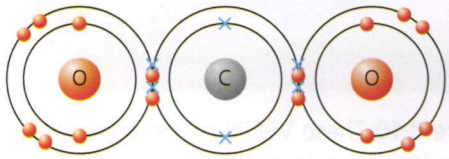



**Figure 8.9** A dot-and-cross diagram of a molecule of carbon dioxide, in which carbon and oxygen atoms bond covalently by sharing two electron pairs in each of two double bonds

# ACTIVITY: Representing bonds

## ATL

- **Communication skills:** Interpret and use effectively modes of non-verbal communication; interpret and use a range of discipline-specific terms and symbols; organize and depict information logically

1 **Formulate** dot-and-cross diagrams to represent the following ionic and covalently bonded compounds:
   a NaF  b $MgCl_2$  c $CH_4$  d $H_2O$
2 **Outline** how the electron arrangement of the ions and compounds in question 1 supports the 'octet rule'.

In modelling kits atoms of elements are usually represented by coloured balls with standardized numbers of holes (Table 8.4), in which the number of holes corresponds to the number of single bonds an atom of the element may form. High quality models also show the molecular shape. For example, VSEPR (valence shell electron-pair repulsion) models (Figure 8.10) model the repulsion of electron pairs around the central atom of a molecule, and can reveal whether a central atom has non-bonding pairs of electrons, resulting in a bent molecule.

| Colour | Number of holes 'combining power' or valency | Atom name | Atom symbol |
|---|---|---|---|
| Black | 4 | Carbon | C |
| White | 1 | Hydrogen | H |
| Red | 2 | Oxygen | O |
| Green | 1 | Chlorine | Cl |

**Table 8.4** Standard colours and number of holes found in atomic model kits

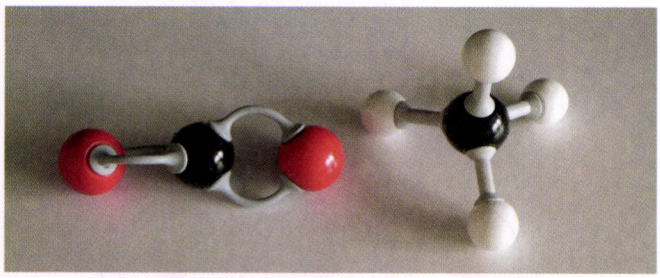


**Figure 8.10** These VSEPR models help determine molecular shape. In these examples, carbon dioxide has two bonding pairs of electrons and a linear shape, and methane has four bonding pairs producing a tetrahedral arrangement

| Elements | | Structural formula | Formula |
|---|---|---|---|
| H | O | H—O—H | $H_2O$ |
| H | Cl | | |
| O | Cl | | |
| C | H | | |
| C | Cl | | |
| C | O | | |
| N | H | | $N_2H_4$ |
| C | S | | $CS_2$ |
| C | N | | $C_2N_2$ |

**Table 8.5** Structural formulas of molecules

3 a **Construct** models of compounds from each pair of elements listed in Table 8.5. Structural formulas should represent each atom by its symbol and each bond with a line. Use two or three lines to show double and triple bonds.
   b **Describe** the relationship between the valency and the total number of single bonds an element may form.
4 Silicon forms a compound with carbon called silicon carbide. Silicon carbide is a solid with a giant three-dimensional structure similar to that of diamond (Figure 8.11).
   a **Deduce**
      i the valencies of the silicon and carbon atoms
      ii the empirical formula of silicon carbide.
   b **Predict** and **explain** three likely physical properties of silicon carbide.
   c Hot silicon carbide burns in excess oxygen to form a gaseous oxide and a solid oxide. **Formulate** a balanced equation, with state symbols, for the reaction.

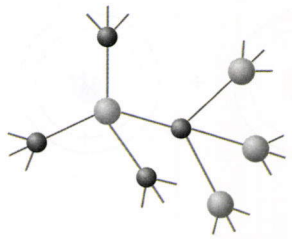


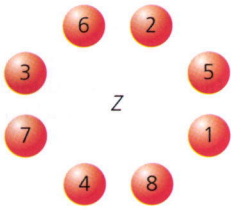
**Figure 8.11**

## Assessment opportunities

- In this activity you have practised skills that are assessed using Criterion A: Knowing and understanding.

## LEWIS (ELECTRON DOT) NOTATION

Lewis electron dot notation (or simply Lewis structures) is an alternative method for depicting the 'octet rule', focusing on the valence electrons. The notation centres on the atomic symbol, which represents the nucleus and core electrons. Up to eight 'dots', representing electrons in a shell, are written around the atomic symbol in the order shown in Figure 8.12. All the elements that share a group can be represented by the same number of dots surrounding their symbols (Table 8.6).




■ **Figure 8.12** The order in which the dots are completed in a Lewis electron dot structure

In this notation, paired electrons are shown as two dots side by side. Paired electrons in the valence shell are known as a 'non-bonding valence pair', or simply '**lone pairs**'.

In Lewis dot notation, unpaired electrons appear as single dots. The number of unpaired electrons indicates the atom's oxidation number, the number of electrons that will be gained or lost during a redox reaction.

When a bond forms between atoms, two unpaired electrons need to combine. All electrons have a magnetic property related to the way they 'spin'. Only electrons with opposite 'spin states' can form a bond.

In Lewis notation for ionic bonds (Table 8.7) the bracketing convention used in dot-and-cross diagrams is also used. The ionic charge is shown outside the brackets surrounding the symbol.

| Group | Number of valence electrons | Example atom | Representation |
|---|---|---|---|
| 1 | 1 | Sodium (Na) | Na· |
| 2 | 2 | Calcium (Ca) | ·Ca· |
| 13 | 3 | Boron (B) | ·B· |
| 14 | 4 | Carbon (C) | ·C· |
| 15 | 5 | Nitrogen (N) | ·N: |
| 16 | 6 | Oxygen (O) | ·O: |
| 17 | 7 | Fluorine (F) | :F: |

■ **Table 8.6** Lewis dot notation for valence electrons of atoms of elements representing groups in the contracted form of the periodic table

| Example ionic compound | Representation, ions | Representation, ionic compound |
|---|---|---|
| Sodium chloride, NaCl | $[Na]^+$ $[:\ddot{Cl}:]^-$ | $[Na]^+$ $[:\ddot{Cl}:]^-$ |
| Aluminium fluoride, $AlCl_3$ | $[Al^{3+}]$ $[:\ddot{F}:]^-$ | $:\ddot{F}:^-$ $Al^{3+}$ $:\ddot{F}:^-$ $:\ddot{F}:^-$ |

■ **Table 8.7** Lewis dot notation for ionic compounds

In Lewis notation for covalent bonds (Table 8.8, overleaf), single, double or triple bonds between the nuclei of the covalently bonded atoms can be indicated either as side-by-side dots, or indicated by the appropriate number of lines. When representing molecules, it may also be necessary to rotate or flip the positions of the dots, to make the 'valence electrons' fit together.

Polyatomic ions (Table 8.9) involve covalently bonded atoms that share a charge, and therefore both these conventions can be found in the Lewis structures.

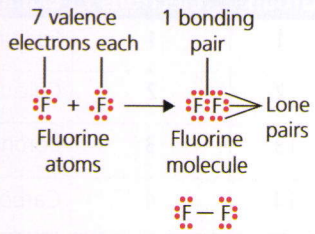
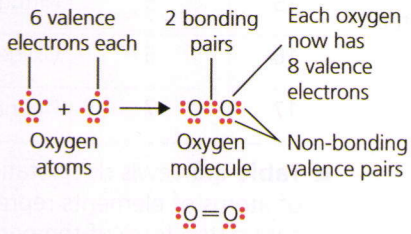
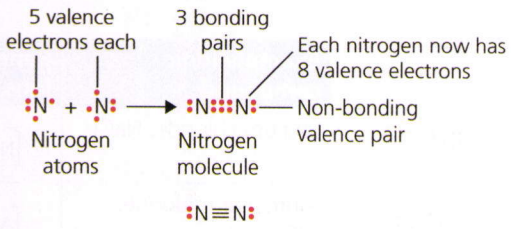
| Number of pairs of electrons | Example | Representation |
|---|---|---|
| Single covalent bond<br>1 shared pair of electrons | $F_2(g)$ |  |
| Double covalent bond<br>2 shared pairs of electrons | $O_2(g)$ |  |
| Triple covalent bond<br>3 shared pairs of electrons | $N_2(g)$ |  |

**Table 8.8** Lewis dot structures for covalent bonds

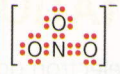
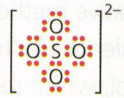
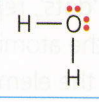
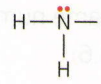
| Example | Representation |
|---|---|
| Nitrate ion, $NO_3^-$ |  |
| Sulfate ion, $SO_4^{2-}$ |  |
| Water molecule, $H_2O$ |  |
| Ammonia molecule, $NH_3$ |  |

**Table 8.9** Polyatomic ions and compounds can also be represented using the Lewis dot notation. The square brackets indicate the charge is shared by the ion as a whole

## ACTIVITY: Practising Lewis electron dot structures

### ATL

- **Communication skills:** Use and interpret a range of discipline-specific terms and symbols

### Assessment opportunities

- In this activity you have practised skills that are assessed using Criterion A: Knowing and understanding.

1. **Construct** the Lewis structures of the following atoms or ions:
   - a a phosphorus atom (P)
   - b a phosphide ion ($P^{3-}$)
   - c a silicon atom (Si)
   - d a 'hydronium' ion ($H_3O^+$) (Chapter 5).
2. **Identify** the number of valence electrons and the oxidation number of atoms in each of these elements, representing the groups in the shortened version of the periodic table.

| Group | 1 | 2 | 13 | 14 | 15 | 16 | 17 | 18 |
|---|---|---|---|---|---|---|---|---|
| Dot notation | Li• | •Be• | •B• | •C• | •N: | •O: | :F: | :Ne: |
| Number of valence electrons | | | | | | | | |
| Oxidation number in compounds | | | | | | | | |

# How does the organization of electrons in shells contribute to an atom's oxidation state?

## DESCRIBING REDOX REACTIONS WITH LEWIS DOT NOTATION

Oxidation once meant 'the combination of an element to form an oxide', but you have learnt another, more general, definition: 'oxidation means the loss of electrons' (Chapter 3). Lewis dot notation clearly demonstrates how this later definition incorporates the traditional definition. For example, consider what happens when iron rusts to form iron(III) oxide:

$$4Fe(s) + 3O_2(g) \rightarrow 2Fe_2O_3(s)$$

Iron is oxidized because electrons are transferred from two iron atoms to three oxygen atoms (Figure 8.13), forming the ionic compound iron(III) oxide.

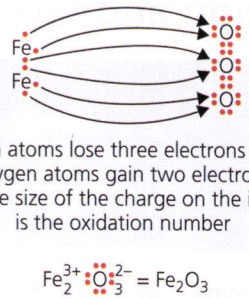



**Figure 8.13** Oxidation of iron shown with Lewis dot notation

Lewis dot notation makes clear that oxygen is not required for oxidation. For example, in the demonstration synthesis reaction (Chapter 6) of iron reacting with sulfur to form iron(II) sulfide, $Fe(s) + S(s) \rightarrow FeS(s)$, iron atoms are oxidized because electrons are transferred to the more electronegative sulfur atoms.

Lewis dot notation also shows that the sulfur atoms were reduced in this reaction, because they have gained electrons. You will recall that oxidation and reduction are paired processes and involve the transfer of electrons.

Lewis dot notation can also help identify how oxidation numbers change during a redox reaction of a covalently bonded molecule, such as hydrogen fluoride. The rules of oxidation numbers assume the more electronegative atom (fluorine) has a preferential attraction for the electrons, a bias that vanishes when the molecule decomposes (Figure 8.14). The half-reaction describing the decomposition of the hydrogen fluoride is a redox reaction.

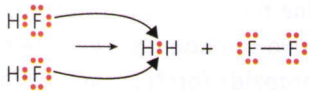



**Figure 8.14** A redox reaction of hydrogen fluoride: $2HF(g) \rightarrow H_2(g) + F_2(g)$ shown with Lewis dot notation. It has been oxidized to fluorine and reduced to hydrogen

$2F^- \rightarrow F_2 + 2e^-$ involves loss of hydrogen (H) and is oxidation. Notice how the oxidation number of fluorine increased from –1 to 0.

$2H^+ + 2e^- \rightarrow H_2$ involves gain of hydrogen (H) and is reduction. The oxidation number of hydrogen has decreased from +1 to 0.

## ACTIVITY: Extending your understanding of oxidation and reduction

### ATL

- Critical-thinking skills: Interpret data; revise understanding based on new information and evidence

**1** **Known masses of zinc powder were added to excess copper(II) sulfate solution. The copper formed was washed, dried and weighed.**

| Mass of zinc used/g | 0.20 | 0.30 | 0.40 | 0.50 | 0.60 | 0.70 |
|---|---|---|---|---|---|---|
| Mass of copper produced/g | 0.20 | 0.30 | 0.41 | 0.49 | 0.58 | 0.68 |

**Plot** the results as a suitable line graph. Use it to **determine** the mass of zinc needed to produce 0.65 g of copper.

**2** **Chlorine forms a range of oxides which are usually explosive compounds. They are coloured except for the heptoxide (prefixes are explained in Chapter 4). Oxygen is more electronegative than chlorine.**

**a** **Deduce** the formulas and oxidation numbers required to complete the following table.

| Name of chlorine oxide | Formula | Oxidation number of chlorine |
|---|---|---|
| Dichlorine monoxide | $Cl_2O$ | |
| | $ClO_2$ | |
| Dichlorine hexoxide | $Cl_2O_6$ | |
| Dichlorine heptoxide | | |

**b** When dichlorine monoxide is heated, the gas explodes to its constituent elements.

i **Formulate** a balanced chemical equation for this reaction.

ii **Explain** why this is a redox reaction.

**c** When chlorine monoxide is dissolved in water, chloric(I) acid ('bleach') is formed.

i **Formulate** a balanced chemical equation for this reaction.

ii **Explain** why this is not a redox reaction.

**d** Chlorine dioxide is a yellow–green gas and a powerful oxidizing agent. It breaks the octet rule and has an unpaired electron on the chlorine. Species with unpaired electrons are known as free radicals. **Suggest** a Lewis (dot-and-cross) diagram for the molecule.

**e** Dichlorine hexoxide, $Cl_2O_6$, exists in a reversible equilibrium with chloride trioxide, $ClO_3$:

$Cl_2O_6(l) \rightleftharpoons 2ClO_3(g)$

**Explain** why this reaction is not a redox reaction.

### Assessment opportunities

- In this activity you have practised skills that are assessed using Criterion A: Knowing and understanding.

## ACTIVITY SERIES OF METALS

The chemical reactivity of a metal depends on how easily it forms positive ions (cations). The more reactive a metal is, the more easily it forms positive ions.

It is useful to arrange metals in an **activity series**. Table 8.10 lists some familiar metals from the most reactive to the least reactive. The pattern is the same regardless of the reactions.

## The reactions of metals with air

Nearly all metals react with oxygen in the air to form an oxide. The rate of the reactions increases by heating the metal. With some metals, the reaction is vigorous. Potassium, sodium, calcium and magnesium all ignite on heating and an exothermic reaction occurs. Potassium, sodium and calcium burn with characteristic flame colours (Figure 8.1). Other metals, including zinc in powdered form, may glow but not catch fire, indicating they are far less reactive. With other metals, including aluminium, copper and lead, there is little reaction. These metals may already have an unreactive compound covering their surface, which prevents reaction with oxygen in the air. Sometimes this oxide is coloured.

## The reactions of metals with water

Potassium and sodium react violently with the surface of water, producing enough heat to melt the metals, and ignite the hydrogen gas formed. Owing to the presence of excited metal atoms, it burns with a coloured flame. An alkaline solution is formed. Lithium reacts less vigorously, but the reaction is similar. Calcium sinks, steadily produces hydrogen gas and forms a dilute alkaline solution and a white suspension of calcium hydroxide, which has low solubility. Magnesium turnings sink and a very, very slow reaction takes place, producing hydrogen gas. Aluminium, zinc, iron, lead and copper do not react with water.

Metals can also be reacted with steam to establish the reactivity of metals.

## The reactions of metals with dilute acid

Potassium, sodium, lithium and calcium should never be added to dilute acids as they react explosively. Magnesium, zinc, iron and lead, from the middle of the activity series, react with dilute hydrochloric acid to form the metal chloride (a salt) and hydrogen gas.

The reaction of dilute hydrochloric acid with magnesium is fairly fast, but the lower the reactivity of the metal the slower the reaction becomes. Lead reacts very slowly with dilute hydrochloric acid. Copper (the least reactive metal in this activity series) does not react with dilute hydrochloric acid.

In each of these reactions, the metal becomes oxidized, losing electrons to form the positively charged ion in an ionic compound, for example:

$Na \rightarrow Na^+ + e^-$

$Ca \rightarrow Ca^{2+} + 2e^-$

$Al \rightarrow Al^{3+} + 3e^-$

<table>
<tr><th>Metal</th><th>General trend</th><th>Reaction with oxygen</th><th>Reaction with water</th><th>Reaction with dilute hydrochloric acid</th></tr>
<tr><td>Potassium</td><td rowspan="10">Most reactive<br>↓<br>Decreasing reactivity<br>↓<br>Least reactive</td><td rowspan="5">React with oxygen when heated<br>↓<br>Reaction becomes less violent</td><td rowspan="5">React with cold water, forming metal hydroxide with hydrogen gas</td><td>Explosive</td></tr>
<tr><td>Sodium</td></tr>
<tr><td>Lithium</td></tr>
<tr><td>Calcium</td></tr>
<tr><td>Magnesium</td><td rowspan="4">React forming metal chloride salt and hydrogen gas</td></tr>
<tr><td>Aluminium</td><td>Protected by thin oxide film</td><td>Protected by thin oxide film</td></tr>
<tr><td>Zinc</td><td rowspan="2">Very slow</td><td rowspan="2">Only react with steam</td></tr>
<tr><td>Iron</td></tr>
<tr><td>Lead</td><td rowspan="2">Very slow with heat</td><td rowspan="2">No reaction</td><td>Very slow</td></tr>
<tr><td>Copper</td><td>No reaction</td></tr>
</table>

**Table 8.10** Summary of a reactivity or activity series of selected metals

# ACTIVITY: Displacing metal ions from aqueous solution

## ATL

- Transfer skills: Change the context of an inquiry to gain different perspectives

**Safety:** Wear eye protection and gloves. Solutions with copper(II) and lead(II) ions should be disposed of in the heavy metal waste bottle.

### Materials and equipment

- six clean iron nails
- six pieces of foil (5 mm × 5 mm) of each of the following metals: aluminium, copper, lead, magnesium, zinc
- 0.1 M solutions of
  - $Al(NO_3)_3(aq)$
  - $Cu(NO_3)_2(aq)$
  - $Pb(NO_3)_3(aq)$
  - $Mg(NO_3)_3(aq)$
  - $Zn(NO_3)_3(aq)$
  - $[(NH_4)_2Fe(SO_4)_2 \cdot 6H_2O]$. This is called aqueous ammonium iron(II) sulfate and is less liable to oxidation by oxygen in the air than iron(II) sulfate
- test tubes or spotting tiles, pipettes
- heavy metal waste residue bottle

### Method

1. **Design** a matrix (table) listing all combinations of the metals and the ion solutions.
2. Place a 1 cm depth of each solution in separate test tubes/spotting tiles. To each tube, add a small piece of aluminium foil. Record evidence for the displacement of the metal ion.
3. After five minutes, empty all the tubes or spotting tiles (disposing of lead(II) and copper(II) solutions in the heavy metal waste bottle), and rinse them.
4. Repeat the experiment using a different metal until all of the combinations have been tested.

### Analysing data

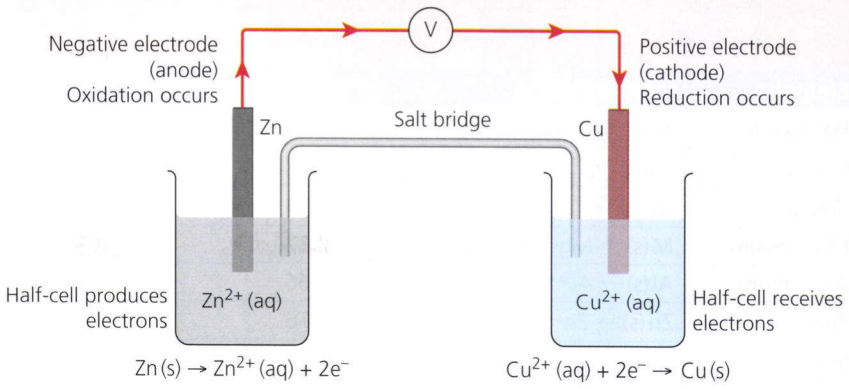
1. **Present** a 'reactivity series' from your results.
2. **Compare** your results with Table 8.10, explaining any anomalies.
3. **Formulate**, for the reactions you observed
   a. half-equations to describe the substance being oxidized and the substance being reduced
   b. ionic equations.
4. **Discuss** the relationship between the reactivity of a metal and the ease (energy required) with which it loses electrons, its electronegativity, valency and ionization energy.
5. **Evaluate** the work of an MYP student who completed a similar investigation, in which she tested a number of metals with dilute sulfuric acid. A page from her laboratory notebook is shown below.

| Metal | *Gas released* | *Other changes* |
|---|---|---|
| Zinc | | Zinc reacts and slowly disappears. Solution remains colourless. |
| Magnesium | | Magnesium reacts and disappears quickly. |
| Iron | No gas | Iron reacts very slowly.<br><br>Solution turns pale green. |
| Gold | No gas | |
| Sodium | This experiment was not attempted. | This experiment was not attempted. |

   a. **State** information that could have been shown in the blank cells.
   b. **Suggest** why the student did not attempt the experiment with sodium.
   c. **Identify** a possible error in the data, and cite evidence for your judgment.
   d. **Construct** the ionic equation for the reaction of iron with sulfuric acid.
6. The metal beryllium (an alkaline earth metal) reacts slowly with hydrochloric acid, but does not react with steam. Where should beryllium be placed in the activity series?

## Assessment opportunities

- In this activity you have practised skills that are assessed using Criterion A: Knowing and understanding.




■ **Figure 8.15** An example of a voltaic cell, consisting of a zinc half-cell and a copper half-cell. The electric current results from the two metals having different reactivities. The salt bridge, typically filter paper dipped in a solution of $KNO_3(aq)$, completes the circuit and is necessary for ion flow

## Displacement reactions of metals

The activity series is a useful tool to make predictions about whether a metal is able to displace the ions in solutions of metal ions (from soluble salts). In general, a more reactive metal will displace a less reactive metal from a solution of one of its salts. For example, magnesium can be expected to displace iron(II) ions from iron(II) sulfate solutions, and iron would displace copper(II) ions from copper(II) sulfate solutions, because magnesium forms ions more readily than iron, and iron forms ions more readily than copper. Conversely, lead will not react with zinc ions from zinc sulfate solution, or with magnesium ions from magnesium sulfate.

**Displacement reactions** of metals are redox (reduction–oxidation) reactions.

The more reactive metal changes from atoms into metal ions. For example, if a piece of zinc is added to a solution of copper(II) sulfate:

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

This half-equation describes oxidation (loss of electrons).

The ions of the less reactive metal change into metal atoms. For example:

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

This half-equation describes reduction (gain of electrons).

Combining the two half-equations results in an ionic equation that describes the reaction between zinc and copper(II) sulfate solution:

$$Cu^{2+}(aq) + Zn(s) \rightarrow Zn^{2+}(aq) + Cu(s)$$

This redox reaction involved the transfer of electrons from the zinc atoms to the copper(II) ions. The zinc atoms are reducing agents and the copper(II) ions are oxidizing agents.

# VOLTAIC CELLS

A **voltaic cell** is a device in which the relative difference in the chemical reactivity of two elements is used to generate an electric current via a redox reaction. Figure 8.15 shows a zinc–copper voltaic cell, named after each of its metal electrodes, which are metals placed in ionic solutions. Unconnected in their 'half-cells', each of the metal atoms will be in equilibrium with its ionic solution, $M(s) \rightleftharpoons M^{n+}(aq) + ne^-$, where M indicates the metal and $n$ the number of electrons it loses.

Zinc is a more active metal than copper (Table 8.10). This means that compared to copper atoms, zinc atoms will oxidize (give up electrons) more readily. When the two electrodes are connected in a circuit with a conductor (wire), and a **salt bridge**, the electrode with the more active metal is where oxidation occurs:

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

By definition, this makes the zinc electrode the negative electrode, or anode.

The electrode with the less reactive metal is where reduction occurs. This is the positive electrode, or cathode. In the example, the electrons are accepted by copper(II) ions:

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

The overall reaction is a redox reaction, exactly the same as the example discussed in the activity above, except that the electrons flow through a circuit:

$$Zn(s) + Cu^{2+}(aq) \rightarrow Zn^{2+}(aq) + Cu(s)$$

| Element | Ionic equation | $E^{\ominus}$ (volts) | Notes |
|---|---|---|---|
| Potassium | $K(s) \rightarrow K^+(aq) + e^-$ | −2.93 | Most active metal |
| Calcium | $Ca(s) \rightarrow Ca^{2+}(aq) + 2e^-$ | −2.87 | |
| Sodium | $Na(s) \rightarrow Na^+(aq) + e^-$ | −2.71 | |
| Magnesium | $M(s) \rightarrow Mg^{2+}(aq) + 2e^-$ | −2.37 | |
| Aluminium | $Al(s) \rightarrow Al^{3+}(aq) + 3e^-$ | −1.66 | |
| Zinc | $Zn(s) \rightarrow Zn^{2+}(aq) + 2e^-$ | −0.76 | |
| Iron | $Fe(s) \rightarrow Fe^{2+}(aq) + 2e^-$ | −0.45 | |
| Tin | $Sn(s) \rightarrow Sn^{2+}(aq) + 2e^-$ | −0.14 | |
| Lead | $Pb(s) \rightarrow Pb^{2+}(aq) + 2e^-$ | −0.13 | |
| Hydrogen | $2H^+(aq) + 2e^- \rightarrow H_2(g)$ | 0.00 | Reference element |
| Copper | $Cu(s) \rightarrow Cu^{2+}(aq) + 2e^-$ | +0.34 | |
| Iodine | $2I^-(aq) \rightarrow I_2(g) + 2e^-$ | +0.54 | Least active non-metal |
| Silver | $Ag(s) \rightarrow Ag^+(aq) + e^-$ | +0.80 | Least active metal |
| Bromine | $2Br^-(aq) \rightarrow Br_2(g) + 2e^-$ | +1.09 | |
| Chlorine | $2Cl^-(aq) \rightarrow Cl_2(g) + 2e^-$ | +1.36 | |
| Fluorine | $2F^-(aq) \rightarrow F_2(g) + 2e^-$ | +2.87 | Most active non-metal |

**Table 8.11** Examples of standard reduction potentials of elements ($E^{\ominus}$)

## The standardization of electrode potential differences

In the voltaic cell, the difference in chemical activities between the two metals will be recorded as a relative voltage. **Standard electrode potentials** are always referenced to a **standard hydrogen electrode** (SHE), using an inert electrode (platinum) in 1.0 M hydrogen ions (acid electrolyte) in one half-cell, and 1.0 M ionic solutions in the second half-cell at STP (25 °C and 0.1 MPa pressure). The standard hydrogen electrode has a relative electrode potential of 0.00 V (Table 8.11).

# ACTIVITY: Linking the reactivity series of metals and voltage

## ATL

- Critical-thinking skills: Interpret data; recognize and evaluate propositions

1. **Table 8.11 shows standard reduction potentials. Suggest how this would this differ from a table of standard oxidation potentials, found in some texts.**
2. **Identify the two elements listed in Table 8.11 that would generate the greatest potential difference.**
   **Formulate ionic equations for the reactions, including half-equations for the reaction that could occur.**
3. **A shorthand way of describing the electrodes in a voltaic cell is to summarize the reactants, for example $Zn(s)/Cu^{2+}(aq)$ for the cell in Figure 8.15. The size of the potential difference in a voltaic cell can be calculated using the equation below:**

$$\text{Voltage generated} = E^{\ominus}_{\text{cell}} = E^{\ominus}_{\text{cathode}} - E^{\ominus}_{\text{anode}}$$

**To carry out the calculation, the cell with the more positive reduction potential becomes the reduction cell (cathode). The reaction will only proceed if the potential difference (voltage) generated is positive.**

**Calculate the potential differences generated in voltaic cells with the following pairs of electrodes, and predict whether each reaction will occur. The first example has been completed to guide you.**

| Electrodes | Voltage generated (standard solutions) | Does the reaction proceed? |
|---|---|---|
| $Cu^{2+}(aq)/Zn(s)$ | (0.34 V) − (− 0.76 V) = 1.11 V | Yes |
| $Zn(s)/Ag^+(aq)$ | | |
| $Fe(s)/Cu^{2+}(aq)$ | | |
| $Mg(s)/Pb^{2+}(aq)$ | | |
| $Sn^{2+}(aq)/Ag(s)$ | | |

## Assessment opportunities

- In this activity you have practised skills that are assessed using Criterion A: Knowing and understanding.

# ACTIVITY: Corrosion and corrosion protection

## ATL

- Collaboration skills: Delegate and share responsibility for decision making; help others succeed; encourage others to contribute

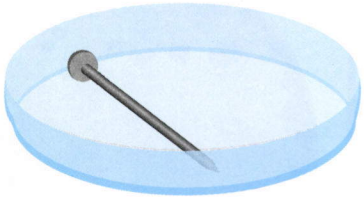
**Safety:** Always wear eye protection and gloves. The ferri cyanide solution is a mild irritant to eyes and skin.

### Materials and equipment

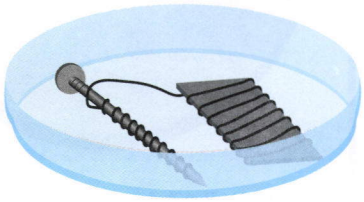
- 2 × Petri dishes
- 2 × iron nails
- emery paper
- zinc strip
- fine wire
- 1.0 M NaCl(aq)
- 0.4 M $K_3Fe(CN)_6$(aq)
- phenolphthalein

### Method

1. Clean the surfaces of the nails and the zinc with emery paper.
2. Attach one nail to the zinc using the fine wire.
3. Place one nail in one Petri dish, and the other, attached to the zinc, in the second Petri dish, as shown in Figure 8.16. Cover both nails with the sodium chloride solution.
4. Add six drops of the potassium ferricyanide solution to each Petri dish. In the presence of this solution, iron(II) ions ($Fe^{2+}$) appear blue and iron(III) ions ($Fe^{3+}$) appear green.
5. Add six drops of phenolphthalein to each Petri dish. You will recall that this indicator is pink in the presence of hydroxide ions ($OH^-$).
6. You may be able to see evidence of a reaction within a few minutes, but leave the dish overnight or a few days. Expect a series of reactions to take place, and therefore examine the Petri dishes regularly.



(a)



(b)

Figure 8.16

### Analysis

1. In the first Petri dish:
   - a **Identify** the location where iron ions ($Fe^{2+}$ or $Fe^{3+}$) and hydroxide ions ($OH^-$) were generated. **State** which of the two iron ions appeared first, and the oxidation numbers for each of these ions.
   - b **Formulate** a half-equation to describe the first oxidation of iron.
   - c **Formulate** a half-equation for the reduction of oxygen gas to hydroxide ions.
   - d **Identify** the parts of the nail that acted as the cathode and anode.
   - e **Synthesize** an ionic equation for the first stage of the reaction by combining the two half-equations.
   - f **Suggest** the direction for the flow of current inside the nail.
   - g **Formulate** a half-equation for the second stage of the reaction, when the blue colour changes to green, indicating a different iron ion has formed. **State** whether this is caused by oxidation or reduction, and what has happened to the oxidation number of the first iron ion.
   - h **Synthesize** an ionic equation for the second stage of the reaction. You may want to refer to the half-equation you wrote for part c.
   - i The products of reaction (h) react together to produce iron(III) hydroxide, $Fe(OH)_3$(s). **Formulate** an ionic equation for this reaction.
   - j If this solution is heated and dehydrates, iron(III) oxide is produced. **Formulate** an equation for the reaction.
2. In the second Petri dish:
   - a **Identify** the location where hydroxide ions ($OH^-$) were generated and deduce the metal that was corroded. **Explain** why this metal was corroded 'preferentially'.
   - b **Formulate** a half-equation to describe the corrosion of zinc.
   - c **Identify** the substances that acted as the cathode, and the anode.
   - d **Suggest** the direction for the current flow between the two metals.
   - e **Synthesize** an ionic equation to describe the reaction, by combining two half-equations.
3. **Suggest** a role for the sodium chloride used in the demonstration.

## Assessment opportunities

- In this activity you have practised skills that are assessed Criterion A: Knowing and understanding.

## ACTIVITY: The implications of the reactivity series

### ATL

- Transfer skills: Apply skills and knowledge to unfamiliar situations; inquire in different contexts to gain a different perspective; combine knowledge, understanding and skills to create products and solutions

$E^{\ominus}$, the standard electrode potential, measures ease of reduction in aqueous solutions under standard conditions. A suggested approach is: *when comparing two reduction potentials you can be **positive** that the species with the more **positive** reduction potential will be reduced. Therefore the direction of the other half-equation needs to be reversed so that it becomes an oxidation.*

1. **The $E^{\ominus}$ value of zinc (Table 8.11) is more positive than aluminium, so zinc will be reduced and aluminium will be oxidised. You might, therefore, expect that aluminium protects iron more effectively from corrosion than zinc. However, aluminium is not useful as a 'sacrificial' metal. Suggest a reason.**
2. **In Australia, iron roofs are usually 'galvanized', or plated with zinc. Explain how galvanizing protects the roof from rusting.**
3. a **Several definitions of redox reactions have been introduced in this text. Write down the correct definitions by using one word from each pair shown in brackets.**
   **Oxidation means the (loss / gain) of oxygen; reduction means the (loss / gain) of oxygen.**
   **Oxidation means the (loss / gain) of hydrogen; reduction means the (loss / gain) of hydrogen.**
   **Oxidation means the (loss / gain) of electrons; reduction means the (loss / gain) of electrons.**
   **Oxidation means (a / an) (increase/decrease) in oxidation number; reduction means (a / an) (increase/decrease) in oxidation number.**
   b **Evaluate which of these definitions is the 'most complete', and why.**

### Assessment opportunities

- In this activity you have practised skills that are assessed using Criterion A: Knowing and understanding.

## ACTIVITY: Antiquing metals: verdigris and patinas

### ATL

- Creative-thinking skills: Create novel solutions to authentic problems; create original works and ideas; use existing works and ideas in new ways.

Many types of metal oxidation are considered very desirable. The attractive green colour of Evgeny Vuchetich's bronze statue *Let Us Beat Our Swords into Ploughshares* (Figure 3.3) and on the Statue of Liberty is a **patina**. Patinas are mixtures of compounds, including the minerals cuprite ($Cu_2O$), tenorite (CuO), brochantite ($Cu_4(OH)_6SO_4$) and antlerite ($Cu_3(OH)_4SO_4$). Patinas usually vary in colour from greenish to blue-grey depending on the chemical composition, but can include browns, blues and red. Patinas protect metals by acting as a barrier that prevents further exposure to reactive chemicals. In the natural environment, the formation of a patina is usually self-limiting, when all the surface metal has been oxidized.

Natural patinas can sometimes increase the value of artefacts, for example antique coins.



**Figure 8.17** A patina created by an MYP student on a bronze token, which would later be used to make a brooch

# The reduction and oxidation of metals

**Safety:** Always wear eye protection and always wear gloves. The acid or metal cleaner can be very hazardous. Avoid inhaling fumes and rinse spills immediately with large amounts of water. All spraying should be conducted in a fume cupboard.

In this activity we will manipulate conditions to produce three 'fake antique' patinas.

## Materials and equipment

- small bronze, copper or pewter items supplied by you. Bronze is an alloy of approximately 88% copper and 12% tin; pewter is an alloy of 85–99% tin, with the remainder consisting of copper, antimony, bismuth or (sometimes) lead and silver.
- gloves
- goggles
- cotton swabs
- metal cleaner (this could be 1 M $H_2SO_4$ or a commercial chemical metal cleaner)
- spray bottles
- a facility that provides a humid environment, such as a small aquarium with open containers with water
- fume cupboard
- wax or varnish to seal the patinas

Patina recipe 1 (common household materials)

- ¼ cup lemon juice
- ¼ cup table salt (NaCl)
- ¼ cup household ammonia
- ¼ cup vinegar

Mix these together in a spray bottle.

Patina recipe 2 (for a sulfate patina)

- solution of 65 g $AlCl_3$ and 1.8 g $CuSO_4$, dissolved in 0.5 $dm^3$ water and presented in a spray bottle – this mixture needs to be prepared by your teacher or the school laboratory technician
- household ammonia in a spray bottle

These two solutions should be sprayed alternately.

Patina recipe 3 (for a chloride patina)

- a saturated solution of ammonium chloride, $NH_4Cl(aq)$ in a spray bottle

## Method

1. Put on eye protection and gloves.
2. Clean the metal object thoroughly. When the metal is really clean, water should not 'bead' on the surface.
3. In a fume cupboard, spray the patina-developing mixture or combination of mixtures onto the object, allowing it to dry. You need to do this about six times.
4. Leave the metal object in a humid environment, such as a large glass jar or small aquarium with small open containers of water in it. The patina will develop over a few days.
5. Sometimes the compounds that form patinas are flaky. After the patinas have developed, the metal objects should be washed, dried and waxed or varnished.
6. The object may be modified further, for example by using it to make an item of jewellery.

## Interpreting results

1. **Suggest** approaches that may help the results to be more predictable.
2. **Identify** evidence in Figure 8.17 that the patina consists of more than one compound.
3. **Evaluate** whether it would be safe to eat from a bronze plate covered in a patina.

### Assessment opportunities

- In this activity you have practised skills that are assessed using Criterion B: Inquiring and designing.



**Figure 8.18** Rusting can

## PREVENTING CORROSION

**Corrosion** is the chemical reaction of a metal with air, usually forming an oxide. **Rusting** (Figure 8.18) is a form of corrosion. The iron(III) oxide then reacts with water to form **hydrated** iron(III) oxide ($Fe_2O_3.xH_2O$) which is rust. 'Hydrated' means the iron(III) oxide has water chemically combined with it and the *x* indicates a variable number of water molecules. This rust is brittle and it swells up and flakes off as it formed. A fresh iron surface is then exposed to contact with more air and water, and so the rusting continues. The rusting occurs even faster if the water contains impurities with ions, like salt (NaCl), or acidic pollutants such as sulfur dioxide. Rusting can also cause environmental problems if the iron(III) ions from the rust enter soil or streams, rivers and lakes. Iron(III) ions are acidic and can be poisonous at high concentrations.



**Figure 8.19** This famous 4th century wrought iron pillar in Delhi has apparently not rusted in 1600 years. Yet when small samples have been removed for analysis they do rust. What prevents it rusting at its location?

## PREDICT–OBSERVE–EXPLAIN: Why rust?

### ATL

- Critical-thinking skills: Practise observing carefully to recognize problems; evaluate evidence and arguments

A sample of dry rust was heated strongly in a test tube. Droplets of a colourless liquid A, formed on the cooler parts of the tube. Liquid A changed the colour of anhydrous copper(II) sulfate, which is white, to blue. The residue left in the tube, B, was heated strongly in a stream of gas, C. A conducting grey–black solid, D, was formed and a colourless liquid, E, condensed on the cooler parts of the apparatus.

**Identify** substances A to E.

**Predict** items that are likely to be affected by rust.

**Observe** items around your home and garden, your local streets, and school. **Identify:**

1. **the object that has rusted**
2. **its situation (for example outdoors/indoors, wet/dry, exposed to salt)**
3. **whether it had been provided with rust protection (for example painting, greasing or covering with plastic)**
4. **the parts that have rusted particularly badly (for example at joints or where the metal has been bent).**

**Explain**: In each case, try to **suggest** reasons why rusting occurred where it did.

### Assessment opportunities

- In this activity you have practised skills that are assessed using Criterion C: Processing and evaluating.



**Figure 8.20** Iron is commonly used to reinforce concrete in construction work, as can be seen in this 65 year old fence post

Iron and its many alloys (steel is an alloy of iron with carbon, manganese, phosphorus, nickel and/or chromium) are widely used in infrastructure such as bridges, railroads and buildings (Figure 8.20), transport, machinery and tools. Iron is therefore a useful model for developing any strategy that will limit the corrosion of metals generally.

## ACTIVITY: Investigating the corrosion of iron

### ATL

- Organization skills: Create plans to prepare for summative assessments (examinations and performances); set goals that are challenging and realistic)

Understanding how to control conditions to reduce corrosion helps us to increase the working lifetime of metal objects. In this activity you will investigate how to limit the corrosion of iron.

You will be supplied with a selection of iron nails and emery paper for your experiment, but you need to identify the remaining materials, including your controls, yourself. Both a risk analysis and environmental impact analysis must be included in your plan.

Reflect on some of the redox chemistry you have learnt for suggestions for limiting the rusting of iron, and refer to Chapter 1 to refresh your understanding of the inquiry cycle.

**Write** the **aim** of your experiment as an **inquiry question**.

### Assessment opportunities

- This activity can be assessed using Criterion B: Inquiring and designing and Criterion C: Processing and evaluating.

## ACTIVITY: Reflecting on the applications of redox

### ATL

- Organization skills: Create plans to prepare for summative assessments (examinations and performances); set goals that are challenging and realistic.
- Communication skills: Write for different purposes; organize and depict information logically

Corroded metals are similar to minerals, in that the metal atoms have been oxidized to form compounds. The practical strategies you investigated to limit the corrosion of nails have applications to many similar contexts. For example, objects such as surgical implants and instruments, and battery terminals, must be kept corrosion free. Related approaches are used to restore tarnished or corroded objects, including items recovered from shipwrecks.

In a formal essay of 700–1200 words, **describe** the way redox chemistry is applied to a specific metal object or artefact we currently use, or which is a remnant of a past culture or ancient civilization. You should consider

- oxidation, for example the chemistry of its corrosion (or corrosion potential), or
- reduction, for example the chemistry of its corrosion prevention or restoration.

Science does not work in isolation. When metal objects are extracted from their ores or are maintained for current use, these processes must interact with the moral, ethical, social, economic, political, cultural or environmental dimensions of our or past societies. **Discuss** the relationship of your selected object with one of these factors.

All primary and secondary sources of information should be **documented**, in a bibliography and as internal references in the text.

### Assessment opportunities

- This activity can be assessed using Criterion D: Reflecting on the impacts of science.




**Figure 8.21** The main stages involved in obtaining metals from their ores

# EXTRACTION OF METALS

Only a very small number of unreactive metals, such as silver, gold and platinum, occur in nature as pure (native) metals (Chapter 3). Most metals exist in the form of ores. An ore is a natural resource where a mineral, a compound that can be described with a chemical formula, is sufficiently concentrated to be mined commercially. Ores are rarely pure, but are usually mixtures of minerals.

Two common processes used for recovering metals from minerals are smelting and electrolysis.

# SMELTING

**Smelting** is the process of removing metals from their ores by heating with a reducing agent.

When a metal reacts, each metal atom forms a positive ion by the loss of one or more electrons. The atoms are oxidized to the ion:

$$M \rightarrow M^{n+} + ne^-$$

where $n$ is 1, 2, 3 or 4.

To extract a metal from one of its compounds, each ion must accept the same number of electrons as were lost when the compound was formed. The metal ion must be reduced to the atom:

$$M^{n+} + ne^- \rightarrow M$$

The more active the metal in the activity series (Table 8.10), the more difficult it is to reduce. Although chemical reducing agents are used wherever possible to reduce metal oxides to metals, they cannot be used to reduce the oxides of group 1 metals, group 2 metals and aluminium. These metals can only be produced by electrolysis (Chapter 3).

## A case study: smelting iron ore

The cheapest reducing agent to reduce iron from its main ore, haematite ($Fe_2O_3$), is carbon monoxide in a reaction that occurs in a **blast furnace** (Figure 8.22). All the raw materials in this process are cheap and the reaction is exothermic, and therefore helping to keep the furnace hot. The iron is sufficiently pure for most steel-making purposes.

The extraction process is continuous, when an impure form of carbon called **coke** and haematite are added to the top of the blast furnace, while hot air is blown into the base. Table 8.12 summarizes stages of the reaction.

Smelting metals with coke is limited to metals that do not react with carbon to form carbides (e.g. titanium) and are less reactive than iron. A disadvantage of the process is its contribution to **greenhouse gas** pollution.

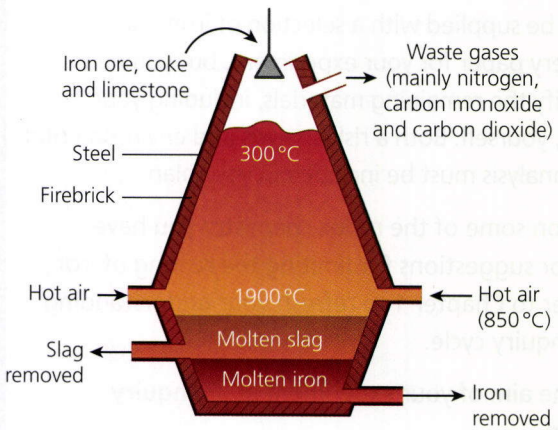



**Figure 8.22** A summary of the arrangement of a blast furnace

## ACTIVITY: 'Smelting' a metal oxide

### ATL

- Affective skills: Perseverance – demonstrate persistence and perseverance

**Safety:** Wear eye protection and gloves to avoid contact with the 'flux'. You will be using very small amounts.

### Materials and equipment

- eye protection
- gloves
- matches
- Bunsen burner
- copper(II) oxide powder (CuO)
- hand lens
- 'flux' (powdered $Na_2CO_3$ and $K_2CO_3$, in about equal proportions)

### Method

1. Put on eye protection and gloves.
2. Burn a match about half-way down.
3. Mix a little 'flux' with the copper(II) oxide powder.
4. Touch the burnt match head to the mixture (it may help to moisten it slightly).
5. Hold the powder in the top of a luminous Bunsen flame for 1 minute.
6. Examine the result using a hand lens. If there is no evidence of a chemical change, repeat the process at 1 minute intervals.

### Assessment opportunities

- In this activity you have practised skills that are assessed using Criterion A: Knowing and understanding.

## THINK–PAIR–SHARE

1. **Identify** conditions that limit the use of smelting.
2. **Suggest** why the 'flux' is necessary.

Hint:
Consider the role of limestone in iron smelting.

3. **Suggest** how you could test that copper was produced in this activity.

| Process | | Reaction |
|---|---|---|
| (i) Heating the furnace | The coke reacts with the oxygen at the base of the furnace to produce carbon dioxide. This is an exothermic reaction, and therefore keeps the furnace hot. | $C(s) + O_2(g) \rightarrow CO_2(g)$ |
| (ii) Forming the reducing agent | Limestone is added to the furnace and decomposes to calcium oxide and carbon dioxide. | $CaCO_3(s) \rightarrow CaO(s) + CO_2(g)$ |
| | The carbon dioxide rises up the furnace and reacts with more coke to produce carbon monoxide. This is an endothermic reaction. | $C(s) + CO_2(g) \rightarrow 2CO(g)$ |
| (iii) Reducing the iron(III) oxide | The carbon monoxide is a powerful reducing agent and reduces the iron(III) oxide to iron. The dense liquid iron sinks to the base of the furnace and is tapped off. | $Fe_2O_3(s) + 3CO(g) \rightarrow 2Fe(l) + 3CO_2(g)$ |
| | Some of the iron(III) oxide is also reduced directly by the carbon. | $Fe_2O_3(s) + 3C(s) \rightarrow 2Fe(l) + 3CO(g)$ |
| (iv) Formation of slag, a waste product | The calcium oxide produced from the limestone reacts with sand and minerals in the ore, to form calcium silicates and slag.<br>The slag is less dense than the molten iron, and can be removed from a different level of the furnace. It can be used for road construction. | $CaO(s) + SiO_2(s) \rightarrow CaSiO_3(l)$ |

**Table 8.12** Processes in a blast furnace.

# ELECTROLYSIS

The invention of electrolysis resulted in the discovery of many new, highly reactive metallic elements (see Chapter 3). The cost of the energy required makes this method expensive, but it produces a very pure metal.

## Sodium

Sodium chloride (table salt) is the most common compound of sodium, and can be obtained by mining underground or by evaporating sea water. Electrolysing the molten compound produces chlorine at the positive electrode (anode) which is made of graphite (carbon).

$$2Cl^-(l) \rightarrow Cl_2(g) + 2e^-$$

Molten sodium is formed at the negative electrode (cathode) which is made of iron.

$$Na^+(l) + e^- \rightarrow Na(l)$$

Overall equation:

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

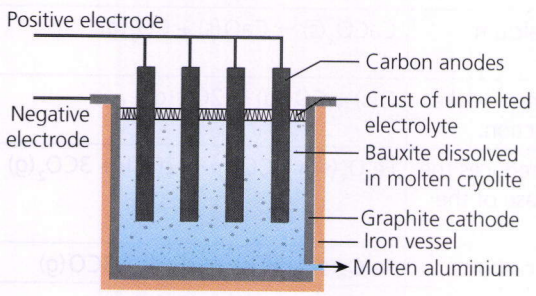



**Figure 8.23** Electrolysis of aluminium is a continuous process, which is efficient. However, the energy costs for both melting and electrolysis are high. For this reason, in countries like Australia, aluminium **refining** occurs at locations with cheap sources of electricity

## Aluminium

Bauxite, an ore rich in aluminium hydroxide minerals, is the most common source of the metal, aluminium. The first purification stage, involving sodium hydroxide, results in alumina, aluminium oxide ($Al_2O_3$).

Electrolysing molten alumina (Figure 8.23) produces molten aluminium at the negative electrode (cathode) and oxygen at the positive electrode (anode). Both electrodes are made of graphite. These electrodes become heated by the large amounts of electric current involved, and eventually are oxidized by oxygen in the surrounding air.

Cathode: $Al^{3+}(l) + 3e^- \rightarrow Al(l)$

Anode: $2O^{2-}(l) \rightarrow O_2(g) + 4e^-$

Overall equation:

$$2Al_2O_3(s) \rightarrow 4Al(s) + 3O_2(g)$$

## ACTIVITY: Evaluating extraction processes

**ATL**

Critical-thinking skills: Interpret data; draw reasonable conclusions and generalizations

1. **Identify** how the methods used for the extraction of iron, sodium and aluminium are related to the positions of the metals in the activity series.
2. With reference to the extraction of iron,
   a. **state** the reactions which the coke (carbon) undergoes
   b. **formulate** equations for the conversion of the following three iron oxides to metal: iron(II) oxide (FeO), iron(III) oxide ($Fe_2O_3$) and iron(II, III) oxide ($Fe_3O_4$).
3. With reference to the extraction of aluminium,
   a. **state** the material used for the electrodes
   b. **formulate** a half-equation for the formation of the product at the cathode (negative electrode)
   c. **explain**, with the help of equation(s), why the anodes have to be replaced periodically.

## RECYCLING

Oxides of aluminium and iron are very abundant in the Earth's crust, and shortages are not anticipated. There are, however, a number of important reasons why recycling is desirable. These reasons are more important when the metals are rare:

- Recycling generally uses less energy than extraction.
- Mines have an environmental impact, especially if open cast.
- The extraction process produces polluting gases like sulfur dioxide which causes acid rain (Chapter 5) and carbon dioxide which contributes to the greenhouse effect and hence global warming (Chapter 9).
- Disposing of scrap metal is difficult.
- Most scrap contains a high percentage of the desired metal, so the process can be quite efficient.

There are costs associated with recycling. Scrap metal needs to be collected from wherever it was used or disposed of. Once collected, the desired metal needs to be separated from the other metals. Unless the metal is **magnetic**, this needs to be done manually. Once separated, the metal needs to be returned to the purity required for it to be useful.

### Aluminium recycling

Most of the recycled aluminium is from drinks cans and foil. The cans are collected at recycling points. The cans are shredded and the paint is removed. The metal is melted down into large ingots (bars). The ingots are rolled into sheet metal from which more cans are cut.

### Iron recycling

Most of the recycled iron is from old trains, ships and cars. Because of the large size of these objects, the collection is done by specialist metal reclaiming companies. The objects are cut into a manageable size. The iron is separated from the other metals using a powerful electromagnet (see Figure 2.11). The scrap is melted and purified.

### ! Take action: Become a 'sustainable school'

#### ■ ATL

- Information literacy skills: Researching information to be informed and inform others

! Programmes in schools to 'reduce, recycle and reuse' that are managed by students are often highly successful. Investigate which metals can be collected and recycled in the school context where you live.

! **Research** how one of these metals can be extracted from recycled goods.

! **Describe** the chemistry involved in the extraction process for this metal.

! **Evaluate** the possible impact of extraction of the metal on the local and global environment, economies and communities.

! **Decide** yourself whether it is worthwhile extracting metals for recycling this way.

! **Take action** to design an action campaign to advocate your findings (whether positive or negative). Produce campaign materials such as brochures, posters, or online information that summarize your research and conclusions.

#### ◆ Assessment opportunities

◆ This activity can be assessed using Criterion D: Reflecting on the impacts of science.

## SOME SUMMATIVE PROBLEMS TO TRY

Use these problems to apply and extend your learning in this chapter. The problems are designed so that you can evaluate your learning at different levels of achievement in Criterion A: Knowing and understanding.

A copy of the periodic table should be provided for reference.

### THESE PROBLEMS CAN BE USED TO EVALUATE YOUR LEARNING IN CRITERION A TO LEVEL 1–2

1 **State** electron arrangements of the main energy levels (shells) of
   - a atoms of two noble gas elements
   - b a nitride ion
   - c a magnesium ion.

2 **Draw** electron shell diagrams (dot-and-cross diagrams) (see Figures 8.7–8.9) for the following compounds, and **suggest** why these compounds are less reactive than the elements of which they are composed:
   - a water ($H_2O$)
   - b lithium chloride (LiCl)
   - c magnesium oxide (MgO).

3 **Interpret** the information below about four metals **A**, **B**, **C** and **D** to judge their order of reactivity.
   - a Metal **A** and metal **B** react slowly with water.
   - b Metal **C** displaces metal **B** from an aqueous solution of its chloride salt.
   - c Metal **D** does not react with dilute acids.
   - d Metal **B** does not displace metal **A** from an aqueous solution of its sulfate salt.

### THESE PROBLEMS CAN BE USED TO EVALUATE YOUR LEARNING IN CRITERION A TO LEVEL 3–4

4 **Construct** the formulas for the following compounds by using Lewis electron dot notation:
   - a tin(II) nitrate
   - b potassium bromide
   - c silver(I) chloride
   - d iron(III) oxide.

5 In the following reactions, **identify** the substance being oxidized and the substance being reduced.
   - a $Zn(s) + 2H^+(aq) \rightarrow Zn^{2+}(aq) + H_2(g)$
   - b $2KI(aq) + Cl_2(g) \rightarrow 2KCl(aq) + I_2(aq)$
   - c $IO_3^-(aq) + 3HSO_3^-(aq) \rightarrow I^-(aq) + 3HSO_4^-(aq)$
   - d $F_2(g) + NaCl(aq) \rightarrow 2NaF(aq) + Cl_2(g)$
   - e $2K(s) + I_2(g) \rightarrow 2KI(s)$

6 **Interpret** the information in the following scenarios and make a scientifically supported judgment to explain the event:
   - a To protect it from a kind of barnacle called woodworm, a boat's hull was coated with brass plate. Brass is an alloy of copper and zinc. The plates were attached with steel screws but soon came apart.
   - b Bill left a steel spanner lying in the bottom of his aluminium dinghy when he moored it. When he wanted to go fishing a few weeks later, he discovered the dinghy had sunk.

## THESE PROBLEMS CAN BE USED TO EVALUATE YOUR LEARNING IN CRITERION A TO LEVEL 5–6

7 **Describe** how:

- **a** when two different metals are in physical contact under water, one of them corrodes more readily
- **b** when a copper wire is dipped in silver(I) nitrate solution, a silvery crystalline deposit (coating) of metal starts 'growing' on the wire, and the solution becomes pale blue
- **c** when an iron roof is 'galvanized' or coated with zinc, it does not rust
- **d** the insides of food cans are coated with tin (or plastic) but not galvanized with zinc
- **e** iron in shipwrecks in deep, cold water rusts slowly
- **f** strips of magnesium are used to protect iron hulls of ships but not to protect the iron drain pipes on a house
- **g** 1960s car bumper bars, and bicycle handlebars are chromium ('chrome') plated.

8 You are provided with eight cards of unknown elements (below). **Suggest** how they should be sorted in a logical sequence across a period based on your understanding of their physical and chemical properties.

9 You travel to an alternate universe where the atomic orbits are different from those on Earth, but all other aspects of the atoms are the same. In this universe, you find that the first (lowest energy) shell is filled with three electrons and the second shell can hold a maximum of nine electrons. You discover an element Z that has five electrons in its atom.

Would you expect Z to be more likely to form a cation or an anion? **Suggest** a possible charge on this ion.

10 **Analyse** the following information to make a scientifically supported judgment about the reactivity of the compound aluminium oxide:

- **i** Aluminium is very reactive with oxygen. When exposed to air, it forms the compound aluminium oxide.
- **ii** Zinc is less reactive than aluminium.
- **iii** When a piece of aluminium is added to hydrochloric acid, no reaction occurs.
- **iv** When a piece of zinc that was lying on the bench is added to hydrochloric acid, bubbles of hydrogen gas are produced as the metal reacts with the acid.

| A | B | C | D |
|---|---|---|---|
| **Solid** at room temperature<br>Non-metal<br>Oxide formula: $AO_2$<br>The oxide bond has *covalent* properties<br>Chloride formula: $ACl_4$<br>The chloride bond has *covalent* properties | **Gas** at room temperature<br>Non-metal<br>Forms no compounds | **Solid** at room temperature<br>Metal<br>Oxide formula: CO<br>The oxide bond has *ionic* properties<br>Chloride formula: $CCl_2$<br>The chloride bond has *ionic* properties | **Gas** at room temperature<br>Non-metal<br>Oxide formula: DO<br>The oxide bond has *covalent* properties<br>Chloride formula: $DCl_2$<br>The chloride bond has *covalent* properties |
| **E** | **F** | **G** | **H** |
| **Solid** at room temperature<br>Semi-metal<br>Oxide formula: $E_2O_3$<br>The oxide bond has *covalent* properties<br>Chloride formula: $ECl_3$<br>The chloride bond has *ionic* and *covalent* properties | **Solid** at room temperature<br>Metal<br>Oxide formula: $F_2O$<br>The oxide bond has *ionic* properties<br>Chloride formula: FCl<br>The chloride bond has *ionic* properties | **Gas** at room temperature<br>Non-metal<br>Oxide formula: $G_2O$<br>The oxide bond has *covalent* properties<br>Chloride formula: GCl<br>The chloride bond has *covalent* properties | **Gas** at room temperature<br>Non-metal<br>Oxide formula: $H_2O_5$<br>The oxide bond has *covalent* properties<br>Chloride formula: $HCl_3$<br>The chloride bond has *covalent* properties |

## THESE PROBLEMS CAN BE USED TO EVALUATE YOUR LEARNING IN CRITERION A TO LEVEL 7–8

**11** The first electron affinity is the energy change when one mole of gaseous atoms gains a mole of electrons.

The table below shows the first electron affinity for selected atoms.

| Element | First electron affinity/kJ mol$^{-1}$ | Element |
|---|---|---|
| Oxygen | –141 | |
| Chlorine | –349 | |
| Bromine | | |
| Iodine | –295 | |
| Neon | +29 | |

**a** **Explain** the reason for the relative sizes of the values of the electron affinity for all the elements.

**b** **Explain** the meaning of 'the first electron affinity of oxygen is –141 kJ mol$^{-1}$'.

**c** The equation for the first electron affinity of oxygen is $O(g) + e^- \rightarrow O^-(g)$.

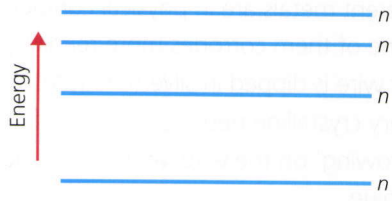
**Formulate** an equation (with state symbols) for the second electron affinity of oxygen.

**d** **Explain** why, in terms of electrostatics, oxygen has a lower first electron affinity than chlorine.

**e** **Explain** why neon has a positive value of electron affinity.

**f** **Estimate** the first electron affinity of bromine.

**12** A hydrogen atom has the main energy levels (shells) shown in the diagram below. *n* refers to the shell number. This is the Bohr model of the atom.




**a** **Describe** the electron transition (movement) within the hydrogen atom using the shell numbers indicated above, that will:

**i** release the most energy

**ii** absorb the least energy.

**b** **List** these electron transitions in order of *increasing wavelength* of light absorbed or emitted:

**i** $n = 1$ to $n = 2$

**ii** $n = 3$ to $n = 2$

**iii** $n = 2$ to $n = 4$

**iv** $n = 3$ to $n = 1$

**c** **Explain** why a ladder is a good analogy or model for visualizing the energy levels of atoms (and molecules), and what are the limitations of the analogy.

**13** **Analyse** and **evaluate** the data about ionic compounds that are listed in the table below.

**Identify** and make scientifically supported judgments to **explain** any relationships between the size (radius) of ions present, and predicted properties of their compounds. Your explanation should refer to your knowledge of ions, ionic bonding and behaviour of electric charges. **State** any assumptions in your explanation.

| Compound | Cation | Cation radius/pm | Anion | Anion radius/pm | Melting point/°C |
|---|---|---|---|---|---|
| Sodium chloride, NaCl | $Na^+$ | 98 | $Cl^-$ | 181 | 801 |
| Potassium chloride, KCl | $K^+$ | 133 | $Cl^-$ | 181 | 775 |
| Sodium bromide, NaBr | $Na^+$ | 98 | $Br^-$ | 196 | 755 |
| Sodium iodide, NaI | $Na^+$ | 98 | $I^-$ | 206 | 661 |
| Sodium oxide, $Na_2O$ | $Na^+$ | 98 | $O^{2-}$ | 146 | 1132 |
| Magnesium oxide, MgO | $Mg^{2+}$ | 65 | $O^{2-}$ | 146 | 2827 |

(1 picometre (pm) = $10^{-12}$ m).

# Reflection

In this chapter you explored the evidence for an organization of electrons around the nucleus, through flame tests and by evaluating patterns of valency, oxidation numbers and the relative reduction potentials of elements. You are able to describe the relationships of valence electrons in the formation of ionic and covalent compounds with electron shell (dot-and-cross) diagrams and Lewis dot electron notation. An introduction to electrochemical cells has helped you recognize how the relative electronegativity of elements explains patterns of corrosion and the processes used in the extraction of metals.

| **Use this table to reflect on your own learning in this chapter.** | | | | | |
|---|---|---|---|---|---|
| Questions we asked | Answers we found | Any further questions now? | | | |
| **Factual:** How does the main energy level affect an atom's chemical reactivity? How can we represent the organization of electrons in an atom? | | | | | |
| **Conceptual:** How does the organization of electrons in shells contribute to an atom's oxidation state? | | | | | |
| **Debatable:** To what extent could human progress be defined by its ability to control the reduction and oxidation of metals? | | | | | |
| Approaches to learning you used in this chapter: | Description – what new skills did you learn? | How well did you master the skills? | | | |
| | | Novice | Learner | Practitioner | Expert |
| **Communication skills** | | | | | |
| **Collaboration skills** | | | | | |
| **Organization skills** | | | | | |
| **Affective skills** | | | | | |
| **Reflection skills** | | | | | |
| **Critical-thinking skills** | | | | | |
| **Creative-thinking skills** | | | | | |
| **Transfer skills** | | | | | |
| **Information literacy skills** | | | | | |
| **Learner profile attribute(s)** | How did you demonstrate your skills as a thinker in this chapter? | | | | |
| **Thinker** | | | | | |

# 9 How are environmental systems sustained by their chemistry?

**Balancing** the chemical inputs and outputs of Earth's **systems** is a prerequisite to **sustain** an environment that is hospitable to human life.



**Figure 9.1** Air pollution (smog) in China

## CONSIDER AND ANSWER THESE QUESTIONS:

**Factual:** What are the implications of uncontrolled emissions? How do environmental cycles interconnect?

**Conceptual:** How important are biological contributions to global systems?

**Debatable:** How do we balance the environmental risk and the societal benefits of the exploitation of chemical resources? To what extent do we need to change to counter the predictions of environmental models?

Now **share and compare** your thoughts and ideas with your partner, or with the whole class.

## IN THIS CHAPTER, WE WILL ...

- **Find out** how the atmosphere was formed and changed over time.
- **Explore**
  - the composition of air and structure of the atmosphere;
  - the properties of gases from the air and their industrial uses;
  - how greenhouse gases contribute to global warming and climate change;
  - how individuals, societies and companies can reduce greenhouse gas emission.
- **Take action** by investigating the environmental impacts of drinking bottled water and through a dance performance.

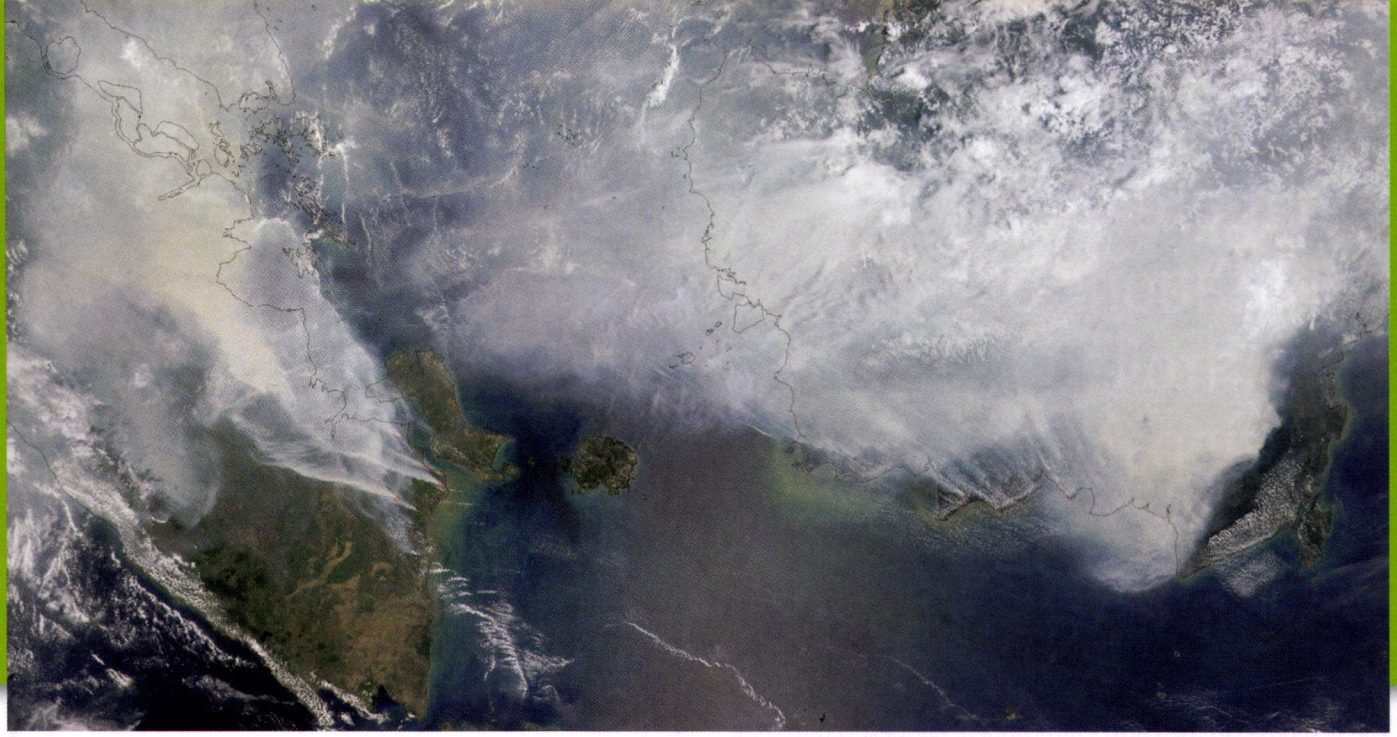


**Figure 9.2** Haze in Singapore and Malaysia in 2015

## These Approaches to Learning (ATL) skills will be useful …

- Collaboration skills
- Communication skills
- Organization skills
- Information literacy skills
- Critical-thinking skills
- Transfer skills

## We will reflect on this learner profile attribute …

- Caring – Why should we care about our environment? How can we use science to help solve real global and local problems? How do you respond when communities you work with care less about the environment than you do, and how can you make a difference to how they think?

## KEY WORDS

| | |
|---|---|
| accrete | pollution |
| cycle | potable |

## Assessment opportunities in this chapter:

- Criterion A: Knowing and understanding
- Criterion B: Inquiring and designing
- Criterion C: Processing and evaluating
- Criterion D: Reflecting on the impacts of science

## THINK–PAIR–SHARE

Look at Figures 9.1 and 9.2. Discuss with a partner what the images reveal.

1. **List** examples of the immediate causes of air pollution.
2. **Compare and contrast** adverse and beneficial effects of events like this.
3. **Suggest** how the responsibility for a clean environment might be shared.

Pollution refers to harmful changes in the equilibrium (or balance) of biological and non-biological systems, as a result of human activity. Many **pollutants** are substances that occur naturally, such as sulfur dioxide or carbon dioxide. However, human activity has led to an increase in the concentrations of such substances, which upsets the delicate balance of natural cycles. For example, carbon dioxide is released naturally by volcanoes and all living organisms, but human combustion of fossil fuels is contributing to global warming and climate change.

# What are the implications of uncontrolled emissions?

## EARTH CHANGES THROUGH TIME

The first gases in the Earth's atmosphere are believed to have come from deep inside the young Earth through volcanoes. This first atmosphere has been described as a 'reducing atmosphere' and is believed to have consisted mainly of carbon dioxide, water vapour, nitrogen and ammonia.

In 1953, the American chemist Stanley Lloyd Miller (1930–2007) conducted a famous experiment of this early atmosphere in Harold Clayton Urey's laboratory at the University of Chicago. A mixture of methane, ammonia (in the form of concentrated ammonia), hydrogen, carbon dioxide and nitrogen was exposed to sparks to simulate the extensive lightning believed to have been present when the Earth was newly formed. After some days, traces of amino acids, the molecules used to build proteins, could be found.

### EXTENSION

**Explore further:** There are many video documentary excerpts of the **Miller–Urey experiment** online, or watch this animation: **https://www.youtube.com/watch?v=qyt6IlcOJLo.**

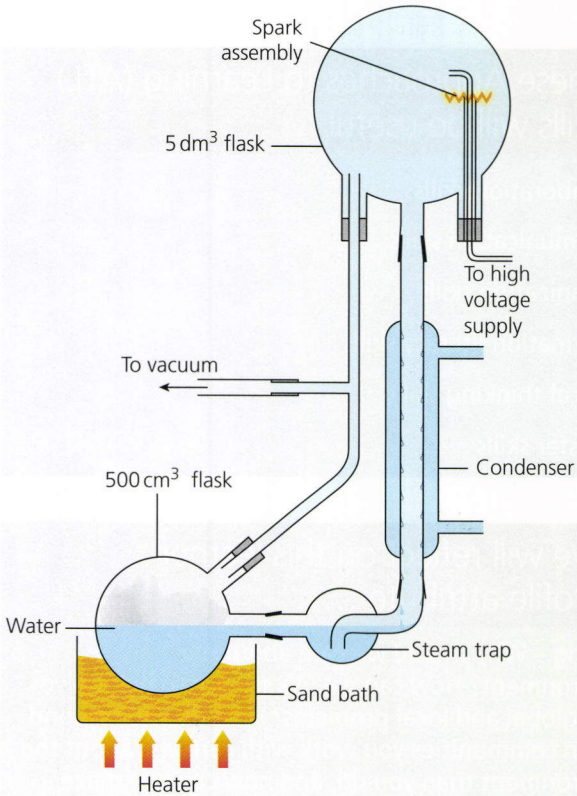



**Figure 9.3** The Miller–Urey apparatus

## ACTIVITY: Reflecting on the changing Earth

### ATL

- Critical-thinking skills: Recognize unstated assumptions and bias; interpret data; draw reasonable conclusions and generalizations

1 Ammonia was present in the early atmosphere. It can act as a reducing agent.
   a **Outline** the reaction between ammonia and oxygen to form nitrogen and water using a chemical equation.
   b **Determine** the oxidation numbers for nitrogen and oxygen in the reactants and products.
2 The very first atmosphere of the Earth would have contained helium and hydrogen. **Suggest** why these gases are now only present in trace amounts in the air.
3 **Evaluate** whether the Miller–Urey experiment proves life originated on Earth.
4 **Interpret** the outline of the method and judge whether you expect Miller–Urey's results to be replicable.
5 Table 9.1 shows the approximate composition of the Earth's atmosphere every 500 million years from when the Earth was formed $4.5 \times 10^9$ years ago.
   **Present** the information given in the table using spreadsheet software to show how the approximate percentages of the three gases, carbon dioxide, oxygen and gas **X** have changed over time.
   a **Identify** gas **X**, **explaining** your reasoning.
   b **Identify** the phenomenon that led to the introduction of oxygen gas in the Earth's atmosphere.
   c **Estimate** the likely time in which the following events occurred:
      i the '**oxygen catastrophe**' (also called the **Great Oxygenation Event**), during which the rising concentration of atmospheric oxygen poisoned early life forms, which were anaerobic
      ii '**snowball Earths**', periods lasting many millions of years during which the Earth became covered in ice, including to the equator, which reflected solar radiation.
   d **Explain** how changes in percentage of carbon dioxide over many millions of years may have triggered these events.
6 **Discuss** the implications of this information on the stability of the present composition of the atmosphere.

### Assessment opportunities

- In this activity you have practised skills that are assessed using Criterion A: Knowing and understanding and Criterion C: Processing and evaluating.

| Millions of years ago | Approximate percentage of $CO_2$ | Approximate percentage of $O_2$ | Approximate percentage of gas X |
|---|---|---|---|
| 4500 | 92 | 0 | 10 |
| 4000 | 42 | 0 | 30 |
| 3500 | 22 | 1 | 40 |
| 3000 | 18 | 1.5 | 56 |
| 2500 | 12 | 5 | 62 |
| 2000 | 9 | 12 | 72 |
| 1500 | 7 | 15 | 75 |
| 1000 | 3 | 18 | 78 |
| 500 | 1 | 30 | 69 |
| 0 | 0.05 | 21 | 78 |

**Table 9.1** The composition of the atmosphere over Earth's history

# How do environmental cycles interconnect?

## SYSTEMS OF THE EARTH

On Earth, matter cycles through several interlinked systems (Figure 9.4). Chemical changes occur as a result of geological cycles or biological activity. Organisms like plants, which can make complex compounds from simple chemicals, form the bridge between the three non-living systems based on gases, water, and rocks and minerals. The organic matter they 'fix' as a result of reactions between simple inorganic substances is passed on through food chains and food webs. If the three systems are perfectly balanced, this matter returns to the non-living systems when the organisms die and decompose.

Look at Figure 9.4. The **biosphere** consists of living organisms on the Earth, and the dead organic matter they produce; the **hydrosphere** consists of liquid water, and therefore is described by oceans, seas, lakes, ponds, rivers and streams; the **atmosphere** is the layer of gases held by the planet's gravitational force, and the **lithosphere** is the Earth's crust and upper mantle.

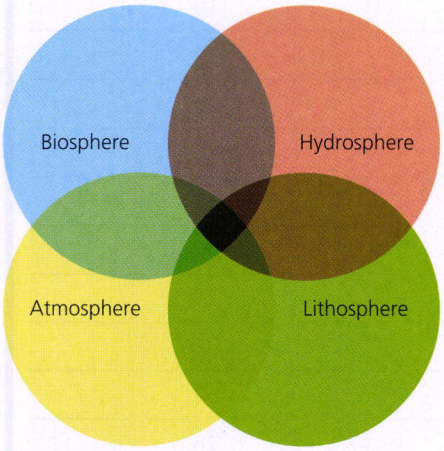



**Figure 9.4** Four interconnected systems for organizing matter on Earth

We know Earth's atmosphere changed through time. Today, the atmosphere is made up of nitrogen, oxygen, noble gases and a number of compounds, including water vapour and carbon dioxide.

- Nitrogen is a very unreactive gas and is not involved in photosynthesis and respiration. The gases released from volcanoes contain small quantities of ammonia, $NH_3$. This gas was eventually converted to nitrogen by soil bacteria, building up in the atmosphere over millions of years.
- Oxygen is the most reactive gas in the air and is required for aerobic respiration. The oxygen in our current atmosphere was formed by photosynthetic bacteria and, later, by plants living on the land. The oxygen in the atmosphere also led to the formation of the **ozone layer** which protected the Earth's surface from the harmful effects of ultraviolet radiation. Reactions involving oxygen are known as oxidations (see Chapter 8).
- Argon, neon and other noble gases are inert (see Chapter 3).
- Carbon dioxide is present in a small but increasing amount. Plants absorb and use it during photosynthesis, and it contributes to the **greenhouse effect**.
- Water vapour is also present in the air but the percentage varies according to the weather. It is measured as the humidity of the air.

Many of the gases in the air are very useful. Separating the gases from one another in the air is achieved by fractional distillation of liquid air. Air is liquefied by cooling and compressing it. The liquid air is then allowed to warm up and it begins to boil. Each different gas boils at a different temperature and can be collected separately (Figure 9.5).

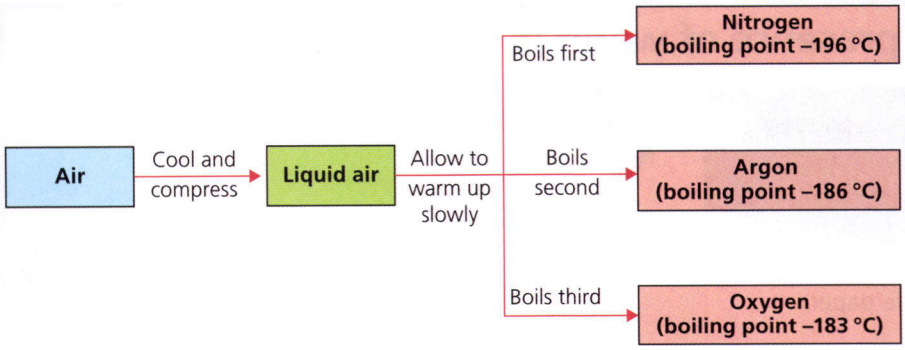



**Figure 9.5** Fractions from the distillation of liquefied air

## ACTIVITY: Evaluating the contribution of living organisms to the atmosphere

### ATL

- Critical-thinking skills: Gather and organize relevant information to formulate an argument; interpret data

1 **Suggest** examples of scientific evidence that have been used to resolve the composition of Earth's early atmosphere.

*Hint:*
*see Chapter 7.*

2 **Describe** how living organisms contributed to the changing composition of the atmosphere.

3 **Outline** similarities between the fractional distillation of liquid air and that of essential oils (Chapter 2) or crude oil (Chapter 12).

4 **Suggest** how carbon dioxide may be removed from the air before it is liquefied.

5 Industrial gases have to be transported in liquid form in tankers or in cylinders carried on trucks. **Outline** examples of safety problems involved and how these might be overcome.

6 **Predict** the consequences of the gases in air being 78 per cent oxygen and 21 per cent nitrogen (i.e. the reverse of their current percentages).

7 The Earth is the only planet in the solar system with oxygen in its atmosphere and large amounts of water in rivers, lakes and oceans. Other astronomical bodies, such as Mars, have some water vapour and polar ice caps, and Saturn's second-largest moon, Rhea, has an atmosphere rich in carbon dioxide and oxygen.

**Suggest** what this may imply about the distribution of life in the solar system.

### Assessment opportunities

- In this activity you have practised skills that are assessed using Criterion A: Knowing and understanding.

# ACTIVITY: How can the presence of water in the air be shown?

## ATL

- Organization skills: Select and use technology effectively and productively

**Safety:** Do not handle cobalt(II) chloride paper directly. Use forceps or wear gloves.

### Materials and equipment

- ice
- sodium chloride (solid)
- conical flask
- retort stand, clamp
- evaporating dish or watch glass
- dry cobalt(II) chloride paper

### Method

1. Mix crushed ice and sodium chloride in the approximate proportion of 10 : 1. This is called a freezing mixture and it has a temperature lower than that of the melting point of pure ice.
2. Fill a conical flask with the mixture and allow it to stand, suspended in a retort stand, for 30 to 40 minutes (Figure 9.6).
3. Scrape the ice that forms on the outside of the flask into an evaporating dish, or empty the flask and allow the ice to melt and drip into the watch glass.

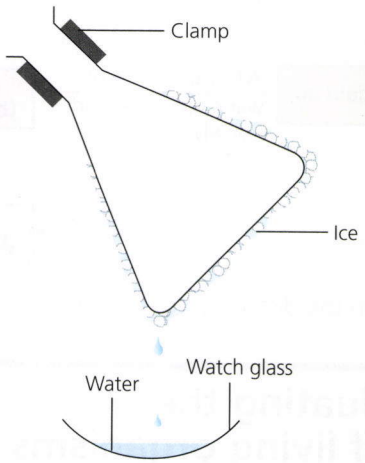



**Figure 9.6** Apparatus to show the presence of water vapour in air

4. Test the liquid with a piece of dry cobalt(II) chloride paper; this turns from blue to pink in the presence of water. If sufficient liquid water is collected, it could be shown to have the properties of pure water, for example, via measuring its boiling point, freezing point or density.

## Assessment opportunities

- In this activity you have practised skills that are assessed using Criterion A: Knowledge and understanding.

## DISCUSS

1. **State** the conditions that determine the amount of water in the atmosphere.
2. **Suggest** where the water in the atmosphere comes from.
3. Water vapour is a powerful **greenhouse gas**. **Explain** why water vapour does not attract the same media attention as increasing levels of carbon dioxide.

## EXTENSION

**Explore further:** Find out how much **water vapour** contributes to global warming. You may want to consider this:
www.nasa.gov/topics/earth/features/vapor_warming.html.

# How do we balance the environmental risk with the societal benefits of using chemical resources?

## THE CENTRAL ROLE OF THE ATMOSPHERE

The atmosphere (Figure 9.7) is the thin layer of gas surrounding the Earth. It extends to a height of approximately 100 km (the Earth's radius is 6400 km), decreasing in density with the reduction in gravitational pull and in the pressure from the height of the column of air above it. At a height of 5 km, the air density is less than half that at sea level (Chapter 1).

The atmosphere consists of four layers: the troposphere, the stratosphere, the mesosphere and the thermosphere. They are separated by their thermal properties, resulting in a zigzag temperature gradient (Figure 9.7). The troposphere incorporates the air around us, and therefore you are probably familiar with the observation that higher altitudes tend to be cooler. However, at about 18 km above the surface, twice the height of Mt Everest, this trend suddenly reverses. This signals the beginning of the stratosphere, which includes a layer of concentrated **ozone** gas ($O_3$).

When an ozone molecule absorbs ultraviolet (uv) radiation, it re-emits the energy in the infrared spectrum, warming the stratosphere. Then, at about 48 km above the Earth's surface, another layer is indicated by another reversal of the temperature gradient. Although ozone is still present, the temperature gradient of the mesosphere is explained by the rapidly decreasing density of the air. Finally, at about 80 km about the Earth's surface, chemical reactions in the outermost layer cause the gradient to reverse again. The intense radiation from the Sun causes the breakdown of oxygen ($O_2$) and nitrogen ($N_2$) molecules to their ions, and the temperature in the thermosphere rises as a result.

All the features of our weather occur in the troposphere, which includes 90 per cent of the gases in the atmosphere. Warm gases rise and cooler gases sink in the temperature gradient, and winds also cause sideways dispersion (Figure 9.2). As a result, atmospheric pollutants formed near the ground quickly mix throughout the troposphere.

## THE GREENHOUSE EFFECT

Carbon dioxide and water vapour have important roles in maintaining a uniform temperature on the Earth's surface. These gases allow the visible radiation from the Sun to reach the Earth's surface, but trap some of the infrared radiation which is emitted by the Earth's surface. This is known as the **greenhouse effect** (Figure 9.8).

The greenhouse effect is an analogy for the warming effect caused by carbon dioxide. A garden greenhouse keeps plants warmer than they would be outside, by insulating them with a layer of warm air. When substances at the surface of the Earth absorb some of the Sun's energy, they re-emit it as infrared radiation. Greenhouse gases in the atmosphere, including carbon dioxide, keep the Earth warm by trapping some of the re-emitted infrared radiation that would otherwise escape. Without the greenhouse effect the average surface temperature of the Earth would be about 33°C lower than it is; –18°C instead of 15°C.

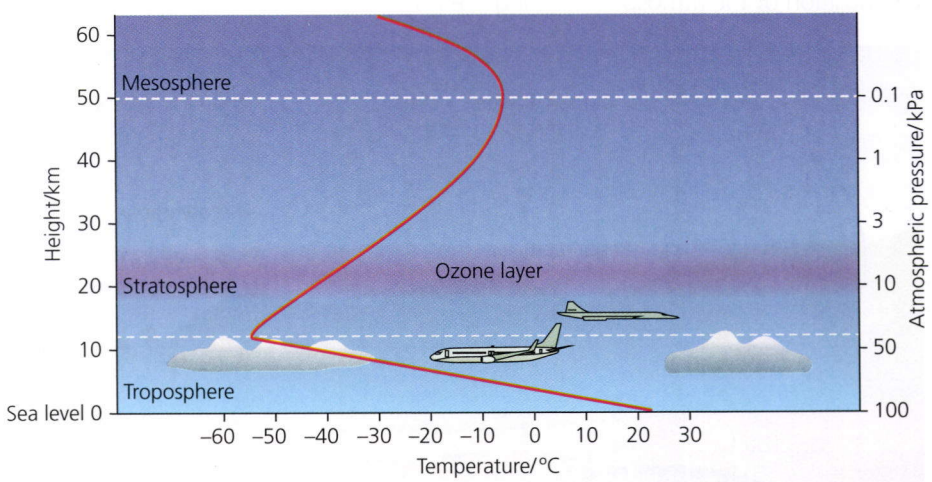
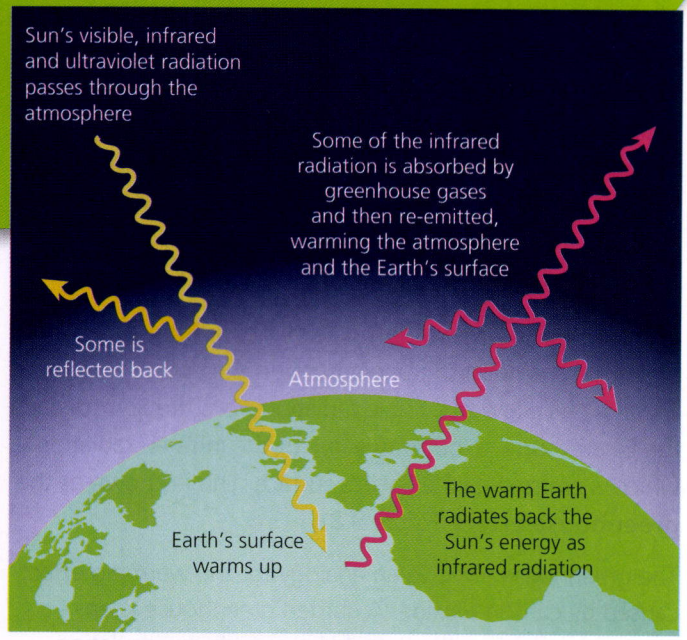


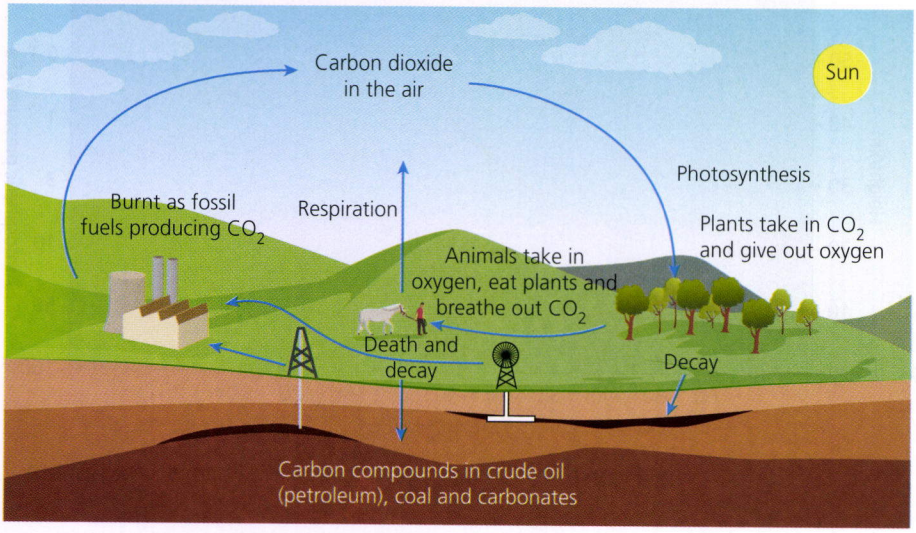

**Figure 9.7** The composition of the Earth's atmosphere




■ **Figure 9.8** The greenhouse effect

Oxygen and nitrogen are not greenhouse gases, but carbon dioxide, water vapour and methane are very effective greenhouse gases. The composition of the atmosphere has stayed approximately constant for the last 200 million years. This is due to the processes in the **carbon cycle**, the **water cycle** and the **nitrogen cycle** which maintain equilibrium.

Various human activities, however, have begun to affect the composition of the atmosphere during the last 150 years.




■ **Figure 9.9** The carbon cycle

Scientists are concerned that human activity is adding additional carbon dioxide and methane into the atmosphere and that the Earth is undergoing **global warming** and climate change. You can find out more about the greenhouse effect in *MYP Physics by Concept,* Chapter 8.

# THE CHEMISTRY OF THE CARBON CYCLE

## Sources

When analysing systems, a **source** is the origin of a component, such as a gas or a pollutant. Important natural sources of carbon dioxide include active volcanoes, forest fires, decomposition and respiration, the process by which organisms transform energy from glucose. All living organisms (e.g. plants, bacteria and animals) respire, so respiration produces carbon dioxide. Most chemical changes in living organisms involve a series of redox reactions controlled by enzymes. The equations below therefore summarize the overall chemical changes.

Anaerobic respiration (for example, **fermentation** by yeasts):

glucose → carbon dioxide + ethanol

$C_6H_{12}O_6(aq) \rightarrow 2CO_2(g) + 2C_2H_5OH(aq)$; $\Delta H$ negative

Aerobic respiration:

glucose + oxygen → carbon dioxide + water

$C_6H_{12}O_6(aq) + 6O_2(g) \rightarrow 6CO_2(g) + 6H_2O(l)$; $\Delta H$ negative

Most **fuels** are hydrocarbons and produce carbon dioxide and water when they burn in excess oxygen (Chapter 10). The equation for the complete combustion of natural gas (Figure 9.10), which contains mainly methane, is:

methane + oxygen → carbon dioxide + water

$CH_4(g) + 2O_2(g) \rightarrow CO_2(g) + 2H_2O(l)$

$\Delta H$ negative

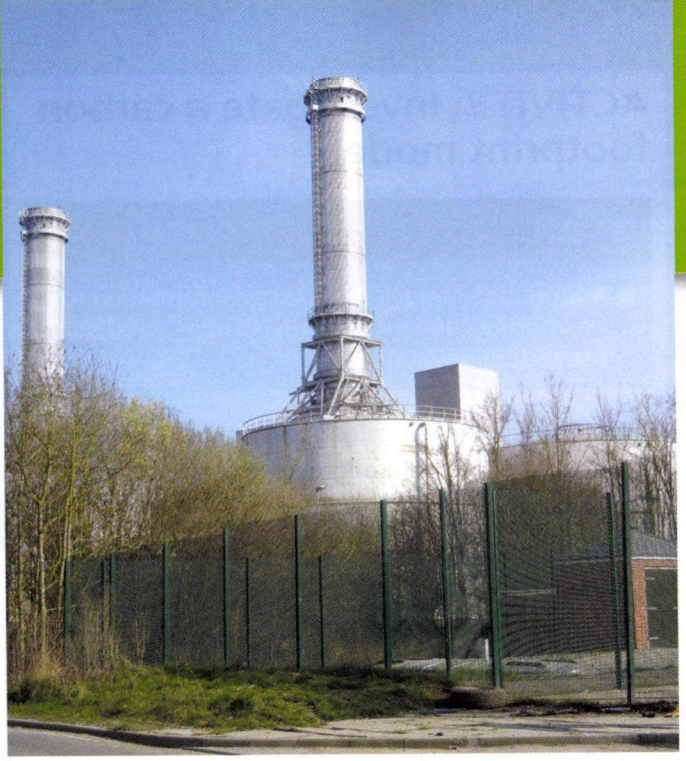


**Figure 9.10** Gas-fired powered station near Corby, United Kingdom

## Sinks

When analysing systems, a **sink** is the destination of a component, such as a gas or a pollutant. For example, oceans act as a sink for atmospheric carbon dioxide and other water-soluble gases. Groundwater and soil water also act as sinks for pesticides used in agriculture.

Carbon dioxide is removed from the atmosphere by photosynthesis. This is the process by which plants produce glucose (starch) using the energy from the Sun:

carbon dioxide + water → glucose + oxygen

$6CO_2(g) + 6H_2O(l) \rightarrow C_6H_{12}O_6(aq) + 6O_2(g)$; $\Delta H$ positive

Burning fossil fuels is effectively a one-way process. Fossil fuels are burnt much faster than new supplies are formed, and faster than natural sinks can absorb the increase. This results in an increasing concentration of carbon dioxide in the atmosphere. The human population releases about five thousand million tonnes of carbon dioxide into the air every year. Some scientists believe that by the year 2020 the concentration of carbon dioxide in the atmosphere will have doubled from what it is currently (0.04 per cent). Scientists are concerned about this **anthropogenic** global warming, in other words, the warming caused as a result of human activity, because changes in complex systems like the Earth are difficult to reverse.

Current $CO_2$ measurements at the Mauna Loa Observatory may be tracked here: **https://www.co2.earth/**

## ACTIVITY: Reflecting on the carbon cycle

### ATL

- Communication skills: Use appropriate forms of writing for different purposes and audiences

1 **Interpret** Figure 9.9 to **state**
   - a the effect of deforestation on the carbon cycle
   - b how the carbon cycle could be balanced.

2 Water bodies have not been included in Figure 9.9. Carbon dioxide dissolves in water, where algae use it in photosynthesis. Some marine organisms convert dissolved carbon dioxide to calcium carbonate to build shells for themselves. Eventually, this calcium carbonate is deposited as limestone rocks.
   - a **Draw** a carbon cycle which also includes this information.
   - b **Suggest** whether oceans act as a source or a sink.

3 Excess carbon dioxide causes production of carbonic acid which decreases the pH of the oceans.
   **Evaluate** the effect of ocean acidification on marine life, including on animals which have calcium carbonate exoskeletons.

### Assessment opportunities

- In this activity you have practised skills that are assessed using Criterion B: Inquiring and designing and Criterion C: Processing and evaluating.

## EXTENSION

In December 2015 the United Nations Climate Change Conference (COP21 or CMP11) was held in Paris to negotiate a legally binding treaty to reduce emission of greenhouse gases, with the aim of limiting anthropogenic global warming to below 2°C.

The official website of COP21 can be found here: **http://www.cop21.gouv.fr/en/**. Compare the information in the glossary in this link with the decisions made at this international meeting, using **The Paris Agreement Summary**.

## THE CARBON FOOTPRINT

The concern about the quantity of carbon dioxide entering the atmosphere due to human activities has resulted in a standard measure for emissions of particular activities, for example, using a car for a year, taking an international airline flight, or producing a certain product, such as a mobile phone. Most of these activities also involve the emission of other gases in addition to carbon dioxide, which might also contribute to global warming. For example, a given mass of methane ($CH_4$), the second most abundant greenhouse gas, has a global warming potential 25 times greater than carbon dioxide, so emissions of methane must be multiplied by this factor. In comparison, the rarer greenhouse gases, nitrogen oxides and ozone, have much greater warming factors than carbon dioxide, 300 and 1000 times respectively. The 'carbon footprint' model factors in the potential contribution to global warming of this series of greenhouse gases, as 'tonnes of carbon dioxide equivalent'.

The carbon footprint gives a clear and simple measure of the climate change impact of the activity in question. In order to calculate the carbon footprint, it is necessary to know the mass of each greenhouse gas emitted by the particular activity and the global warming potential of each.

## EXTENSION

**Explore futher:** This interactive website which models the effects of a 2 °C difference in temperatures on your continent: www.cbc.ca/news2/interactives/2degrees/.

## ACTIVITY: Investigate a carbon footprint model

### ATL

- Information literacy skills: Access information to be informed and inform others; understand and use technology systems

Use **carbon footprint calculators** online to find a way to measure the amount of greenhouse gas generated by our daily activity.

1. **Suggest** some uses and limitations of the carbon footprint model.
2. **Suggest** the environmental impact based on the model calculations in these situations:
   - a. You are a person living a traditional hunter–gatherer lifestyle.
   - b. You are a leader of a developed country, constantly travelling by air to meet delegations in other countries.
3. **Compare** the environmental impacts of the carbon footprint of a product in these situations:
   - a. A corporation that develops a tiny consumer device (for example, a mobile phone):
     - i. the product is made using locally sourced materials in the country of origin, and the finished product is posted to you, the consumer (and all other consumers in your country)
     - ii. the product is made using imported materials in your country, so that you (and all other consumers in your country) can source it locally.
   - b. A consumer product that can be made using two alternative industrial processes, one that releases 1000 tonnes of $CO_2$ to the atmosphere, or one that releases 4 tonnes of nitrogen oxides.
4. **Evaluate** the feasibility of addressing anthropogenic climate change by reducing the carbon footprint, based on how the examples in (2) above interact with moral, ethical, social, economic, political, cultural or environmental factors in our communities.

### Assessment opportunities

- In this activity you have practised skills that are assessed using Criterion D: Reflecting on the impacts of science.

## TERRAFORMING MARS

Humans have conquered most of Earth except the deepest oceans. We are good at changing our environment to suit our needs. The population of Earth is rapidly increasing and consuming more resources than the Earth can provide. Already, potable water supplies have been reduced in some parts of the world because of climate change.

Although Mars is a much smaller planet, its land area is similar to that found on Earth, because our nearest planet does not have oceans. The recent discovery of seasonal flows of liquid water hints at the exciting suggestion that the planet could be made suitable for human habitation.

What infrastructure is needed so that humans can live there and mine its valuable resources? An alternative proposition is to 'terraform' the planet, to deliberately change its environment to provide Earth-like ecosystems and therefore suitable for humans.

## ACTIVITY: Life on Mars

### ATL

- Communication skills: Structure information in summaries, essays and reports

**Evaluate** the feasibility of moving to Mars and setting up life there. Your 800–1200 word report should:

- **Explain the problem or issue your project solves. Your scientific discussion could address scientific, technical solutions to transport, infrastructure and the conservation of supplies, or, alternatively, investigate the feasibility of terraforming a planet, including the timeframes involved.**
- **Evaluate how such a project would interact with a moral, ethical, social, economic, political, cultural or environmental factor. Examples of discussions you may wish to consider include the selection of pioneers, or whether humans should exploit a unspoiled part of the solar system.**
- **Demonstrate appropriate communication skills for a scientific audience, for example, terminology and details of chemical reactions involved, and documentation of primary and secondary sources of information.**

### Assessment opportunities

- This activity can be assessed using Criterion D: Reflecting on the impacts of science.

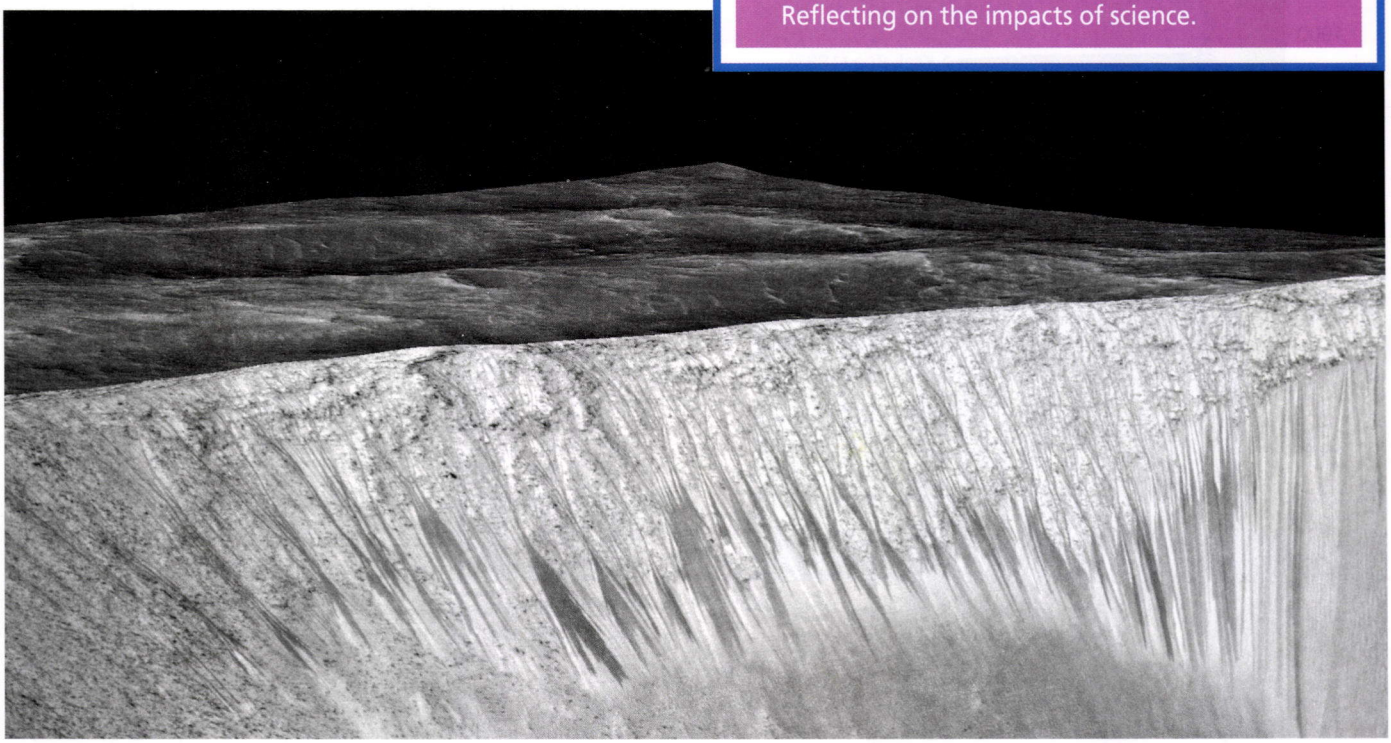
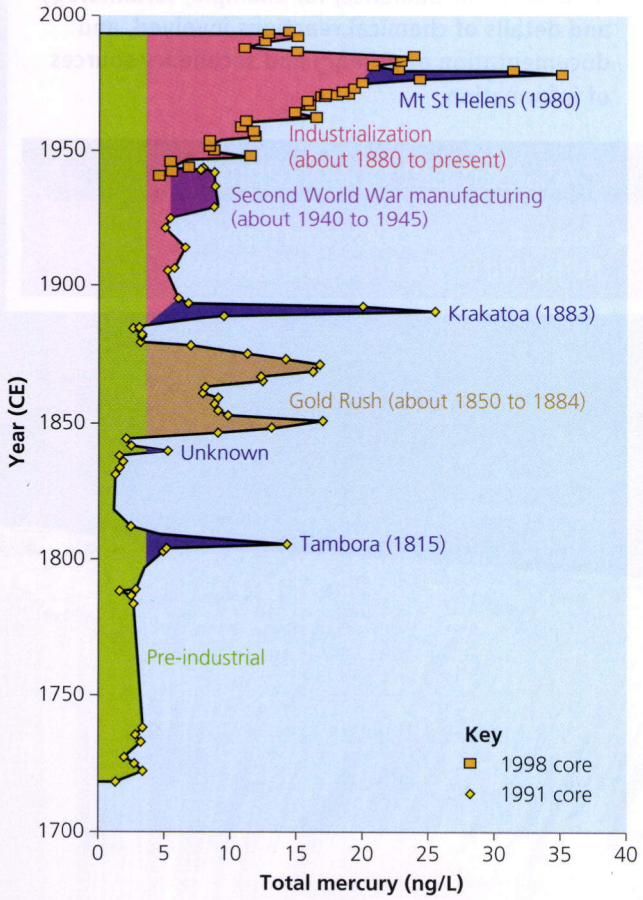


**Figure 9.11** Evidence of water on the surface of Mars

## INVESTIGATING ATMOSPHERIC POLLUTANTS

A **pollutant** is any substance that produces a harmful effect on the environment (Table 9.2). Sources of pollutants can be natural (Figure 9.12) or anthropogenic, as a result of human activities.




## ACTIVITY: Investigating the air pollution produced by different solid fuels

ATL

- Organization skills: Plan short- and long-term assignments; meet deadlines; bring necessary equipment and supplies to class

Refer to the experiment investigation cycle in Figure 1.11 to plan and carry out an investigation into the potential of natural solid fuels for generating acid-rain forming gases.

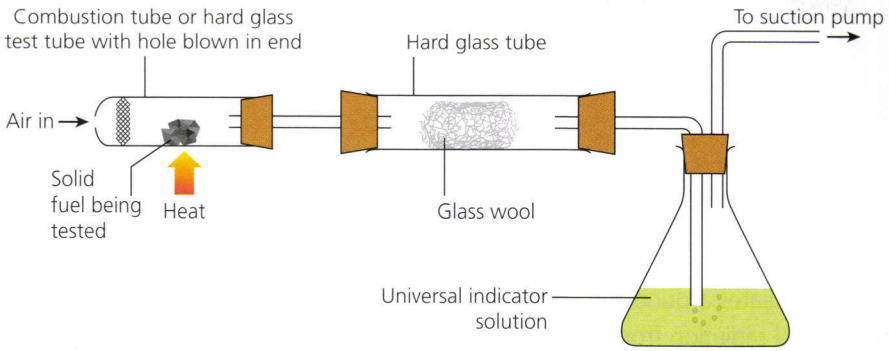
**Safety:** Solid fuels such as hexamine and 1,3,5-trioxane should **not** be investigated.

In some cases the anthropogenic output is not a large proportion of the worldwide total. However, such pollutants can cause problems due to high concentrations in localized areas. Many atmospheric pollutants arise from the combustion of fossil fuels, in motor vehicles, or in power stations. These substances dissolve in rain droplets to produce 'acid rain', which has the potential to cause damage to the built and natural environments.

By modifying the design of vehicle engines and power stations, and cleaning the exhaust gases, the amount of pollutants entering the atmosphere can be minimized.

**Figure 9.12** Natural events (major volcanic eruptions) and human activities contributed to changes in the mercury concentration in ice cores from Fermont Glacier in Wyoming, USA. What caused the differences in the size of the mercury 'spikes' in this sample?

Safety precautions: both a risk analysis and environmental impact analysis must be included in your completed plan, since some of the products will be toxic. Suggested equipment is shown in Figure 9.13.




■ **Figure 9.13** Suggested apparatus for investigating air pollution caused by different solid fuels

## ◆ Assessment opportunities

◆ This activity develops skills that can be assessed with Criterion B: Inquiring and designing and Criterion C: Processing and evaluating.

| Compound | Natural sources | Anthropogenic sources |
|---|---|---|
| CO | Incomplete oxidation of methane, e.g. $2CH_4(g) + 3O_2(g) \rightarrow 2CO(g) + 4H_2O(l)$, volcanoes, forest fires | Incomplete combustion of fossil fuels, e.g. (petrol) $2C_8H_{18}(l) + 17O_2(g) \rightarrow 16CO(g) + 18H_2O(g)$ |
| $CH_4$ | Intestinal fermentation in wild animals, termites, emissions from natural wetlands | Cattle rearing, emissions from rice paddies, leakages from landfills, sewage |
| Volatile organic compounds (VOCs) | Tree emissions – isoprene ($C_5H_8$) and monoterpenes (various isomers of $C_{10}H_{16}$) | Motor vehicles – evaporation and incomplete combustion, gas leakage, refinery emissions |
| Particulates | Wind-borne dust, sea spray and volcanoes | Incomplete combustion of fossil fuels |
| NO | Forest fires, anaerobic processes in soils, electric storms | Combustion of fuel oil, coal, e.g. $N_2(g) + O_2(g) \rightarrow 2NO(g)$ |
| $NO_2$ | Forest fires, electric storms | Combustion of fuel oil, coal, e.g. $2NO(g) + O_2(g) \rightarrow 2NO_2(g)$ |
| $N_2O$ | Emissions from denitrifying bacteria | Combustion of oil and coal |
| $SO_2$ | Oxidation of hydrogen sulfide, volcanic activity, decay of biological material | Combustion of coal and heavy fuel oil (containing sulfur impurities), roasting or smelting sulfide ores, e.g. $S(s) + O_2(g) \rightarrow SO_2(g)$ |
| $H_2S$ | Anaerobic fermentation (eutrophication), volcanoes | Oil refining, animal manure, coke oven gas |
| HCXs (halogenoalkanes) | | Solvents, aerosols, etc. |
| Ozone, $O_3$ | From stratosphere, NO–$NO_2$ conversion | NO–$NO_2$ conversion |
| $SF_6$ | | Electrical insulators |

■ **Table 9.2** Summary of sources of pollution

# How important are biological contributions to global systems?

## HOW THE ATMOSPHERE INTERACTS WITH THE WATER CYCLE

The water cycle (Figure 9.14) describes how water circulates around the Earth. The driving force behind the water cycle is the thermal radiation from the Sun. Sources of water vapour in the air include evaporation of water from oceans, seas and lakes, from inside leaves of plants (via transpiration), and as a reaction product of respiration and combustion (burning). Sinks for water vapour take the form of precipitation, rain, hail or snow, caused when water vapour cools and condenses. The first tiny droplets of water form clouds and eventually precipitate and gather into streams and rivers and then on into lakes, seas and oceans.

Water is very good at dissolving substances due to its polar nature. As water droplets move through the air, as clouds blown by wind or as precipitation, they absorb substances like carbon dioxide from the air, to form carbonic acid, a weak acid. On land, rain may wash soluble chemical fertilizers off farmland and add nitrate ions ($NO_3^-$) and phosphate ions ($PO_4^{3-}$) to the rivers; these ions are present because of the use of artificial fertilizers such as ammonium nitrate and ammonium phosphate. Storm water may also contain human waste, as well as insoluble impurities such as grit, bacteria, oil, lead and dust from the exhaust fumes of vehicles.

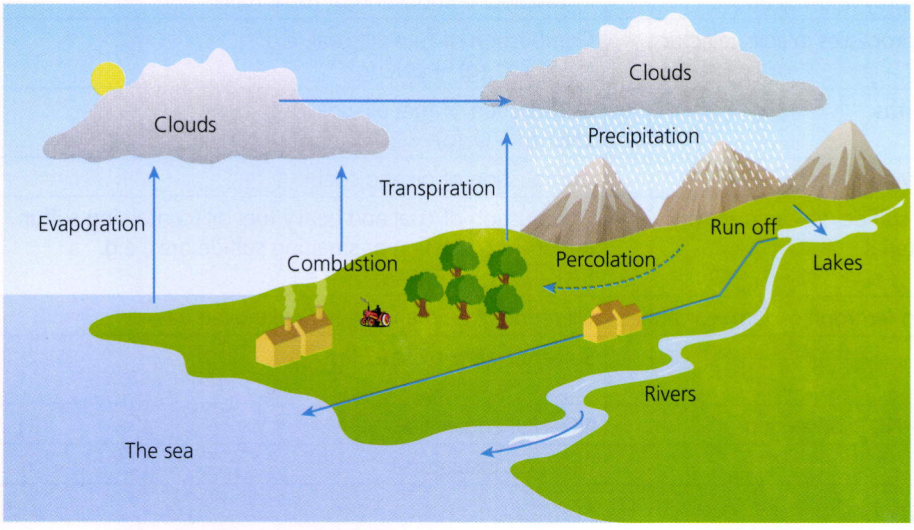



**Figure 9.14** The water cycle

## Field studies and the experimental method

Field studies require data to be collected outside an experimental setting, often in natural environments. Because natural environments are complex, it may be difficult to control variables, or repeat longitudinal studies. Results may show '**correlations**', rather than direct '**causal**' relationships between causes and effects. A **causal link** means that one variable directly causes a change in another; **correlation** means that the change in one variable occurs with a change in another variable.

The scientific value of a field study is that it is an 'authentic' context. Field studies augment designed investigations, for example by evaluating a model, and their very complexity can reveal unexpected outcomes that suggest new directions for research.

## ACTIVITY: A longitudinal stream study

### ATL

- Collaboration skills: Help others succeed; delegate and share responsibility for decision making
- Organization skills: Set goals that are challenging and realistic

**Safety:** Wear gloves and wash hands after this activity. Assess risk factors such as managing responses to cuts and grazes, avoiding sunburn and water awareness.

To understand global impacts we need to begin with local impacts. In this activity, you will use samples from a local water source to evaluate the way that local effects can have a wider impact on ecosystems.

Plan a collaborative investigation of local water resources (lakes, rivers, reservoirs, canals, ponds or streams) or from different locations along the same source, ideally one which provides opportunities to compare evidence of disturbance such as changes in nearby land use or waste discharge. Sampling should include at least two or three of these local sources.

Predict the impact of these conditions on the physical, chemical or biological variables you plan to investigate.

When reporting and analysing your results, link evidence of variation to possible environmental impacts.

### Assessment opportunities

- In this activity you have practised skills that are assessed using Criterion B: Inquiring and designing and Criterion C: Processing and evaluating.

## ACTIVITY: Investigating pollutants dissolved in water

### ATL

- Critical-thinking skills: Gather and organize relevant information to form an argument
- Organization skills: Create plans to prepare for summative assessments (examinations and performances)

What are the consequences of water's ability to accrete soluble pollutants as a result of the water cycle? How could these dilute solutions affect living or built environments over time?

**Design** an investigation of how pollutants in water may interact with living plants or minerals. Refer to the experiment investigation cycle in Figure 1.11. A risk analysis and environmental impact analysis must be included in your plan.

### Assessment opportunities

- This activity can be assessed using Criterion B: Inquiring and designing and Criterion C: Processing and evaluating.

## Take action: Do we need to drink bottled water?

### ATL

- Collaboration skills: Encourage others to collaborate
- Information literacy skills: Make connections between various sources of information

As a class, collect the labels from bottles of mineral water (Figure 9.15).




**Figure 9.15** What information is shown on the reverse of this label?

1. **Compare** the dissolved substances listed on the different brands of mineral water. Make a scientifically supported judgment about their contribution to health.
2. 'Food miles' are the distance a consumable such as food travels from where it has grown to where it is eventually purchased and consumed. These transport costs contribute considerably to global emissions.
   **List** the mineral water brands, from those which have the highest to lowest environmental cost, according to this definition. Make a scientifically supported judgment about the environmental cost of using imported and local bottled mineral waters.
3. Most drinks are sold in plastic bottles made of PET (polyethylene terephthalate), produced from crude oil (petroleum).
   **Evaluate** whether replacing this material with an alternative carries fewer environmental costs.
4. **Present** and promote your findings about local mineral water consumption and the decisions you have made to improve the environmental impact of your school and local community.

### Assessment opportunities

- In this activity you have practised skills that are assessed using Criterion A: Knowing and understanding and Criterion D: Reflecting on the impacts of science.

# HOW THE ATMOSPHERE INTERACTS WITH NUTRIENT CYCLES

Nitrogen gas has no smell and is colourless. The molecule consists of two nitrogen atoms covalently bonded together by a strong triple covalent bond. Nitrogen gas forms about 80 per cent of the air and is very unreactive. Few living organisms can use it directly, but it is an essential element in proteins, nucleic acids and biological compounds found in all forms of life. Nitrogen, in the form of nitrates ($NO_3^-$), is therefore often the limiting nutrient controlling the amount of matter transferred in biological cycles such as food chains.

The main source of atmospheric nitrogen is from anaerobic, denitrifying bacteria (Figure 9.16).

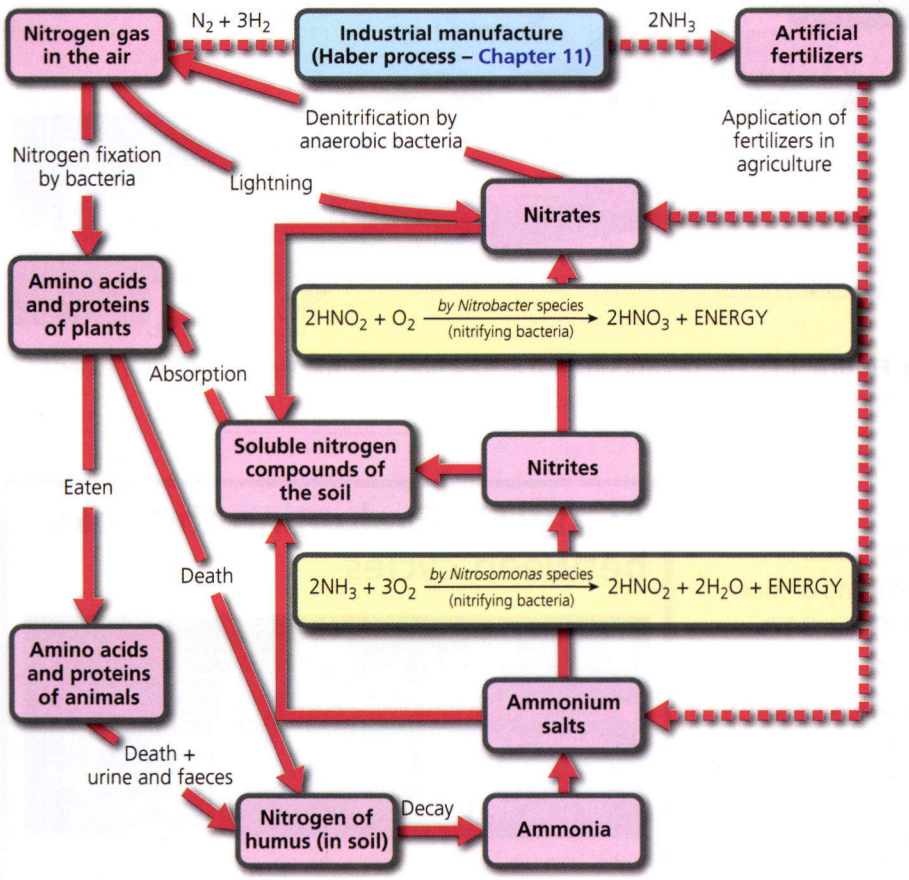



**Figure 9.16** The nitrogen cycle summarizes the vital importance of nitrogen to both plants and animals

Nitrogen is removed from the atmosphere by several important processes, both natural and anthropogenic. Nitrogen fixation involves nitrifying bacteria, which are found in soil and in special nodules on legumes (plants like beans and clover). Their enzymes can convert elemental nitrogen from the atmosphere into nitrates via oxides of nitrogen; the nitrates then dissolve in water in the soil.

Direct reactions between nitrogen gas and oxygen to form nitrates can only occur at very high temperatures. Examples include lightning strikes, and the reactions within internal combustion engines, where the energy from the spark plug helps convert some of the nitrogen in air to nitrogen oxides ($NO_x$). However, modern **catalytic converters** prevent the emission of these polluting nitrogen oxides in exhaust fumes by converting them back to nitrogen gas before they leave the exhaust pipe.

The Haber process (Chapter 11) is an industrial process for 'fixing' nitrogen from the air and making ammonia. A small amount of nitrogen gas is also extracted by industrial purification using the fractional distillation of liquid air.

A Flash-based animated version can also be found here: **www.sumanasinc.com/webcontent/animations/content/phosphorouscycle.html**

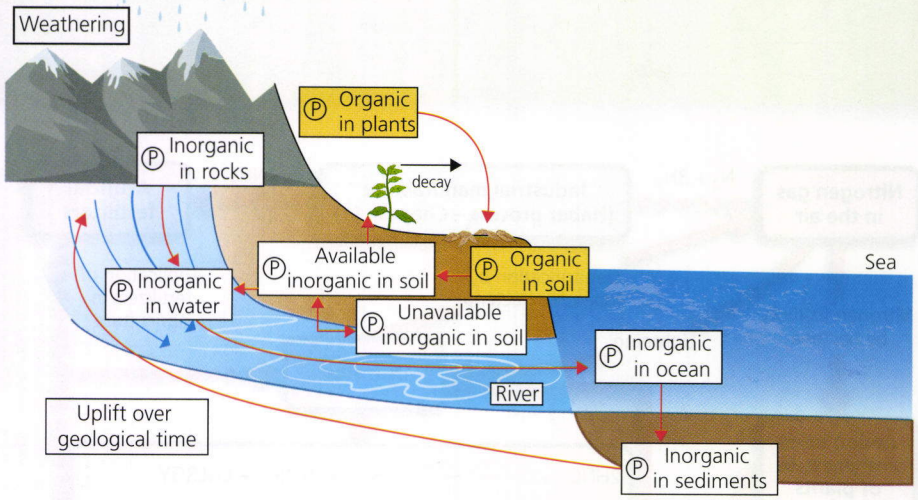



**Figure 9.17** The phosphorus cycle describes the movement of this element through rocks, water, soil and sediments and organisms

## Phosphorus – an essential nutrient

Like nitrogen, phosphorus is an essential nutrient for all organisms. The amount of available phosphorus limits how much matter can move through food chains.

The source of inorganic phosphate is from the release of phosphate ions ($PO_4^{3-}$) as a result of the weathering of rocks by rain, and they are also dispersed by water (Figure 9.17). The quantities of phosphorus compounds in soil are generally small. Outside the range of pH 4 to pH 8, inorganic phosphorus can be chemically bound (adsorbed) to soil particles, making it less available to plants. Some species of plants have relationships with other organisms, usually fungi, to help them extract these limiting phosphates.

The sink for phosphates is plants, which absorb inorganic phosphate and are eaten by animals. When organisms die and decay, or produce wastes, the phosphate is returned to the soil. Organic forms of phosphate can be made available to plants by bacteria that break down organic matter to inorganic forms of phosphorus, a process known as mineralization.

If the plants are harvested and removed, or phosphate is the limiting nutrient in an agricultural system, humans may apply phosphate fertilizers to replenish soils. This additional phosphorus is often mined from non-renewable sources such as bird and bat guano, sometimes thousands of years old.

Eventually, excess phosphate is leached into waterways and oceans, where it can be incorporated into sediments over time. However, like the geological cycling of organic carbon compounds, the extraction and use of phosphorus is effectively a one-way process. Globally, phosphorus resources are being used much faster than new supplies are forming.

## ACTIVITY: Evaluating the links between cycles

### ATL

- Critical-thinking skills: Gather and organize relevant information to formulate an argument
- Transfer skills: Make connections between subject groups and disciplines

The environment is sometimes divided into abiotic (non-living) and biotic (living) components.

1. **Identify inorganic substances other than nitrogen and phosphorus that are likely to have roles in both components of the environment.**
2. **Suggest, based on your scientific knowledge of the nitrogen and phosphorus cycles, how all other elements are also likely to enter the food chain.**
3. **Suggest how plant growth connects nutrients such as phosphorus to the atmosphere.**

### Assessment opportunities

- In this activity you have practised skills that are assessed using Criterion A: Knowing and understanding.

# To what extent do we need to change to counter the predictions of environmental models?

## REPAIRING OZONE DEPLETION

The former Director General of the United Nations, Kofi Annan, was quoted as saying that *'perhaps the single most successful international agreement to date has been the Montreal Protocol'*. This famous example of international, collaborative action engenders hope for a positive future for all. The 1987 Montreal Protocol has now been signed by every sovereign country.

In environmental science, a **contaminant** is a substance which does not occur naturally but is introduced by human activity. It may or may not be harmful to living organisms. Harmful contaminants are also pollutants. Chlorofluorocarbons (CFCs) were used as coolant liquids in refrigerators and as the solvent in aerosol sprays. They are volatile (low boiling point), non-flammable, non-toxic and were initially believed to be almost inert (very unreactive). The ability of gases to mix freely and convection currents in air meant that once released, these contaminants slowly diffused and eventually reached the stratosphere.

### The ozone 'layer'

Ozone is a gas found mainly in the lower portion of the stratosphere, from approximately 20 to 30 kilometres above the Earth, though the thickness varies seasonally and geographically. Ozone ($O_3$) is an allotrope of oxygen ($O_2$) and is formed when oxygen molecules in the stratosphere absorb ultraviolet radiation and split into two reactive oxygen atoms. Some of the highly reactive oxygen atoms called free radicals react with molecules of oxygen to form ozone molecules:

$$O_2(g) \rightarrow 2O\cdot(g)$$

$$O\cdot(g) + O_2(g) \rightarrow O_3(g)$$

Ozone is a dangerous substance if inhaled at ground level because it can cause respiratory problems, but it performs a vital role in the stratosphere. It absorbs ultraviolet B radiation with a range of wavelengths between 290–320 nm, preventing it from reaching the surface of the Earth. This extreme ultraviolet radiation harms marine phytoplankton and land plants, affecting food chains. It can also cause skin cancers and damage eyes, leading to cataracts.

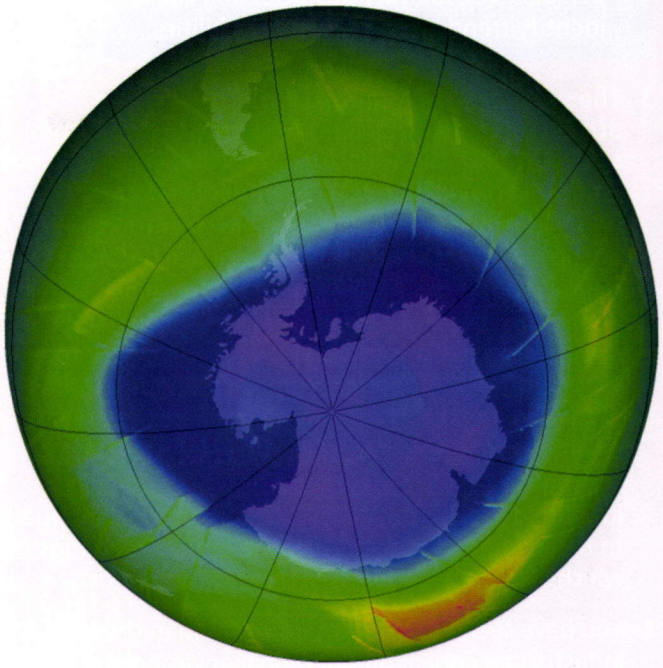


**Figure 9.18** The 'ozone hole'. What special weather features of Antarctica contribute to the chemistry of ozone depletion?

### How CFCs damage ozone

During the 1980s measurements from the ground and satellites suggested that CFCs were causing the removal of ozone from the upper atmosphere. The ozone concentration has been reduced most significantly in the atmosphere above Antarctica. **Ozone depletion** is greatest there because of wind and cloud conditions and is sometimes referred to as the 'ozone hole' (Figure 9.18). Parts of the Arctic ozone layer also develop 'thinning' during spring, but not nearly to the extent of the Antarctic.

## Take action: Performing chemistry to educate and entertain

### ATL

- Critical-thinking skills: Consider ideas from multiple perspectives; identify obstacles and challenges; identify trends and forecast possibilities

! The success of the Montreal Protocol has been attributed to many factors. When the first countries signed in 1987, the science of ozone depletion was not entirely certain. Therefore, the treaty was designed to be a flexible instrument, in which controls could be increased or decreased as the science became clearer. For example, when in 1991 it became apparent the danger from ozone depletion had been underestimated, a special fund was established to support the 142 signatories representing developing nations in meeting their obligations. There were also incentives to industry to develop new, patentable alternatives to CFCs, gases which could be readily identified in the atmosphere. Collaboration continues to be an important feature of the regular meetings, which were often addressed directly by scientists.

! You have seen in this chapter how human chemical industry can impact on our global environment. Global impacts require global solutions – but it has not been easy to communicate this across the world.

! A powerful way to communicate the message and educate people is to use performance.

! In this activity, you will research two global initiatives to limit or control environmental impacts. Then you will devise a performance to communicate and educate the world.

1 **List similarities between the Montreal Protocol and the Kyoto Protocol.**
2 **Outline how our lives would be different today if the Montreal Protocol had not been agreed to.**
3 **Suggest why the management of anthropogenic greenhouse gas emissions will be a greater global challenge than the management of ozone-destroying emissions.**

! In groups, devise a mime, short play, performance poem or other performance to dramatize the importance of the Montreal and Kyoto Protocols.

! Perform your pieces to another class, or in a school assembly. Why not video record them, and post online?

### Assessment opportunities

- In this activity you have practised skills that are assessed using Criterion D: Reflecting on the impacts of science.

### Links to: Arts – Dance; Drama

How can expression through dance or mime deliver an understanding of dynamic interactions?

## A catalytic cycle

The intense ultraviolet radiation in the upper atmosphere breaks the weaker C–Cl bonds of CFCs to release very reactive chlorine atoms, also known as chlorine radicals (Cl·) because they contain an unpaired electron.

A chlorine atom (Cl·) reacts with an ozone molecule, taking an oxygen atom to form an oxychlorine radical (ClO·) and leaving an oxygen molecule:

$$Cl\cdot(g) + O_3(g) \rightarrow ClO\cdot(g) + O_2(g)$$

The oxychlorine radical (ClO·) can react with a second molecule of ozone to produce another chlorine radical and two molecules of oxygen:

$$ClO\cdot(g) + O_3(g) \rightarrow Cl\cdot(g) + 2O_2(g)$$

Each alternating reaction generates a molecule that destroys ozone. The cycle can repeat and continue to destroy ozone molecules until it is removed by another reaction.

In the parts of the stratosphere away from the Earth's poles, two alternative reactions also occur. They remove the oxychlorine and chlorine radicals by converting them into stable chlorine nitrate and hydrogen chloride molecules:

$$ClO\cdot(g) + NO_2(g) \rightarrow ClONO_2(g)$$

$$Cl\cdot(g) + CH_4(g) \rightarrow \cdot CH_3(g) + HCl(g)$$

The nitrogen dioxide and methane molecules act as natural sinks for oxychlorine and chlorine radicals. Methyl radicals are very reactive, and quickly combine with other radicals, including chlorine atoms.

The ozone hole contracts during winter and expands over Antarctica during spring, in November. As the temperature increases, accumulated chloric(I) acid and chlorine molecules undergo **photolysis** in sunlight to form chlorine radicals which initiate the catalytic cycle for ozone depletion.

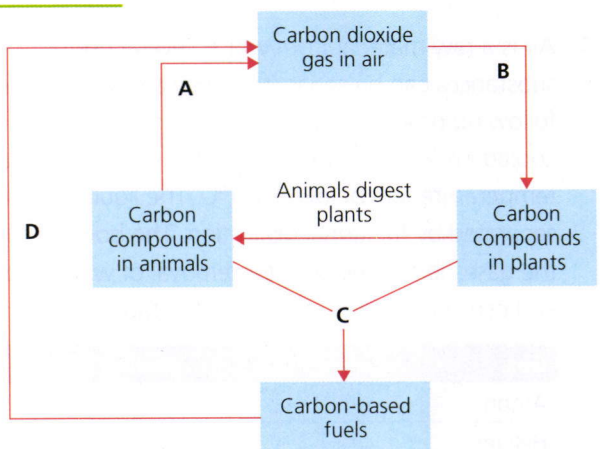
# SOME SUMMATIVE PROBLEMS TO TRY

Use these problems to apply and extend your learning in this chapter. The problems are designed so that you can evaluate your learning at different levels of achievement in Criterion A: Knowing and understanding.

A copy of a periodic table should be available for reference.

## THESE PROBLEMS CAN BE USED TO EVALUATE YOUR LEARNING IN CRITERION A LEVEL 1–2

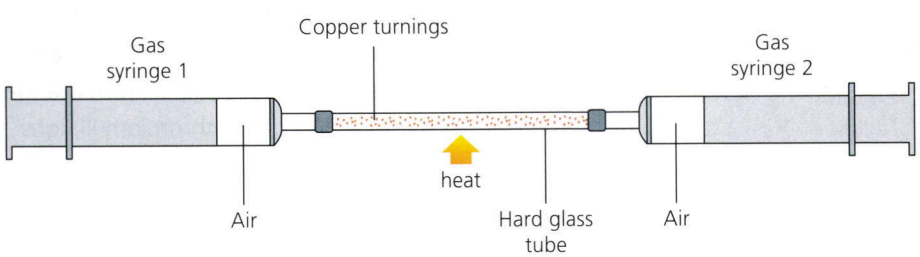
1 Referring to Figure 9.19,
   a **state** the names of the processes **A**, **B**, **C** and **D**
   b **list** names of three fossil fuels that could be listed in the box marked 'fuels'.
2 Referring to Figure 9.19,
   a **present** the biological processes taking place in **A** and **B** as word equations
   b **suggest** how these two processes balance the composition of the air.
3 Referring to Figure 9.19,
   a **interpret** where animals obtained their carbon, directly and indirectly
   b **judge** the effect of stopping process **B**.




■ **Figure 9.19** A simplified version of the carbon cycle

## THESE PROBLEMS CAN BE USED TO EVALUATE YOUR LEARNING IN CRITERION A LEVEL 3–4

4 **Outline** how carbon dioxide in the atmosphere contributes to the greenhouse effect.
5 Air is passed over heated copper turnings using the apparatus shown in Figure 9.20. This experiment is used to determine the percentage (by volume) of oxygen in air.
   a **Formulate** an equation describing the reaction which occurs in the tube.
   b **Suggest** how much the plunger in each of the two syringes will be depressed, by the end of the reaction.
   c **State** two gases that will be present in the apparatus after all the oxygen has been removed.




■ **Figure 9.20**

6 Air is a raw material from which several useful substances can be separated. They are separated in the following process. Dry and 'carbon dioxide free' air is cooled under pressure. Most of the gases liquefy as the temperature falls below –200 °C. The liquid mixture is separated by fractional distillation. The boiling points of the gases left in the air after removal of water vapour and carbon dioxide are given in the table below.

| Gas | Boiling point (°C) |
|---|---|
| Argon | –186 |
| Helium | –269 |
| Krypton | –157 |
| Neon | –246 |
| Nitrogen | –196 |
| Oxygen | –183 |
| Xenon | –108 |

a **Interpret** and **state** which three substances in the liquid mixture will be the first to change from liquid to gas as the temperature is slowly increased.

b **Suggest** why the air needs to be dried, and why carbon dioxide is removed before it is liquefied.

c Make a scientifically supported judgment about which of the gases will not have become liquid at –200 °C.

**THESE PROBLEMS CAN BE USED TO EVALUATE YOUR LEARNING IN CRITERION A LEVEL 5–6**

7 **Describe** how the composition of gases in the atmosphere interacts with the

a carbon cycle

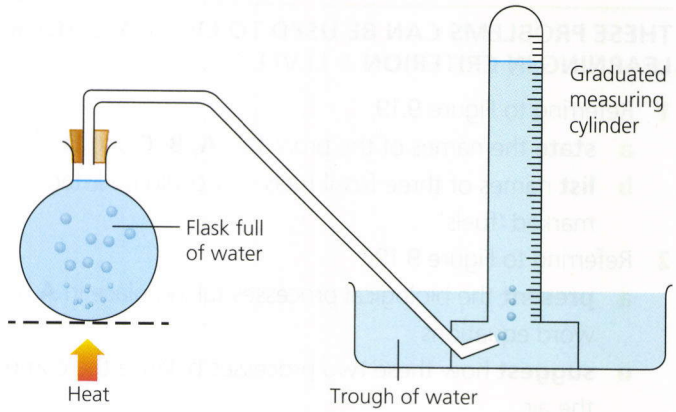
b water cycle

c nitrogen cycle

d phosphorus cycle.

8 This question refers to the following information.
Oxygen and nitrogen are both slightly soluble in water.

The apparatus shown in Figure 9.21 was used to collect 400 $cm^3$ of dissolved air from water heated to boiling. This 400 $cm^3$ of collected air was passed over heated copper powder and its final volume was 264 $cm^3$.




■ **Figure 9.21**

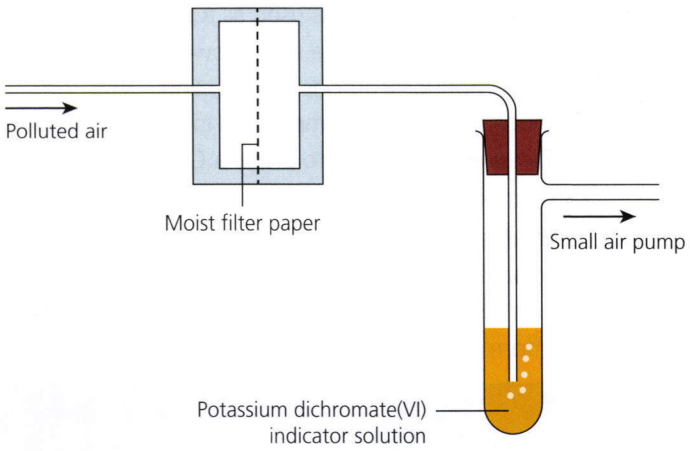
a **Determine** the volume of oxygen that was present in 400 $cm^3$ of dissolved air.

b **Calculate** the approximate percentages of oxygen and nitrogen in dissolved air.

c **Compare** these results with the percentages of these gases in dry atmospheric air and suggest reasons for differences.

d **Suggest** how the results of this experiment may differ if the water sample used had been collected downstream from a sewage outlet which regularly released large quantities of nutrients into the lake.

9 The simple apparatus used in Figure 9.22 could be used to compare the level of the pollutant, sulfur dioxide ($SO_2$), in the air at two different locations. A pump sucks air through the apparatus. The air passes through a filter paper which traps smoke particles. The air passes through potassium dichromate(VI) solution. The time is measured until the indicator changes colour from orange dichromate(VI) ions ($Cr_2O_7^{2-}$) to green chromium(III) ions ($Cr^{3+}$).




■ **Figure 9.22**

| Air sample | Time taken for indicator to change colour (seconds) |
|---|---|
| Location A | 98 |
| Location B | 575 |

■ Results of a comparative study of atmospheric pollution

**a** **Suggest** why the same pump needed to be used in the two experiments.

**b** **Analyse** the results and make a scientifically supported judgment about which of the two locations has cleaner air.

**c** **Suggest** why this example of environmental sampling is not a scientific experiment.

**10** **Analyse** the information about the composition of the atmosphere of Mars.

| Gas | Composition of atmosphere on Mars |
|---|---|
| Carbon dioxide | 95.3% |
| Nitrogen | 1.7% |
| Argon | 1.6% |
| Oxygen | 0.2% |
| Other gases, including carbon monoxide, water vapour and other noble gases | 1.2% |

**a** **Compare and contrast** the atmospheres of Mars and Earth.

**b** Scientists predicted the surface temperature on Mars by calculating its distance from the Sun. The measured surface temperature is slightly higher than the predicted value.

**i** **Suggest** which gas(es) in the table will cause the surface temperature of Mars to increase.

**ii** The Martian atmosphere also appears to contain a small amount of methane. **Suggest** possible source(s) for this gas on Mars.

## THESE PROBLEMS CAN BE USED TO EVALUATE YOUR LEARNING IN CRITERION A LEVEL 7–8

**11** **Explain** the difference between a 'pollutant' and a 'contaminant'.

**12** Chemists have confirmed that the depletion of the ozone layer is caused by a class of compounds called chlorofluorocarbons, CFCs. An example is dichlorodifluoromethane, $CF_2Cl_2$.

In the stratosphere, the dichlorodifluoromethane molecules absorb ultraviolet radiation and undergo dissociation and release reactive atoms.

The bond energies between atoms in the molecule are given below.

| Bond | Energy needed ($kJ\,mol^{-1}$) |
|---|---|
| C–F | 492 |
| C–Cl | 324 |
| C–H | 414 |

**a** **Describe** the outer electron structure of a molecule of $CF_2Cl_2$ using a Lewis structure diagram.

**b** **Suggest** which bond between atoms in dichlorodifluoromethane is most likely to be broken during the dissociation process, and why.

**c** **Predict** and **explain** the relative environmental effects on a per molecule basis of the following three CFCs:

**i** monochlorotrifluoromethane, $CF_3Cl$

**ii** dichlorodifluoromethane, $CF_2Cl_2$

**iii** trichloromonofluoromethane, $CFCl_3$.

**d** Bromomethane, $CH_3Br$, is used as a pesticide in agriculture to fumigate soils. However, hydrobromofluorocarbons (HBFCs) and bromocarbons are also implicated in ozone depletion.

The energy required to break a C–Br bond is $285\,kJ\,mol^{-1}$.

**Evaluate** whether HBFCs are likely to be more or less reactive than CFCs.

**13** 'Lean burn' engines are a type of car engine. This table shows information about 'lean burn' engines.

| Type of engine | Amount of air mixed with petrol | Operating temperature | Concentration of carbon monoxide in exhaust gases | Concentration of nitrogen oxides in exhaust gases |
|---|---|---|---|---|
| Normal | Less air | Higher | Higher | Higher |
| Lean burn | More air | Lower | Lower | Lower |

Another way of reducing the amounts of carbon monoxide and nitrogen oxides from cars is to use catalytic converters. The transition metal catalyst increases the rate of conversion of carbon monoxide and nitrogen monoxide to carbon dioxide and nitrogen.

**a** **Explain** why 'lean burn' engines produce smaller amounts of

**i** carbon monoxide

**ii** nitrogen oxides.

**b** **Describe** the reactions catalysed by the transition metal using a balanced chemical equation.

**c** **Identify** the information you would require to be able to **evaluate** the relative environmental advantages of using a 'lean burn' engine compared to a 'normal' engine with a catalytic converter.

# Reflection

In this chapter you reflected on the global systems on Earth, and their interrelationships. All systems are dynamic, and geological and biological processes have changed Earth's atmosphere through time. The carbon, water and nitrogen cycles involve the atmosphere directly, and the nutrient cycles such as the phosphorus cycle affect the atmosphere indirectly through plant growth. Human ingenuity and collaboration have successfully responded to the global environmental challenge caused by CFC contamination. The challenge posed by anthropogenic greenhouse warming caused by carbon dioxide pollution remains.

| **Use this table to reflect on your own learning in this chapter** | | | | | | |
|---|---|---|---|---|---|---|
| Questions we asked | Answers we found | Any further questions now? | | | | |
| **Factual:** What are the implications of uncontrolled emissions? How do environmental cycles interconnect? | | | | | | |
| **Conceptual:** How important are biological contributions to global systems? | | | | | | |
| **Debatable:** How do we balance the environmental risk and the societal benefits of the exploitation of chemical resources? To what extent do we need to change to counter the predictions of environmental models? | | | | | | |
| Approaches to learning you used in this chapter: | Description – what new skills did you learn? | How well did you master the skills? | | | | |
| | | Novice | Learner | Practitioner | Expert | |
| **Collaboration skills** | | | | | | |
| **Communication skills** | | | | | | |
| **Organisation skills** | | | | | | |
| **Information literacy skills** | | | | | | |
| **Critical-thinking skills** | | | | | | |
| **Transfer skills** | | | | | | |
| **Learner profile attribute(s)** | Reflect on the importance of caring for your learning in this chapter. | | | | | |
| **Caring** | | | | | | |

# 10 How can our energy resources be accessed fairly?

Global exploitation of energy resources relies on **energetic changes** in chemical reactions; **global development** depends on the **fair and equitable** exchange of those resources.

## These Approaches to Learning (ATL) skills will be useful …

- Communication skills
- Collaboration skills
- Organization skills
- Reflection skills
- Media literacy skills
- Critical-thinking skills
- Creative-thinking skills
- Transfer skills

## Assessment opportunities in this chapter …

- Criterion A: Knowing and understanding
- Criterion B: Inquiring and designing
- Criterion C: Processing and evaluating
- Criterion D: Reflecting on the impacts of science

## CONSIDER AND ANSWER THESE QUESTIONS:

**Factual:** What conditions help substances burn?

**Conceptual:** What happens to chemical energy during physical and chemical changes? Why is energy transfer so important? Why are fossil fuels still so attractive as an energy source? What is meant by 'spontaneity' in scientific terms?

**Debatable:** Should people in the developing world be allowed the same energy consumption as ourselves?

Now **share and compare** your thoughts and ideas with your partner, or with the whole class.

## IN THIS CHAPTER, WE WILL …

- **Find out** what happens during combustion.
- **Explore**
  - the contribution of chemical fuels to global energy demands;
  - why chemical reactions are feasible;
  - how to predict whether a chemical reaction or physical change is likely to be endothermic or exothermic.
- **Take action** by raising awareness of the dangers of home fires, and how to fight them.

## KEYWORDS

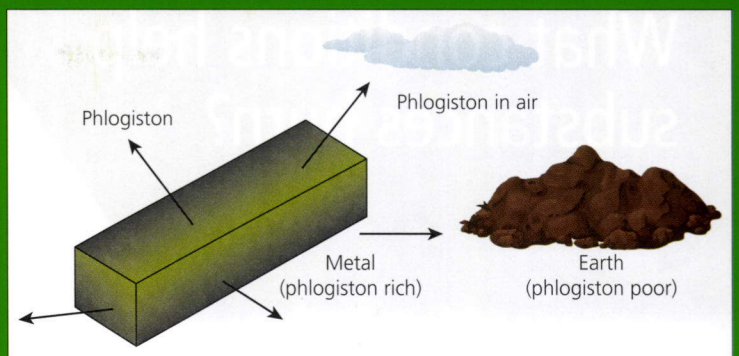
disorder
excess
spontaneity

## We will reflect on this learner profile attribute …

- Reflective – How important is reflection for planning change? How does making mistakes and identifying misconceptions help you learn? Are the ways in which we have supported others in the past also misguided? Will considering the fairness of past energy usage around the world and consequences on our world communities and to the environment lead to actions that make our world equitable for all?



■ **Figure 10.1** Why are combustion reactions of fossil fuels such as methane so important economically?




■ **Figure 10.2** The phlogiston theory

# 'PLAYING' WITH FIRE!

Fires are often easy to light, but difficult to put out. But, how do fuels burn? Until this question was answered, chemistry could not make much progress.

## Phlogiston theory!

By the 17th century, scientists were beginning to realize that the burning of fuels and the reactions of metals in air all had a common feature – they were all faster or slower versions of the same type of reaction.

Johann Becher (1625–1682) and Georg Stahl (1660–1734) explained these observations by the removal (loss) of a mysterious, undetectable substance called phlogiston (Figure 10.2).

According to their theory:

- All combustible substances contain phlogiston, which is released into the air on burning, along with caloric (thermal energy).
- Charcoal (carbon) leaves very little ash when it burns because it is almost pure phlogiston. Charcoal is useful for smelting (Chapter 8) metals from their ashes and earths (metal oxides) because charcoal restores the levels of phlogiston in the ash.
- A candle flame goes out in a sealed container because the air becomes saturated with phlogiston.
- Substances lose mass when they burn because they lose phlogiston; however, phlogiston must have negative mass because metals gain mass when they react with the air!

Lavoisier and Priestley (Chapter 1) disproved the phlogiston theory and replaced it with a theory based on the law of conservation of mass and oxidation.

In May 1794, during the French Revolution, Lavoisier was arrested, accused of a number of crimes and later beheaded. The judge ignored his defence with the words, *'The Republic has no need of men of science.'*

## DISCUSS

1. **List similarities between phlogiston theory and the modern understanding of oxidation.**
2. **Identify other examples of scientific ideas that have changed through time. What caused these ideas to change?**
3. **Suggest a reply to the judge's claim that *'The Republic has no need of men of science.'* Would a person living in an isolated, remote region of the world, whose energy needs are entirely based on biomass, appreciate your argument?**

### ▼ Links to: History

It has been argued that the Enlightenment ideas introduced by scientific philosophers (including Isaac Newton, Blaise Pascal and René Descartes) were related to political ideas that became very important, such as liberalism, nationalism and democracy. Without these ideas, the American and French Revolutions would never have happened! Do you think science changes people's ideas about society? To what extent does society affect the progress of science?

# What conditions help substances burn?

## WHEN CANDLES BURN

You first observed a burning candle in Chapter 1. When solid fuels burn, two changes of state are required. Long-chain hydrocarbons like candle wax (usually around $C_{30}H_{62}$) melt, then the molten wax moves up the wick where the molten wax vaporizes. The combustion reaction involves the wax vapour around the wick (see Figure 10.3) to form carbon dioxide and steam.

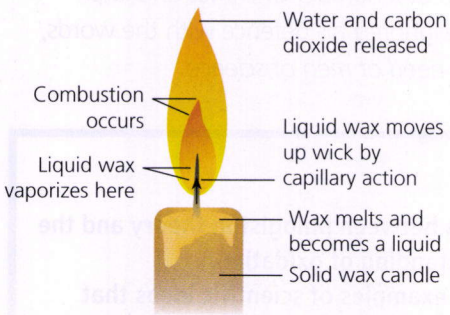



**Figure 10.3** A burning candle

## FLASH POINTS

For a fuel to combine with oxygen, its vaporized gas needs to mix with oxygen in the air. The **flash point** of a fuel is the lowest temperature at which there is enough vapour (gas) for the fuel to ignite.

Petrol vaporizes very easily at room temperature, and will ignite when a lit match is held over the liquid. In a car engine, a spark plug (Figure 10.5) provides the energy needed to start the reaction. Paraffin (kerosene) vaporizes less readily, so it is harder to light. A spirit burner and wick help it vaporize.

## ACTIVITY: Investigating a burning candle

### ATL

- Organization skills: Plan strategies and take action to achieve personal and academic goals; select and use technology effectively and productively

Refer to the inquiry cycle (Figure 1.11) to plan an experimental investigation into the effect of different atmospheres on combustion of candles, held in sealed containers. (Figure 10.4). A risk analysis and an environmental impact analysis must be included in your plan.

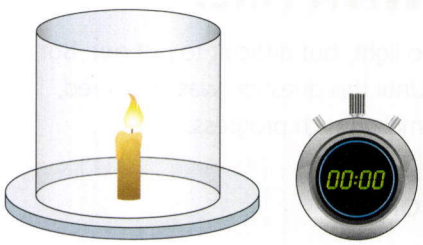



**Figure 10.4** Possible apparatus

### Assessment opportunities

- In this activity you have practised skills that are assessed using Criterion B: Inquiring and designing and Criterion C: Processing and evaluating.



**Figure 10.5** A spark plug ignites petrol vapour (gas) and air




**Figure 10.6** A household carbon monoxide detector

## ACTIVITY: Team research into flashpoints

### ATL

- Collaboration skills: Help others succeed; encourage others to contribute; negotiate effectively

1 **Identify**, using the Internet for a particular flammable substance, **the information needed to complete the table collaboratively.**

| Flammable substance | Flash point/°C | Boiling point/°C |
|---|---|---|
| Benzene | | |
| Butane | | |
| Ethanol | | |
| Propan-1-ol | | |
| Ethoxyethane (ether) | | |
| Glycerine | | |
| Paraffin | | |
| Petrol | | |
| Diesel | | |
| White spirit | | |

2 **Plot the relationship of the flash point and the boiling point against each other. If a range of temperatures is given, consider using a box and whisker representation.**

3 **Suggest why petrol, white spirit (Figure 10.7) and paraffin have ranges for their flash points and boiling points.**

4 **Explain, with reference to intermolecular forces and changes of state, the relationship between flash point and boiling point.**




**Figure 10.7** White spirit

5 **Suggest why is it more dangerous to be trapped in a bushfire (wild fire) in a car with a nearly empty petrol tank than one that is nearly full of fuel.**

### Assessment opportunities

- In this activity you have practised skills that are assessed using Criterion A: Knowing and understanding.

# COMBUSTION PRODUCTS

## Complete combustion

Most fuels contain carbon and hydrogen. During **complete combustion**, a fuel's carbon forms carbon dioxide and its hydrogen forms water. For example,

methane + oxygen → carbon dioxide + water

$CH_4(g) + 2O_2(g) \rightarrow CO_2(g) + 2H_2O(l)$

## Incomplete combustion

In any chemical reaction, a **limiting reactant** is the substance that is completely used up, and which therefore determines when the reaction stops.

During combustion, if oxygen is the limiting reactant, the fuel's carbon atoms may be released as small particles of black soot. This effect can be seen in 'smoking' candles, and on the surface of laboratory glassware that has been incorrectly heated using the 'safety' flame of a Bunsen burner. These soot particles can also be a major source of air pollution in cities that rely on cheap grades of coal for heating and cooking.

**Incomplete combustion** can also form a dangerous alternative product:

methane + oxygen → carbon monoxide + water

$2CH_4(g) + 3O_2(g) \rightarrow 2CO(g) + 4H_2O(l)$

Carbon monoxide (CO) has no colour and no smell, although household detectors exist (Figure 10.6). If accidentally inhaled, it binds permanently with hemoglobin in red blood cells, preventing the transport of oxygen via the circulatory system. Faulty gas heating or using outdoor stoves in enclosed places can cause fatal carbon monoxide poisoning. For this reason, all fuels should be completely combusted to carbon dioxide.

## EXTENSION

**Explore further:** What is the role of the choke and carburettor in the combustion of fuel in a vintage car? How does 'tuning' a car engine reduce the percentage of carbon monoxide present in a vehicle's exhaust gases?

# Why is energy transfer so important?

## GETTING CHEMICAL REACTIONS STARTED

Thermal energy is sometimes referred to as 'heat energy'. However, heat is not a form of energy, but rather a process by which energy is transferred from a hotter object to a cooler one. There are two explanations for saying something is 'heated':

1. Energy has been transferred by convection or conduction and the thermal motion or kinetic energy of the particles receiving the energy has increased. Some of the energy will increase the speed at which the molecules move through space (translation), but some energy will also be transferred to vibrations and rotations if the particles involved are molecules.
2. Energy has been transferred by radiative heating in the form of infra-red radiation, which often leads to an increase in the vibrational motion of molecules.

The term 'thermal energy' in this chapter has been used to describe either mode of heat transfer.

The energy needed to start a chemical reaction is known as the **activation energy**. All reactions need some thermal energy to get them started, but some need so little they can start at room temperature. Rusting and neutralization are examples of such reactions.

To release thermal energy, fuels need to react with oxygen. However, most fuels are safe at room temperature because they 'burn' so slowly that effectively no reaction occurs. Like all chemical reactions, the rate increases at higher temperatures. Combustion or burning can start only after the fuel has been ignited.

The barrier to the reaction is called the 'activation energy' (Figure 10.8) and it can be overcome in different ways. For example, the **ignition temperature** of a fuel is the lowest temperature at which it will spontaneously burn, and at which the reaction releases enough thermal energy to keep it going. The barrier can also be decreased by using a catalyst, which helps the reactants approach each other in directions that optimize the probability they will be able to react. The catalyst itself is not used up, but the rate of the reaction increases because less energy is required to start the reaction and keep it going.

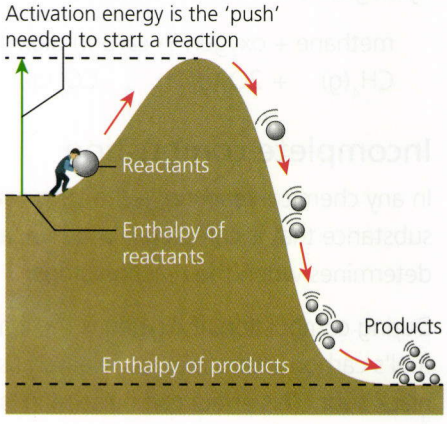
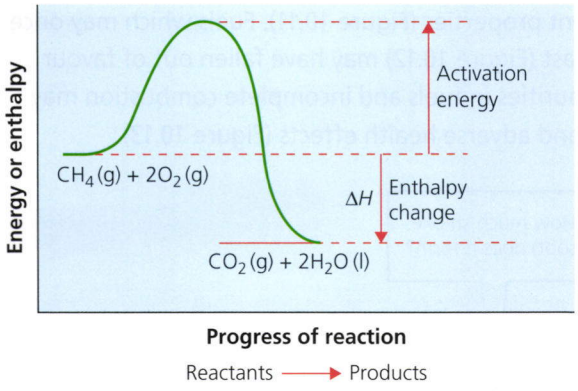



**Figure 10.8** The concept of activation energy as an 'energy barrier'

Figure 10.8 is an example of an **energy** or enthalpy **level diagram**, showing the activation energy input as a positive increase in the system, and the release of energy as a negative value.

Figure 10.9 is an example of an energy level diagram for the **enthalpy of combustion** of a fuel, methane. The value $\Delta H$ represents the energy released in the exothermic reaction (see Chapter 6). The diagram shows that thermal energy has flowed from the chemicals (the system) to the surroundings. For this reason, it is given a negative sign in the **thermochemical equation** of the reaction:

$$CH_4(g) + 2O_2(g) \rightarrow CO_2(g) + 2H_2O(l);\ \Delta H \text{ negative}$$



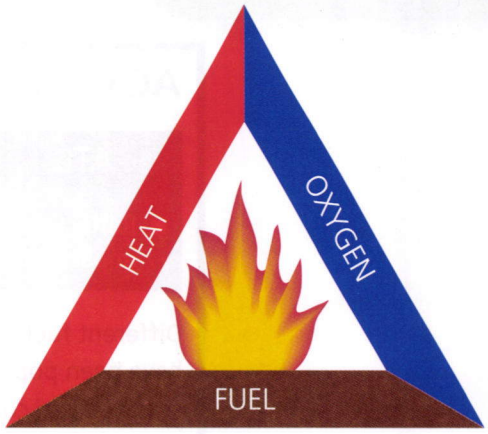

■ **Figure 10.9** An energy level diagram for the enthalpy of combustion of methane, showing the activation energy barrier

## DISCUSS: Reflecting on the enthalpy of combustion

1. **List** six examples of fuels your family used during the year. From the context where the fuel is used, **suggest** the relative size of its 'activation energy'.
2. **Suggest** how Figure 10.8 would need to change if an enzyme lowered the activation energy.
3. **Explain** the concept of activation energy by including kinetic energy of colliding particles.

## THE FIRE TRIANGLE

Fires need fuel, oxygen (usually from the air) and a high temperature to start the fire (provide activation energy). These three variables make up the fire triangle (Figure 10.10).




■ **Figure 10.10** The fire triangle

## DISCUSS

1. **Identify** the fire-fighting equipment that is present in your chemistry laboratory, and **describe** how you would use it.
2. **Describe,** with reference to the fire triangle, how each of these fire-fighting methods prevents fires spreading: a fire blanket, sand, water, carbon dioxide, foam, halon (an inert organic compound) and powder.
3. **Explain** why water should not be used against oil, petrol or electrical fires.

## ! Take action

! Complete a fire risk assessment of your school's facilities, then write a report to the Head of the School and Board of Directors, citing your commendations and recommendations.

# Why are fossil fuels still so attractive as an energy source?

## ACTIVITY: What makes a good fuel?

### ATL

- Reflection skills: Consider ethical, cultural and environmental implications

Different fuels have different properties (Figure 10.11). Fuels which may once have been popular in the past (Figure 10.12) may have fallen out of favour in developed countries. Impurities in fuels and incomplete combustion may contribute to air pollution and adverse health effects (Figure 10.13).

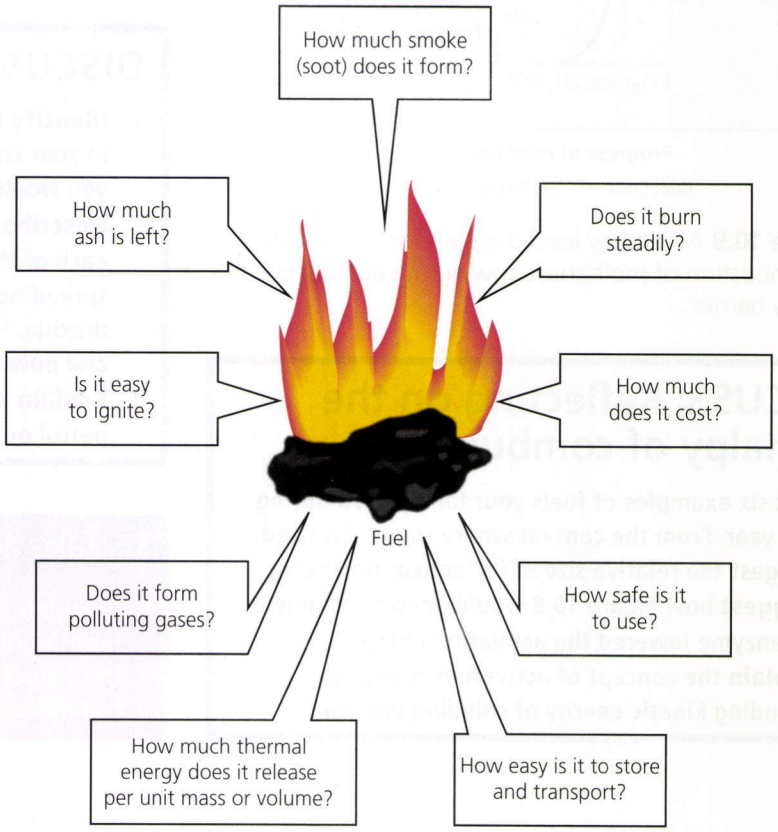



**Figure 10.11** Important properties of a fuel

## EXTENSION

**Explore further:** Fuels in the past. Interview your grandparents and ask them about the fuels that were used for heating, cooking and transport when they were your age. What chemical processes contribute to **smog** and what political processes lead to **oil crises**?




■ **Figure 10.12** A coal-fired steam engine in the United Kingdom




■ **Figure 10.13** A police officer outside the Bank of England attempts to keep traffic moving through the Great Smog of London of 1952

1 **Identify**, with reference to Figure 10.11, properties needed of a fuel intended for use in
   - a transport
   - b camping
   - c long-term storage
   - d indoor use
   - e generating electricity for industry.
2 **Compare and contrast** advantages associated with each of the properties listed in Figure 10.11.
3 **Suggest** how your fuel choice decisions would change if
   - a the air quality standards of your country were lower than surrounding countries
   - b the 'ideal' fuel was not locally available
   - c your business was in a location where storage costs were very high.
4 **Outline** how the chemical qualities might be determined experimentally, explaining measurements and observations you would record and how the variables will be controlled. **Describe** the safety precautions you will take.

### ◆ Assessment opportunities

◆ In this activity you have practised skills that can be assessed with Criterion D: Reflecting on the impacts of science.

# Should people in the developing world be allowed the same energy consumption as ourselves?

## ENERGY FOR A FAIRER WORLD

All living organisms, including humans, require food, shelter, water and warmth. These complex needs are linked through physical–chemical and biological systems (Chapter 9) where the common denominator is energy.

As an example of how energy availability interacts with a range of factors in societies, consider the impact of the inefficient combustion (burning) of coal. Manufacturing and industrial processes will be affected directly. For example, large amounts of energy are needed to refine crude oil, extract aluminium, make plastics and lime (calcium oxide), which is used for making concrete, directly affecting productivity. Wasteful burning also causes air pollution (Figure 10.13), indirectly affecting productivity. For example, people working in these industries may suffer a larger number of sick days because of the quality of the air, and other people will need to care for them.

Rich or developed countries have a long history of using cheap and plentiful fossil fuels (coal, fuel oil and gas) and continue to use most of global energy supplies, contributing unfairly to global, anthropogenic climate change (see Chapter 9). On the other hand, as developing countries transform their industries, some of them may be able to completely bypass inefficient and polluting technologies used in the past.

## ACTIVITY: Realizing a sustainable energy future for all

### ATL

- Critical-thinking skills: Gather and organize relevant information to form an argument; interpret data; consider ideas from multiple perspectives; identify trends and forecast possibilities
- Communication skills: Make inferences and draw conclusions; organize and depict information logically

A sustainable energy future that is fair should recognize the right of every person to benefit equally from the world's energy resources. Each country has access to a range of natural resources to meet some of its energy needs, and a proportion must be met through chemical solutions.

Develop a 1200-word proposal to recommend strategies based on scientific knowledge that could help to end 'energy poverty' in a developing country of choice. Assume a five-year time frame and a hypothetical budget of 10 billion US dollars.

- **Include an assessment of the role of fuels as a resource for contributing to energy needs, and an explanation of energy conversions involved in their use.**
- **Include an evaluation of the consequences of the scientific solution for resource management, and how this may interact with a moral, ethical, social, economic, political, cultural or environmental factor in the country you have selected. Approximately half the length of your written presentation should concern this reflection.**
- **You may wish to consider a presentation that includes headings and subheadings, and refer to tables, diagrams, graphs, lists and appendices.**
- **All sources should be fully documented.**

### Assessment opportunities

- This activity can be assessed using Criterion D: Reflecting on the impacts of science.

# ACTIVITY: Exploring a simple fuel cell

## ATL

- Creative-thinking skills: Create novel solutions to authentic problems

Fuel cells (introduced in Chapter 6) have been used since the 1960s in NASA's vehicles, submarines and the International Space Station (ISS). What are the implications of extending their use?

**Safety:** Eye protection must be worn when using caustic solutions.

### Materials and equipment

- safety goggles
- 6 V DC power supply
- leads with alligator clips
- 0.1 mol $dm^{-3}$ sodium hydroxide solution
- 2 × test tubes
- beaker
- graphite electrodes
- high resistance voltmeter

### Method

1. Put on safety goggles.
2. Set up the electrolysis cell shown in Figure 10.14(a).
3. Connect the cell to a 6 V DC power supply and let electrolysis continue until the tube above the anode (positive electrode) is filled with oxygen and that above the cathode (positive electrode) with hydrogen, as shown in (b) of the diagram.
4. Disconnect the low voltage power supply.
5. The assembly is now ready to be a fuel cell. Connect a high resistance voltmeter across the electrodes.

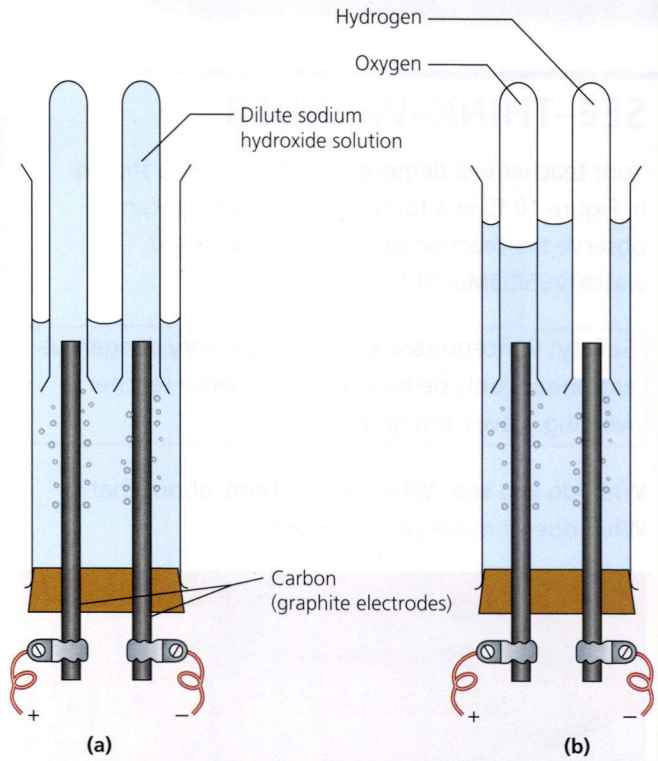



**Figure 10.14** A simple **fuel cell**

### Reflecting on results

1. **List** evidence for a chemical reaction.
2. **Identify** the source for the current observed when the power supply was disconnected.
3. **Suggest** contexts in which fuel cells might have advantages.
4. **Evaluate** the potential of this technology for solving energy poverty.

## Assessment opportunities

- In this activity you have practised skills that can be assessed using Criterion A: Knowledge and Understanding and Criterion C: Processing and evaluating.

# What happens to chemical energy during physical and chemical changes?

## SEE–THINK–WONDER

Your teacher will demonstrate the reaction shown in Figure 10.15 in a fume cupboard, or you can observe the reaction on www.youtube.com/watch?v=5Ib3MuOThTg.

**Safety:** Concentrated sulfuric acid is very dangerous and should only be handled by a science teacher wearing gloves and glasses.

What do you **see**? What do you **think** about that? What does it make you **wonder**?



**Figure 10.15** The reaction between sucrose and concentrated sulfuric acid

## EXPLORING ENERGY CHANGES

Nearly all chemical reactions involve an overall change in energy. Potential **chemical energy** is stored in matter in bonds (and intermolecular forces), which are broken (endothermic processes) in the reactants and formed (exothermic processes) in the product. Changes in thermal energy provide evidence that a chemical reaction has occurred. Most reactions are exothermic overall, involving an increase in temperature as thermal energy is released into the surroundings. Chemical reactions often transfer energy in more than one way. For example, a burning candle transfers energy by heat and light.

Energy changes involving thermal energy measured under standard conditions and constant pressure are known as **enthalpy changes**. Entropy also plays an important role in determining the direction of chemical reactions and physical changes (Chapter 6).

## DISCUSS

1. **Identify** evidence that this is a dehydration reaction.
2. Sucrose is an 'organic' substance. **Identify** the matter in the black product.
3. **Suggest** where the thermal energy in this exothermic reaction came from.
4. **Evaluate** how these energy changes can be measured and standardized.

## PREDICT–OBSERVE–EXPLAIN

The aim of this activity is to provide you with strategies to complete quantitative evaluations of energy changes during chemical and physical changes.

**Safety:** Concentrated sulfuric acid and solid ammonium nitrate are dangerous. Each of the two reactions here needs to be demonstrated separately in a fume hood by a science teacher wearing gloves and glasses.

**Predict** whether the formation of solutions might interfere with the hydrogen bonding (Chapter 4) of the water molecules, and possible temperature changes involved.

**Observe** the temperature change, $\Delta T$, when

- **(Reaction 1) One mole (98.09 g) of concentrated sulfuric acid is added to sufficient water to make 1 dm³ of solution. Concentrated sulfuric acid is a covalent molecular substance.**
- **(Reaction 2) One mole (80.06 g) of solid ammonium nitrate is dissolved in water to make 1 dm³ of solution. Ammonium nitrate is an ionic compound.**

**Explain** the change in the thermal energy of the solutions caused by each reaction.

# CALCULATING THE AMOUNT OF THERMAL ENERGY INVOLVED IN A REACTION

In each reaction, the total volume of the product was 1 dm³. This volume of pure water has a mass of 1000 g.

In order to return to room temperature, each mixture needed to lose or gain thermal energy. Assuming the mixtures have the same **specific heat capacity** as pure water (4.18 J g$^{-1}$ °C$^{-1}$), the quantity of thermal energy involved can be calculated with the following equation:

$$Q = mc\Delta T$$

where $Q$ = thermal energy (J), $m$ = mass of water (g), $c$ = specific heat capacity of water (J g$^{-1}$ °C$^{-1}$) and $\Delta T$ = temperature rise (°C).

### Sample calculation, *Q*

If adding sulfuric acid to 1 dm³ of water caused the temperature of the mixture to rise by 17.0 °C, then

thermal energy lost from the mixture ($Q$)
= 1000 g × 4.18 J g$^{-1}$ °C$^{-1}$ × 17.0 °C

= 71 060 J

= 71.1 kJ

This means the sulfuric acid solution has less chemical (potential) energy than the concentrated sulfuric acid and water from which it was formed. The term $\Delta H$ is used to show this measurable change of potential energy (thermal energy content or enthalpy, $H$) to thermal energy. Note the sign (negative) of $\Delta H$ in the summary of this reaction:

$$H_2SO_4(l) + (aq) \rightarrow H_2SO_4(aq, 1\,mol\,dm^{-3}); \Delta H = -71\,kJ\,mol^{-1}$$

This information is shown by the use of an energy or enthalpy level diagram (Figure 10.16). How would the shape of this diagram, and the direction of the arrow, change if this reaction was endothermic?

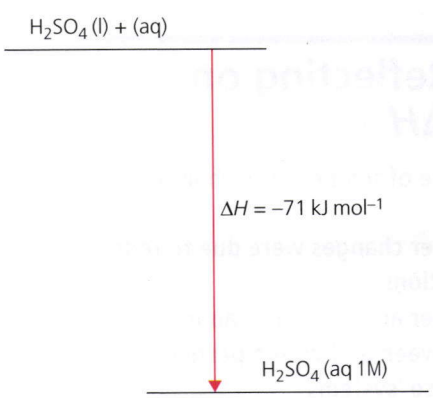



**Figure 10.16** The energy level diagram for the formation of 1 mol dm$^{-3}$ sulfuric acid, an example of an exothermic reaction

## ACTIVITY: The combustion of ethanol

### ATL

- Collaboration skills: Exercise leadership and take on a variety of roles within groups

**Safety:** Wear eye protection near any activity involving naked flames.

### Materials and equipment

- safety goggles
- spirit lamp about half full of ethanol as shown in Figure 10.17
- retort stand, clamp
- stirring rod
- thermometer
- metal can
- electronic balance

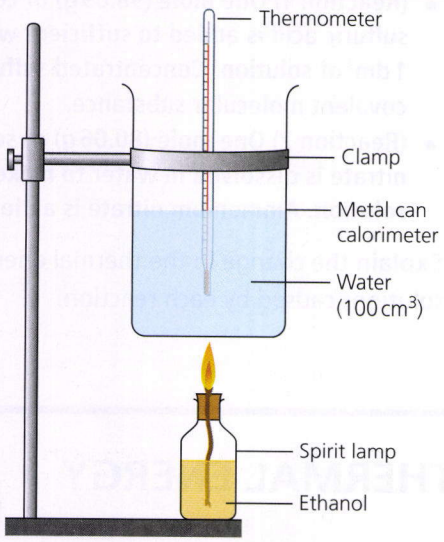



**Figure 10.17** The determination of the enthalpy of combustion of ethanol

### Method

1. Put on safety goggles.
2. Weigh the spirit lamp on the electronic balance.
3. Measure the temperature of the water in the can.
4. Use the spirit lamp to heat the water by about 20 °C, stirring constantly.
5. Extinguish (put out) the flame, recording the final temperature.
6. Reweigh the spirit lamp and its contents.

### Analysing results:

1. **Calculate** $\Delta H$ for the reaction in $kJ\,mol^{-1}$ remembering to give it the correct sign.
2. **Draw** an energy level diagram, including the scale.
3. **Formulate** a thermochemical equation for the combustion of ethanol (spirit) by including $\Delta H$:

$$C_2H_5OH(l) + 3O_2(g) \rightarrow 2CO_2(g) + 3H_2O(l)$$

4. This is an example of a very simple calorimeter. **Evaluate** the validity of the method and suggest modifications that would reduce the errors present in the method used.

### Assessment opportunities

- In this activity you have practised skills that are assessed using Criterion C: Processing and evaluating.

## EXPLORING ENTHALPY CHANGES, $\Delta H$

These practical activities all aim to demonstrate different contexts for the calculation of enthalpy. They can be completed in groups or investigated by separate teams.

## DISCUSS: Reflecting on enthalpy, $\Delta H$

1. **State** the source of temperature change in each activity.
2. **Identify** whether changes were due to redox or non-redox reactions.
3. **Suggest** whether anything else, apart from attractions between and within particles, was changing in these 'systems'.

## ACTIVITY: The precipitation of calcium carbonate

### ATL

- Communication skills: Write and interpret a range of discipline-specific terms and symbols

**Safety:** Wear eye protection and use gloves. At these concentrations, both salt solutions are irritants.

### Materials and equipment

- safety goggles and gloves
- 2.00 mol $dm^{-3}$ calcium chloride solution
- 2.00 mol $dm^{-3}$ potassium carbonate solution
- thermal energy insulating plastic cup
- 2 × 50 $cm^3$ measuring cylinders
- thermometer
- rinse bottle

# ACTIVITY: The displacement of copper(II) ions from a solution by zinc atoms

## ATL

- Collaboration skills: Delegate and share responsibility for decision making

### Materials and equipment

- 0.20 mol dm$^{-3}$ copper(II) sulfate solution
- zinc filings
- 25.00 cm$^3$ pipette
- stopper
- thermometer
- electronic balance

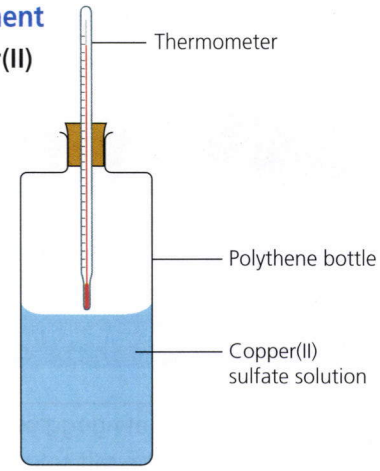



**Figure 10.18** The determination of the enthalpy of the displacement of copper ions by zinc atoms

### Method

1. Use a pipette to place 25.00 cm$^3$ of 0.20 mol dm$^{-3}$ copper(II) sulfate solution in the bottle shown in Figure 10.18.
2. Insert the stopper and thermometer, turn upside down and note the initial temperature.
3. Add about 0.500 g of zinc filings (this is about a two-fold **excess**), shake and record the maximum temperature change occurring.

### Analysing results

1. **Calculate** $\Delta H$ for the reaction in kJ mol$^{-1}$, remembering to give it the correct sign.
2. **Draw** an energy level diagram, including the scale.
3. **Formulate** a thermochemical ionic equation for the reaction of copper ions with zinc atoms by including $\Delta H$:

$$Cu^{2+}(aq) + Zn(s) \rightarrow Cu(s) + Zn^{2+}(aq)$$

4. **Present** this reaction as two half-equations (Chapter 8).
5. **Evaluate** the evidence that virtually all the copper has been precipitated.

## Assessment opportunities

- In this activity you have practised skills that are assessed using Criterion C: Processing and evaluating.

### Method

1. Put on safety goggles and gloves.
2. **Measure** 50 cm$^3$ of 2.00 mol dm$^{-3}$ calcium chloride solution and place it in the insulating plastic cup.
3. **Measure** 50 cm$^3$ of 2.00 mol dm$^{-3}$ potassium carbonate solution in the second measuring cylinder.
4. **Record** the initial temperature of each solution, cleaning the thermometer between the measurements. **Calculate** the average of these initial temperatures. This is the expected temperature of the mixture assuming no chemical reaction takes place.
5. Pour the potassium carbonate solution into the plastic cup and note the temperature of the mixture, having stirred well with the thermometer.

### Analysing results

1. **Calculate** $\Delta H$ for the reaction in kJ mol$^{-1}$, remembering to give it the correct sign.
2. **Draw** an energy level diagram, including the scale.
3. **Formulate** a thermochemical ionic equation for the precipitation of calcium carbonate by including $\Delta H$:

$$Ca^{2+}(aq) + CO_3^{2-}(aq) \rightarrow CaCO_3(s)$$

4. **Evaluate** the validity of the method and suggest modifications that would reduce the errors present in the method used.

## Assessment opportunities

- In this activity you have practised skills that are assessed using Criterion C: Processing and evaluating.

## THE CHEMICAL GENERATION OF ELECTRICAL ENERGY

Voltaic cells (see Chapter 8) are systems in which the electrons described by half-equations are separated in compartments, and their transfer between the electrodes by an external circuit (wires and a voltmeter) forms an electric current ($I$). The potential difference ($V$) generated is determined by the ions present (see Table 8.11).

### THINK–PAIR–SHARE

If power, $P = IV$, predict the maximum power a voltaic cell might generate. (You may want to refer to MYP *Physics by Concept,* Chapter 9.)

### Links to: Mathematics

Conversion of units and scientific notation are standard skills for the practice of science.

## ACTIVITY: Investigating energy production using a voltaic cell

### ATL

- Transfer skills: Apply skills and knowledge to unfamiliar situations; compare conceptual understanding across multiple subject groups and disciplines; make connections between subject groups and disciplines

**Safety:** Wear safety goggles and gloves. At these concentrations, the salt solutions can be irritants.

### Materials and equipment

- **safety goggles and gloves**
- **1 mol $dm^{-3}$ copper(II) sulfate**
- **1 mol $dm^{-3}$ zinc sulfate**
- **a commercial Daniel cell as shown in Figure 10.19; alternatively, half-cells can be made using two beakers and a salt bridge of potassium nitrate in a gel or a simple salt bridge made by soaking filter paper in saturated potassium nitrate solution (e.g. Figure 8.15)**
- **ammeter**
- **high resistance voltmeter**
- **rheostat**
- **extra leads**

## Method

1. Put on safety goggles and gloves.
2. Construct the voltaic cell, making sure that the solution heights are the same in both compartments to avoid mixing due to liquid pressure differences.
3. Check the cell voltage under these conditions is approximately 1.10 V at 25 °C.
4. Connect the voltaic cell into the circuit shown in Figure 10.20.
5. Construct a table with three columns for recording current (*I*), voltage (*V*) and a third column, power (*W*).
6. Check the polarity of the electrodes using a high resistance voltmeter.
7. Adjust the rheostat (variable resistor) to have zero resistance and **measure** the cell voltage (*V*) and current (*I*), recording these measurements in your table.
8. Increase the resistance until the cell voltage is about 0.1 V higher and note the new voltage and current in your table.
9. Repeat the procedure with approximately 0.1 V increases until the total resistance of the rheostat (variable resistor) is in the circuit.

## Analysing results

1. **Describe** the relationship between the polarity of the electrodes and the reactivities of the metals and ions in the system.
2. **Calculate,** for each pair of measurements, the power produced by the voltaic cell. Use the relationship

$$P = IV$$

$$\text{power } (P, \text{ watts}) = \text{potential difference } (V, \text{ voltage}) \times \text{current } (I, \text{ amperes})$$

3. **Plot** relationships suggested by these results.
4. **Evaluate**
   a. the voltage when no current is drawn from the cell
   b. whether your original predictions about the power of a voltaic cell were correct.
5. **Explain** why the partition between the compartments needed to be porous.
6. **Evaluate** the feasibility of the Daniell cell for contributing to global energy requirements.

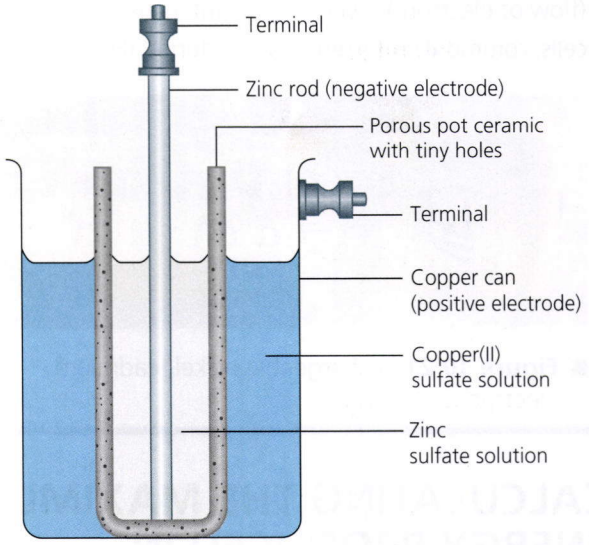



**Figure 10.19** A voltaic cell

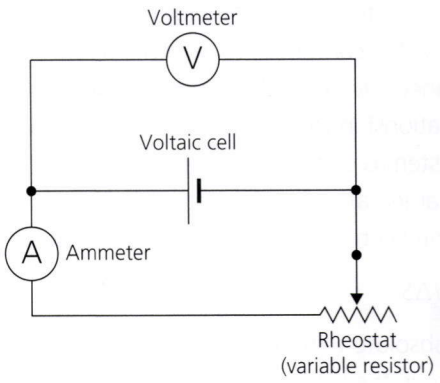



**Figure 10.20** Circuit with voltaic cell, rheostat and ammeter

### Assessment opportunities

- This activity can be assessed using Criterion C: Processing and evaluating.

## ACTIVITY: Investigating 'fruit batteries'

### ATL

- Organization skills: Set goals that are challenging and realistic; use appropriate strategies for organizing complex information; select and use technology effectively and appropriately

Transferring energy from chemicals by means of electricity (flow of electrons) is very important in electrochemical cells, commonly referred to as 'batteries' (Figure 10.21).




**Figure 10.21** Rechargeable nickel–cadmium electrochemical cell

Electrochemical cells based on a 'fruit' or 'vegetable' can be made by inserting two electrodes made from different metals (cleaned with sand paper) into the plant matter and connecting them into a circuit using crocodile clips.

Investigate a variable that affects the energy produced in a circuit which includes a 'fruit battery'. You may wish to refer to the inquiry cycle diagram (Figure 1.11). Both a risk analysis and environmental impact analysis must be included in your plan.

**Evaluate** whether your results suggest fruit batteries could be used as a viable source of energy where commercial batteries may not be easy to obtain.

### Assessment opportunities

- This activity can be assessed using Criterion B: Inquiring and designing and Criterion C: Processing and evaluating.

# CALCULATING THE MAXIMUM ENERGY PRODUCED IN CHEMICAL REACTIONS

You may recall (Chapter 6) that enthalpy changes ($\Delta H$) and entropy changes ($\Delta S$) contribute to whether a reaction will proceed spontaneously, or freely (meaning 'without extra effort'). This relationship to describe the energy available to do work in a system is expressed in the equation for **Gibbs free energy**, named after the American physicist J.W. Gibbs (1839–1903). The Gibbs free energy change is described by

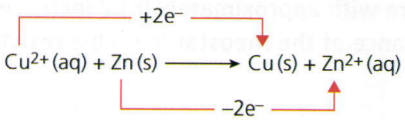
$$\Delta G = \Delta H - T\Delta S$$

where $T$ is the absolute temperature (in degrees kelvin). For a reaction to occur, the value for the change in Gibbs free energy ($\Delta G$) must be negative.

In general, when chemicals mix and react spontaneously, the majority of reactions are exothermic ($\Delta H$ is negative, because heat energy leaves 'the system'). Examples of fast spontaneous reactions include neutralization and precipitation (see Chapter 5). Examples of spontaneous reactions that are endothermic ($\Delta H$ is positive) reveal that enthalpy change alone is not sufficient for predicting the possibility of a chemical reaction, but must be countered with increases in 'disorder', or randomness.

## Calculating $\Delta G$ for a voltaic cell

To convert one mole of copper(II) ions into atoms, two moles of electrons are required (Chapter 8):




Each mole of electrons carries a charge of 96 500 coulombs (C). One mole of electrons is $6.02 \times 10^{23}$ electrons and the coulomb is a unit of electrical charge. Therefore, one electron has a charge of $1.602 \times 10^{-19}$ C.

The maximum voltage possible when the Daniell cell converts copper(II) ions to copper atoms using the ionization of zinc atoms is 1.10V (under standard conditions).

Energy is measured in joules (J) and one joule of work is done when one coulomb of electricity is transferred between two points in a circuit when the potential difference is one volt. Therefore,

energy (in joules) = voltage (volts) × charge (coulombs)

Hence, Gibbs free energy transfer ($\Delta G$) for the voltaic cell is:

$$\Delta G = -(1.10\,\text{V} \times 2 \times 96\,500\,\text{C mol}^{-1})/1000$$

$$= -212\,\text{kJ mol}^{-1}$$

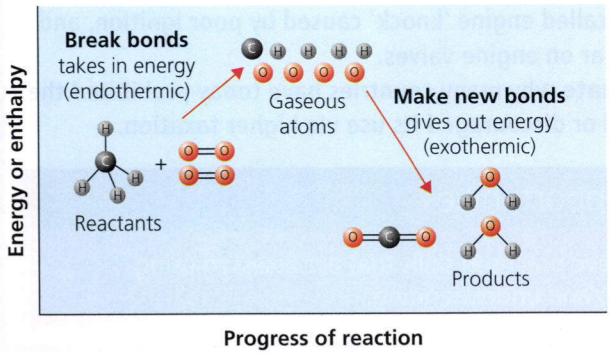
The enthalpy change, $\Delta H$ for the redox reaction in the Daniell cell is $-218\,kJ\,mol^{-1}$. $\Delta H$ represents the thermal energy required by the environment if the reaction is to take place. In this example, the values of $\Delta H$ and $\Delta G$ for the Daniell cell (and related cells) are very similar. However, you can never transfer less energy as thermal energy than that represented by $\Delta H - \Delta G$.

## Calculating $\Delta H$ from bond energy tables

Reactions involve the breaking of chemical bonds in the reactants, which requires energy, and the formation of new bonds in the products, which releases energy (Figure 10.22). Bond breaking is endothermic ($\Delta H$ is positive) and bond formation is exothermic ($\Delta H$ is negative).

The **bond energy** is defined as the amount of energy in kilojoules (kJ) associated with the breaking of one mole of a specific covalent bond in a molecular element or compound (in the gaseous state).

Table 10.1 shows energies needed to break or form the bonds indicated between the atoms shown. We can calculate how much energy is involved in each stage.




■ **Figure 10.22** Breaking and forming bonds during the combustion of methane

| Bond | Bond energy/kJ mol$^{-1}$ |
|---|---|
| C–H | 414 |
| O=O | 498 |
| C=O | 804 |
| H–O | 463 |
| C–C | 346 |
| C–O | 358 |
| H–H | 436 |
| I–I | 151 |
| H–I | 298 |

■ **Table 10.1** Bond energy data

### Sample calculation: complete combustion of methane

Consider the chemical equation,
$CH_4(g) + 2O_2(g) \rightarrow CO_2(g) + 2H_2O(l)$

*Bond breaking:*

Breaking four C–H bonds in a mole of methane molecules requires $4 \times 414 = 1656\,kJ\,mol^{-1}$.

Breaking two O=O bonds in two moles of oxygen molecules requires $2 \times 499 = 998\,kJ\,mol^{-1}$.

Total = $2654\,kJ\,mol^{-1}$ of energy.

*Bond making:*

Making two C=O bonds in one mole of carbon dioxide molecules releases $2 \times 804\,kJ = 1608\,kJ\,mol^{-1}$.

Making four O–H bonds in two moles of water molecules releases $4 \times 463\,kJ = 1852\,kJ\,mol^{-1}$.

Total = $3460\,kJ\,mol^{-1}$ of energy.

$$\text{Energy difference} = \text{energy required to break bonds} - \text{energy given out when bonds are made}$$

$$= 2654\,kJ\,mol^{-1} - 3460\,kJ\,mol^{-1}$$

$$= -806\,kJ\,mol^{-1}$$

The negative sign shows that the chemicals (the system) are losing thermal energy to the air (surroundings) and that it is an exothermic reaction.

## Calculating enthalpy changes ($\Delta H$) using experimental data

The thermal energy transferred in a chemical reaction can be measured using a calorimeter (Figure 10.23).

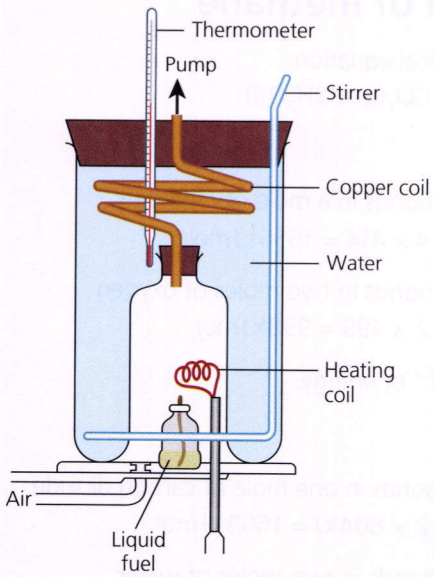



**Figure 10.23** A fuel calorimeter of the type used to measure the thermal energy transferred when a dried chemical burns. It is especially useful for measuring the energy or enthalpy value of foods

## ACTIVITY: Calculating enthalpy changes ($\Delta H$) using bond energy tables

### ATL

- Critical-thinking skills: Interpret data; revise understanding based on new information and evidence
- Communication skills: Use and interpret a range of discipline-specific symbols

1. **If in a chemical reaction, $\Delta H$ is positive:**
   a. **state the type of reaction involved**
   b. **outline the source of this thermal energy, in terms of bonds of the chemical reactants and products.**
2. **Calculate, using the information in Table 10.1, the enthalpy of combustion of**
   a. **ethanol, a biofuel added to petrol in some countries**
   b. **octane ($C_8H_{18}$), a major component of petrol.**
3. **Compare the energy released, per gram of ethanol and octane burnt, using energy (enthalpy) level diagrams to represent the combustion process.**
4. **Calculate the energy released when:**
   a. **0.50 mole of methane is burnt**
   b. **10.0 mole of methane is burnt**
   c. **32.10 g of methane is burnt.**
5. **A lead compound ('tetraethyl lead') was once added to cheap grades of gasoline to improve the apparent 'octane rating' of these fuels, smoothing an effect called engine 'knock' caused by poor ignition, and reducing wear and tear on engine valves.**

   **Analyse and evaluate why many countries have today prohibited the use of 'leaded' petrol or discouraged its use via higher taxation.**

### Assessment opportunities

- In this activity you have practised skills that are assessed using Criterion A: Knowing and understanding.

A pump draws air through the central chamber in which a measured mass of the fuel (usually food) is burnt. The hot gases produced pass through the copper coil, where they heat water. The temperature rise in the water is recorded.

The electrical heating coil then heats by the same amount as was caused by the fuel, which enables the energy transfer to be measured simply by reading a joulemeter. Alternatively, if the voltage and current are known, the amount of energy can be determined from the power, using the relationship power ($P$) = voltage ($V$) × current ($I$). Since the temperature rise is the same for each stage, the amount of thermal energy transferred is the same.

# ACTIVITY: Determining the enthalpy of neutralization

## ATL

- Organization skills: Use appropriate strategies for organizing complex information

Neutralization happens when acid is reacted with an alkali to form a salt and water only (Chapter 5). The **enthalpy of neutralization** is the thermal energy change when one equivalent of acid reacts with one equivalent of alkali to form one mole of water.

The thermochemical equation for neutralization is:

$$H^+(aq) + OH^-(aq) \rightarrow H_2O(l),\ \Delta H = -57\,kJ\,mol^{-1}$$

The negative sign indicates that the reaction is exothermic and thermal energy flows from the chemicals to the water.

**Safety:** Safety goggles need to be worn during this activity, because you are working with acids and bases. Splashes should be rinsed immediately with copious water.

### Materials and equipment

- safety goggles
- 1.00 mol $dm^{-3}$ nitric acid
- 1.00 mol $dm^{-3}$ potassium hydroxide
- 1.00 mol $dm^{-3}$ hydrochloric acid
- 1.00 mol $dm^{-3}$ sodium hydroxide
- 4 × 50 $cm^3$ measuring cylinders
- 2 × thin plastic cups with lids
- thermometer

### Method

1. Put on safety goggles.
2. **Determine** the enthalpy of neutralization of nitric acid and potassium hydroxide, by mixing 50 $cm^3$ of each of the solutions together.
3. **Determine** the enthalpy of neutralization of hydrochloric acid and sodium hydroxide, by mixing 50 $cm^3$ of each of the solutions together.

### Analysing results

1. **Formulate** an ionic equation to describe your results, including the standardized value for $\Delta H$.
2. **List** assumptions you made in your calculations.
3. **Outline** how the accuracy of the experiments can be improved.

## Assessment opportunities

- In this activity you have practised skills that are assessed using Criterion C: Processing and evaluating.

# What is meant by 'spontaneity' in scientific terms?

## EXPLORING THE ROLE OF ENTROPY ($\Delta S$) FOR PREDICTING CHEMICAL CHANGE

Entropy may be thought of as a measure of the disorder or randomness in a system (chemicals and surroundings). Only substances at absolute zero (0 K or –273 °C) have zero entropy because they have maximum order: molecules at 0 K have no kinetic energy and are not vibrating. However, their entropy increases as the temperature is raised. Eventually, the crystal lattice is replaced by the increasing randomness of the liquid and gas states. Similarly, there is an increase in entropy when gases diffuse or solids dissolve in liquids, because both processes lead to a greater degree of disorder.

Spontaneous reactions are feasible only if the net value for Gibbs free energy ($\Delta G = \Delta H - T\Delta S$) is negative. Therefore, endothermic ($\Delta H$ is positive) reactions only occur spontaneously if there is a large increase in entropy ($\Delta S$). $\Delta G$ only predicts whether or not a reaction will take place. The relationship does not provide any information about the *rate* (see Chapter 11).

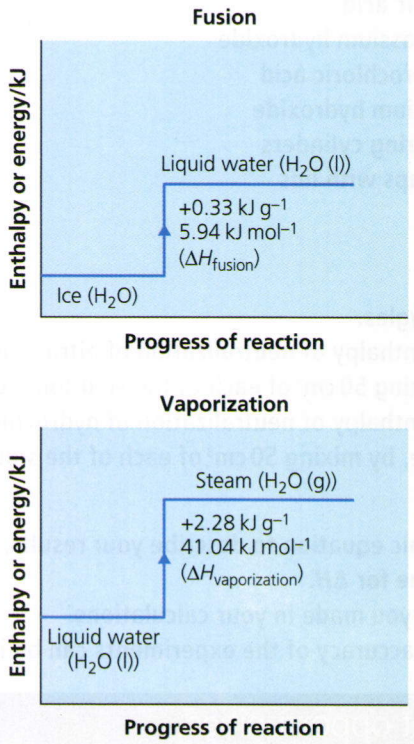
A spontaneous change in an **isolated closed system** (one where matter and energy cannot enter or leave) always results in a gain in entropy ($\Delta S$). Examples of chemical reactions that will have high positive values of $\Delta S$ (often greater than 100 J $K^{-1}$ $mol^{-1}$) are those that cause an increase in the number of moles of gas present. If there is no change in the number of moles of gas present, $\Delta S$ is small. A decrease in the number of moles of gas leads to high negative values of $\Delta S$ (often more than –100 kJ $mol^{-1}$) and such reactions will not be feasible if they are also endothermic.

### Why physical changes involve energy

Physical changes of matter include melting and boiling, condensing and freezing (see Chapter 1). For ice to melt to liquid water, it must absorb thermal energy from its surroundings. This thermal energy is used to break the weak intermolecular forces between the water molecules in the ice. It is called the **enthalpy of fusion** and is given the symbol $\Delta H_{fusion}$.

When liquid water changes into steam (at the boiling point), the energy required for this process is called the **enthalpy of vaporization** and is given the symbol $\Delta H_{vaporization}$.

Figure 10.24 shows the energy level diagrams describing both the fusion (melting) and vaporization (boiling) of water (see Chapter 1).




■ **Figure 10.24** Enthalpy level diagrams for the fusion (melting) and vaporization (boiling) of water

## ACTIVITY: Reflecting on enthalpy of fusion and vaporization

### ATL

- Critical-thinking skills: Evaluate evidence and arguments; identify trends and forecast possibilities

1. **Describe** the energy changes and the changes to the particles' movement and intermolecular forces when melting and boiling are reversed.
2. **Identify** the contribution of the $\Delta S$ component in Gibbs free energy ($\Delta G$) when water boils and when it freezes.
3. **Explain** why a burn from steam (at 100 °C) is more severe (painful) than a burn from boiling water (at 100 °C).
4. 'Car cooler' cans contain a mixture of ethanol (10 per cent) and water (90 per cent). When the mixture is sprayed inside an overheated car, the temperature quickly drops. **Suggest** an explanation for how a 'car cooler' works.

### Assessment opportunities

- In this activity you have practised skills that are assessed using Criterion A: Knowing and understanding.

## ACTIVITY: Enthalpy of fusion in action – making ice cream!

### ATL

- Collaboration skills: Help others succeed; give and receive meaningful feedback

**Safety: Never use laboratory equipment to make products for consumption or personal use.** Your school may have a kitchen with cooking utensils for measuring the ingredients.

### Materials and equipment

- ½ cup milk
- ½ cup whipping cream
- ¼ cup sugar
- ¼ teaspoon vanilla
- ¾ cup salt
- 3 cups ice [preferably crushed/shaved]
- 1 Ziploc bag
- 1 large plastic bag
- thermometer
- paper napkins
- plastic teaspoons

### Method

1. Prepare a data table for recording the temperatures of the milk mixture and ice–salt mixture at the start of the experiment and ten minutes later.
2. Add the sugar, milk, whipping cream and vanilla to the Ziploc bag.
3. **Measure** the temperature of the milk mixture. Seal the bag securely, allowing as little air as possible inside.
4. Put three cups of ice into the large plastic bag. **Measure** the temperature of the ice. Sprinkle all the salt on the ice and add one or two cups of water.
5. Place the Ziploc bag inside the bag of ice so that it is surrounded by the ice.
6. Gently rock the bag for ten minutes or until the contents of the Ziploc bag have solidified into ice cream.
7. Clean the outside of the Ziploc bag with a paper napkin. **Measure** the temperature of the ice cream.

### Analysing results

1. **Suggest** why
   a. large crystals of sodium chloride are preferred to small crystals
   b. sodium chloride is used rather than sucrose
   c. the bag needed to be shaken.
2. **Describe**, using appropriate scientific terminology and concepts, how the ice cream is formed.
3. The greater the concentration of solute, the lower the freezing point of the solution. **Evaluate** whether it is possible to lower the freezing point indefinitely (see Chapter 1).
4. Ice cream is both an emulsion and a foam. **Deduce** how the particles are dispersed in these two types of colloid (see Chapter 2).
5. **Evaluate** the taste sensation using the plastic teaspoon!

### Assessment opportunities

- In this activity you have practised skills that are assessed using Criterion A: Knowing and understanding.



**Figure 10.25** A demonstration of 2.5 kg blocks of TNT detonating

## THE CHEMISTRY OF EXPLOSIVES

The Chinese in 919 CE were the first to mix potassium nitrate, sulfur and charcoal (carbon) together to make an explosive they used in fireworks. Transferred to Europe, their invention was used in bombs, cannons and guns. Today, chemical explosives are used in engineering projects such as tunnelling, mining and road building. Modern explosives replace the work of manual human labour by freeing millions of tonnes of ore or rock with a single blast.

Explosives release much larger quantities of thermal energy than normal combustion reactions (burning) because the explosive compound contains sufficient oxygen for a complete reaction to occur. In the case of the explosive nitroglycerine, the reaction can be written as:

$$4C_3H_5N_3O_9(l) \rightarrow 12CO_2(g) + 10H_2O(g) + 6N_2(g) + O_2(g)$$

## DISCUSS: Reflecting on learning

1. **Describe** how a compound involved in an explosive reaction differs from one involved in combustion by burning in air.
2. **Explain** why nitroglycerine can be a hazardous compound even in sealed, airtight environments.
3. **Suggest** how the entropy and enthalpy components of the Gibbs free energy formula change during an explosive chemical reaction.

## ACTIVITY: Investigating 'hand warmers'

**ATL**

- Critical-thinking skills: Gather and organize relevant information to formulate an argument; test generalizations and conclusions; propose and evaluate a variety of solutions; evaluate and manage risk

Some camping shops sell 'hand warmers' (Figure 10.26). Inside the airtight, plastic bag each hand-warmer consists of a small packet made from a porous fabric, filled with a dark grey powder.

At atmospheric pressure, the reaction products expand to fill a volume 10 000 times larger than the volume of the nitroglycerine. During the blast (Figure 10.25), this gas is usually produced within a small hole where the explosive has been placed; and the products produce huge pressures that shatter the surrounding rock.

## EXTENSION

**Explore entropy further!** Watch Dr Peter Wothers of the Royal Institution in London demonstrate the decomposition of nitrogen triiodide ($NI_3$): **www.youtube.com/watch?v=cWMlUDT2sK8**

1. **Formulate** a balanced equation for the reaction and **outline** the energy change observed.
2. **Calculate** the overall energy change, $\Delta H$, for the following reaction. Refer to the bond energies in Table 10.1 for the reaction:

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

3. **Explain** why the entropy change, $\Delta S$, for this reaction is approximately zero.
4. **State** and **explain** how the enthalpy change would change if the iodine was in the solid state.
5. Unlike changes in enthalpy ($\Delta H$), changes in entropy ($\Delta S$) are difficult to quantify. **Suggest** strategies for evaluating whether entropy has changed significantly in a reaction.




**Figure 10.26** Hand warmers

Research online and deduce how hand warmers work and how you may be able to measure the thermal energy they generate.

Use your ideas to design and conduct an experimental investigation into factors (variables) that may affect the energy they generate. You may wish to refer to the inquiry cycle diagram (Figure 1.11). Both a risk analysis and environmental impact analysis must be included in your plan.

**Evaluate** whether your results suggest the chemistry of hand warmers could be used as a viable source of thermal energy.

### Assessment opportunities

- This activity can be assessed with Criterion B: Inquiring and designing and Criterion C: Processing and evaluating.

## Take Action to address global disparities in access to energy resources

### ATL

- Media literacy skills: Compare, contrast and draw connections among (multi) media resources; understand the impact of media representations and modes of presentation

There is a strong correlation between a person's total energy consumption and their use of electrical energy. All over the world, chemical fuels remain the dominant source of energy for the production of electricity (Figure 10.27). **Compare** the use of electricity by individuals living in developed and developing countries **www.indexmundi.com/g/r.aspx?v=81000**.

1. **In teams, review the experiments and demonstrations of chemical energetics in this chapter and identify chemical resources that are suitable to address global disparities of access to energy by producing energy 'off the grid'.**
2. **Summarize examples of chemical resources that have particular advantages for use in specific locations. For each example, list a moral, ethical, cultural, economic, political or environmental consequence of choosing to use the chemical resource for off-grid power.**
3. **Individually, select a positive example listed by your team.**
4. **Present your recommendation as a 700–1200 word 'informational' to the targeted community, emphasizing the relationship between the off-grid energy source and the identified factor. Be sure to document all sources accurately.**

### Assessment opportunities

- The independent activity can be assessed using Criterion D: Reflecting on the impacts of science.

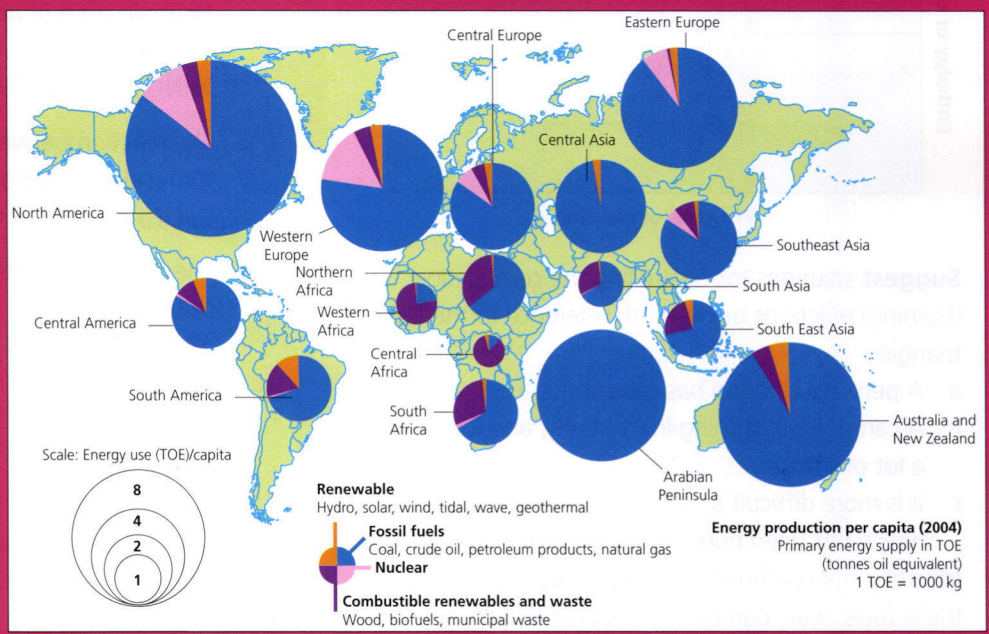



**Figure 10.27** Global comparison of sources of energy used to generate electricity

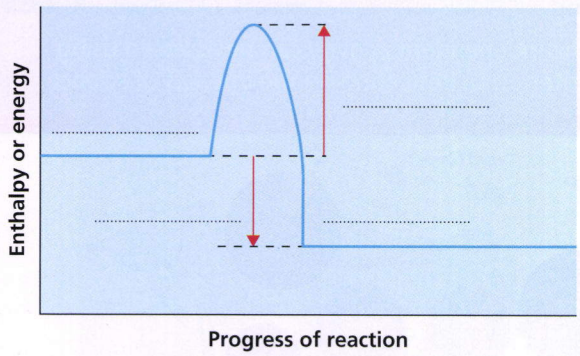
## SOME SUMMATIVE PROBLEMS TO TRY

Use these problems to apply and extend your learning in this chapter. The problems are designed so that you can evaluate your learning at different levels of achievement in Criterion A: Knowing and understanding.

A copy of a periodic table should be available for reference.

### THESE PROBLEMS CAN BE USED TO EVALUATE YOUR LEARNING IN CRITERION A TO LEVEL 1–2

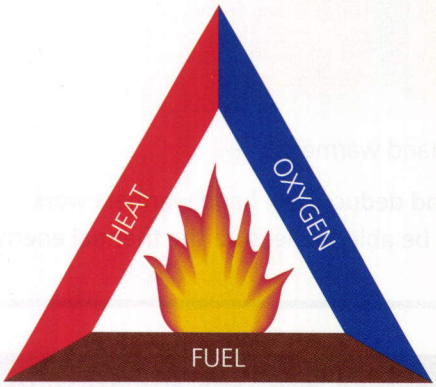
1 **State** the information required to complete the energy level diagram for a combustion reaction.




2 **Suggest** solutions for controlling the combustion (burning) reactions below, with reference to the fire triangle.

- **a** A person's clothing has caught fire.
- **b** A camp fire is burning inefficiently, and is producing a lot of smoke.
- **c** It is more difficult to light a new candle than one which has been burning and has cold wax in its wick.

3 **Identify** the combustion product that is common to these fuels: wax, bamboo splinters and hydrogen.




### THESE PROBLEMS CAN BE USED TO EVALUATE YOUR LEARNING IN CRITERION A TO LEVEL 3–4

4 **Outline** examples of the reaction products of incomplete combustion, which may form if oxygen is a limiting reactant.

5 **Present** each reaction below as a thermochemical equation by including $\Delta H$, to indicate whether it is exothermic or endothermic.

- **a** Combustion of methanol:
  $2CH_3OH(l) + 3O_2(g) \rightarrow 2CO_2(g) + 4H_2O(l)$
- **b** Decomposition of ammonium iodide:
  $NH_4I(s) \rightarrow NH_3(g) + HI(g)$
- **c** Neutralization of nitric acid by barium hydroxide solution:
  $2HNO_3(aq) + Ba(OH)_2(aq) \rightarrow Ba(NO_3)_2(aq) + 2H_2O(l)$
- **d** The reaction between water and calcium oxide to form calcium hydroxide:
  $CaO(s) + H_2O(l) \rightarrow Ca(OH)_2(s)$
- **e** The burning of potassium in air to form potassium oxide:
  $4K(s) + O_2(g) \rightarrow 2K_2O(s)$

6 **Suggest**, with reference to the table below,
   - **a** why water is used in calorimeters
   - **b** why ethanol has a higher specific heat capacity than hexane
   - **c** a material that is useful for storing heat in an energy efficient building.

| Substance | Specific heat capacity/$J\,g^{-1}\,°C^{-1}$ |
|---|---|
| Water | 4.18 |
| Ethanol | 2.46 |
| Kerosene (equivalent to hexane) | 2.18 |
| Nitrogen (gas) | 1.04 |
| Granite | 0.79 |
| Wood | 0.17 |
| Concrete | 0.88 |
| Iron | 0.45 |

■ The specific heat capacity is the amount of energy (J) required to heat a quantity (g) of a substance and raise its temperature by one degree (°C)

**THESE PROBLEMS CAN BE USED TO EVALUATE YOUR LEARNING IN CRITERION A TO LEVEL 5–6**

7 **Describe** the changes in enthalpy during the following processes:
   - **a** physical changes
     - **i** heating water to steam
     - **ii** dissolving solid ammonium nitrate in water to make 1 $dm^3$ of solution
   - **b** chemical changes
     - **i** reacting concentrated sulfuric acid with sucrose
     - **ii** reacting vinegar with sodium hydrogencarbonate in a volcano kit.

8 **a** **Calculate** the amount of thermal energy required to raise the temperature of water in these situations. The specific heat capacity of water is $4.18\,J\,g^{-1}\,°C^{-1}$.
   - **i** 1.00 $dm^3$ of water from 20 °C to 28 °C
   - **ii** 250 $cm^3$ of water from 20 °C to 35 °C

   **b** **Present** energy level diagrams for the reactions below.
   - **i** $Ag^+(aq) + Cl^-(aq) \rightarrow AgCl(s)$; $\Delta H = -59\,kJ\,mol^{-1}$
   - **ii** $C_2H_6(g) + 3½O_2(g) \rightarrow 2CO_2(g) + 3H_2O(l)$; $\Delta H = -1560\,kJ\,mol^{-1}$
   - **iii** $C(s) + 2S(s) \rightarrow CS_2(l)$; $\Delta H = +106\,kJ\,mol^{-1}$

9 Iron and sulfur react to together according to the following thermochemical equation:

$$Fe(s) + S(s) \rightarrow FeS(s);\ \Delta H = -394\,kJ\,mol^{-1}$$

**Analyse** this equation and
   - **a** **estimate** signs and relative values for $\Delta G$ and $\Delta S$ in standard conditions
   - **b** **suggest** whether the equation above enables you to estimate the rate of reaction.

**THESE PROBLEMS CAN BE USED TO EVALUATE YOUR LEARNING IN CRITERION A TO LEVEL 7-8**

10 **Explain**
   - **a** how spontaneous chemical reactions can be endothermic
   - **b** how fuels, such as the food we eat and the petrol we use in cars, 'produce' energy.

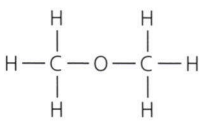
11 **Interpret** the situations below and suggest scientific explanations.
   - **a** The Haber process involves the industrial production of ammonia from its elements according to the following equation:

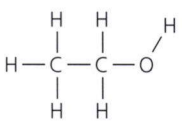
$$N_2(g) + 3H_2(g) \rightarrow 2NH_3(g);\ \Delta H = -75\,kJ\,mol^{-1}$$

     - **i** **Explain** why this reaction has a negative value for its enthalpy change, $\Delta H$.
     - **ii** **Calculate** the energy released when 14.01 g of nitrogen is completely reacted with hydrogen.

   - **b** The substances methoxymethane and ethanol both have the same molecular formula, $C_2H_6O$, but they are structural isomers.

     **Explain** why different amounts of thermal energy are released when one mole of each substance is combusted.


Methoxymethane


Ethanol

**12 Analyse and evaluate** the information in the table below, to explain

**a** general relationships between the three physical properties

**b** why the substances listed can be divided roughly into three types, based on the forces between the particles in each substance.

| Substance | Physical state under standard conditions | Enthalpy of vaporization/kJ mol$^{-1}$ | Melting point/°C | Boiling point/°C |
|---|---|---|---|---|
| Hydrogen, $H_2$ | Gas | 0.8 | –259 | –253 |
| Carbon dioxide, $CO_2$ | Gas | 13 | –78.5 | –55.6 |
| Hydrogen chloride, HCl | Gas | 16 | –114 | –85 |
| Bromine, $Br_2$ | Liquid | 30 | –7 | 59 |
| Trichloromethane, $CHCl_3$ | Liquid | 29 | –-64 | 61 |
| Octane, $C_8H_{18}$ | Liquid | 34 | –57 | 125 |
| Phosphorus, $P_4$ | Solid | 12 | 44 | 280 |
| Naphthalene, $C_{10}H_8$ | Solid | 40 | 80 | 218 |
| Sodium chloride, NaCl | Solid | 172 | 801 | 1413 |
| Copper, Cu | Solid | 331 | 1085 | 2562 |
| Iron, Fe | Solid | 357 | 1535 | 2750 |

# Reflection

All activities on the planet are interrelated through energy changes. In this chapter you explored how chemical fuels, including fossil fuels, burn (oxidize) when their temperature is raised to their ignition points in the presence of oxygen. The activation energy needed to start chemical reactions can be supplied by thermal energy or lowered by using catalysts. This has practical implications for fuel storage and fire safety, as well as the energy choices societies and people have. Spontaneous chemical reactions, however slow, require a net decrease of Gibbs free energy ($\Delta G$). For exothermic reactions, the energy or enthalpy change ($\Delta H$) results from the difference in bond energy between molecules, atoms or ions involved in reactants and products. For endothermic reactions to be spontaneous there must be an increase in disorder, an entropy change ($\Delta S$).

| **Use this table to reflect on your own learning in this chapter.** | | | | | | |
|---|---|---|---|---|---|---|
| Questions we asked | Answers we found | Any further questions now? | | | | |
| **Factual:** What conditions help substances burn? | | | | | | |
| **Conceptual:** What happens to chemical energy during physical and chemical changes? Why is energy transfer so important? Why are fossil fuels still so attractive as an energy source? What is meant by 'spontaneity' in scientific terms? | | | | | | |
| **Debatable:** Should people in the developing world be allowed the same energy consumption as ourselves? | | | | | | |
| Approaches to learning you used in this chapter: | Description – what new skills did you learn? | How well did you master the skills? | | | | |
| | | Novice | Learner | Practitioner | Expert | |
| **Communication skills** | | | | | | |
| **Collaboration skills** | | | | | | |
| **Organization skills** | | | | | | |
| **Reflection skills** | | | | | | |
| **Media literacy skills** | | | | | | |
| **Critical-thinking skills** | | | | | | |
| **Creative-thinking skills** | | | | | | |
| **Transfer skills** | | | | | | |
| **Learner profile attribute(s)** | Reflect on the importance of being reflective for your learning in this chapter. | | | | | |
| **Reflective** | | | | | | |

# 11 How can we shift the balance of a reaction?

**Change** in the **balance** called chemical equilibrium is affected by the collisions of particles in **space and time**

## IN THIS CHAPTER, WE WILL …

- **Find out** how different variables affect the rate of reactions and position of equilibrium.
- **Explore**
  - how the rates of reactions can be described graphically;
  - how a reversible reaction reaches equilibrium;
  - how reactions can be shifted to favour either the reactants or products;
  - how ammonia is made on the industrial scale.
- **Take action** by promoting the value of bioremediation as a low energy solution to environmental contamination.

## CONSIDER AND ANSWER THESE QUESTIONS:

**Factual:** What factors affect reaction rates? Which conditions in reversible reactions at equilibrium will maximize yield?

**Conceptual:** How do catalysts make a difference to reactions?

**Debatable:** To what extent can the Earth be understood as a chemical system in dynamic equilibrium?

Now **share and compare** your thoughts and ideas with your partner, or with the whole class.

## These Approaches to Learning (ATL) skills will be useful …

- Communication skills
- Organization skills
- Reflection skills
- Information literacy skills
- Critical-thinking skills
- Transfer skills

## Assessment opportunities in this chapter …

- Criterion A: Knowing and understanding
- Criterion B: Inquiring and designing
- Criterion C: Processing and evaluating
- Criterion D: Reflecting on the impacts of science



**Figure 11.1** Equilibrium means that different forces balance – if one factor is removed, an apparently static situation will rapidly become kinetic

## We will reflect on this learner profile attribute …

- Balanced – How much do your work habits support your learning in science, and in other subjects? Do you leave yourself enough time to rest, exercise and plan thoughtfully for your research and investigations, including the reflecting needed to succeed in science? How do your habits 'feed back' on your academic progress?

## KEY WORDS

concentration
equilibrium
rate

The conditions that determine the rates of reactions inside our bodies, inside our cells, are in principle the same as for any other chemical reaction (see Chapter 6). In organisms, reactions are compartmentalized by membranes; for example, the membranes of cell organelles may prevent particular substances mixing and reacting, or contain high local concentrations of reactants. In addition, all biological reactions are controlled by proteins called **enzymes**. These proteins are often called ' biological catalysts' because they speed up the chemical reactions without being used up themselves. In cells, a simple chemical process that may take one step in a test tube can involve a chain of reactions, each controlled by its own enzyme. The advantage for cells is that each of the reaction products may become part of a different pathway to another useful substance, or store energy in its chemical bonds.

The cells in our bodies must contain many thousands of enzymes. What might happen if one of these proteins is faulty?

## HEADLINES

Read the story below silently without discussing it, then write a headline that, in your opinion, captures the most important aspect that should be remembered. Then answer the questions about it.

In May 1978, a family in the USA had an apparently normal baby. Before he was 6, Lorenzo Odone spoke three languages fluently and preferred Italian opera to nursery rhymes. Then one evening, he complained that he wasn't able to hear properly. His teachers had also noticed his growing clumsiness. Eventually, Lorenzo was diagnosed with a genetic disorder that caused the production of a single, faulty enzyme. This enzyme should have broken down an intermediate reaction product in his cells. Instead, the substance built up in his nervous system, eventually damaging it. The substance, a type of fatty acid, had been accumulating in his nerve cells since the day Lorenzo was born, but only now were the symptoms becoming apparent. At the time, doctors advised the boy's life expectancy to be two years.

Neither of Lorenzo's parents was a scientist, but they both immediately began to research the chemistry of the disease at the National Institute of Health Library, close to their home in New York. They decided to focus their attention on 'distracting' the enzyme that helped make the dangerous fatty acids that were destroying Lorenzo's nervous system. They reasoned that if this enzyme was physically 'occupied' doing something else, it would not be able to catalyse the other reaction so the damaging product could not accumulate. In biochemistry, this type of substance is called a 'competitive inhibitor'. The use of the competitive inhibitor meant the second, faulty enzyme would be deprived of its reactants.

Lorenzo's parents' growing knowledge of chemistry suggested that he needed a special diet that included a mixture of olive and rapeseed oils. This was ' Lorenzo's oil', later the title of the 1992 Hollywood movie. His parents worked closely with the actors to tell their story which, at the time, countered the medical understanding of the illness. An explanation of the mechanism of his treatment, as shown in the movie, can be found here: **www.youtube.com/watch?v=TiU_J8wJohU**.

Lorenzo's life continued long beyond the film, but by the time he changed his diet, his nervous system had already been damaged forever. Children with the same disorder who supplement their diet with Lorenzo's oil long before their symptoms appear can now expect to live healthy lives for much longer.



**Figure 11.2** Lorenzo's unorthodox treatment helped him live 22 years beyond medical expectations. He died in 2008, aged 30

## ACTIVITY: Reflecting on the messages in this story

### ATL

- Communication skills: read critically and for comprehension

Now answer these questions:

1. **Describe what a catalyst does, according to this story.**
2. **Design a flow chart that identifies the roles of the two enzymes involved in the process that created Lorenzo's symptoms.**
3. **Suggest how reactions being arranged in a pathway can be an advantage. How do the right enzymes contribute to kinetics and balance (Figure 11.1)?**
4. **Lorenzo's parents proposed a therapy that had no medical precedent. Evaluate whether**
   a. **they should have experimented on their son**
   b. **anyone can be a scientist.**
5. **Share your original headline with your peers and reflect on it. How would you change it, based on your discussion? How does its message differ from what you would have said initially?**

### Assessment opportunities

- In this activity you have practised skills that are assessed with Criterion D: Reflecting on the impacts of science.

# How do catalysts make a difference to reactions?

Since catalysts are not used up in a reaction, they are not included in the balanced chemical equation. Catalysts can be physically changed by the reaction, but can often be recovered and used again.

Different catalysts work in different ways. Reactions which involve gases are catalysed by adsorbing them onto the surface of a solid, bringing the molecules of the reactants close together (increasing their concentration). Catalysts may also weaken the bonds of the reactants, so they break more easily (and less energy needs to be absorbed), before forming new covalent bonds. Figure 11.3 shows an example of this type of catalysis involving gases.

The most important types of industrial catalysts are transition metals and their compounds, for example metal oxides. Examples include platinum to manufacture nitric acid, iron to synthesize ammonia in the Haber process, and vanadium(V) oxide in the manufacture of sulfuric acid. A nickel catalyst is used in the hydrogenation of unsaturated oils to form margarine. Transition metals are also often found in the active sites of enzymes.

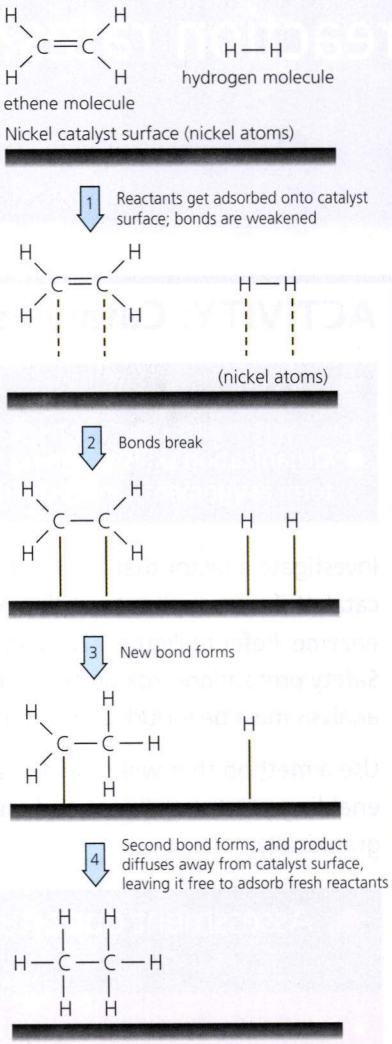



**Figure 11.3** The addition reaction between ethene and hydrogen, in the presence of a nickel catalyst

# What factors affect reaction rates?

## ACTIVITY: Catalysts

### ATL

- Organization skills: planning short- and long-term assignments; meet deadlines

Investigate a factor that affects the behaviour of a catalyst, for example a transition metal oxide or an enzyme. Refer to Figure 1.11 to guide your planning. Safety precautions, risk and environmental impact analysis must be included in your plan.

Use a method that will provide quantitative data, enabling you to represent and **analyse** the results graphically.

### Assessment opportunities

- This activity can be assessed using Criterion B: Inquiring and designing and Criterion C: Processing and evaluating.

### Links to: Mathematics

Graphical skills in mathematics are useful for analysing rates of reactions. As you explore the following examples, consider how the graphs represent change as a reaction rate (the amount of a product generated over time), or compare the reaction rates in response to the change of a single variable.

## What does the slope of a graph reveal?

Graphical skills provide a type of literacy, to support the analysis of data.

During a reaction, reactants are being used up and products are accumulating. The formation of these products can affect the rate of a reaction, for example, by changing the concentrations of reactants. During a reaction in an aqueous solution, the rate of reaction is often expressed as the rate of change of concentration of a reactant or product per unit time.

Figure 11.4 shows the change in concentration of reactants or product as a rate curve. Concentration ($c$) is usually measured in moles per cubic decimetre ($mol\,dm^{-3}$), but can also be expressed in grams per litre ($g\,dm^{-3}$) or, if gases are released, in cubic centimetres per second ($cm^3\,s^{-1}$).

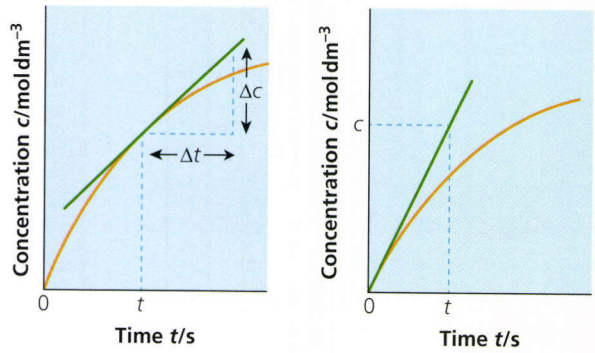



**Figure 11.4** Rate curves showing the graphical calculation of (a) an instantaneous rate at a specific time and (b) initial reaction rate

At any time, the gradient or slope of the curve provides the rate for the reaction. It can be determined by drawing the tangent to the curve, and calculating the slope at that time (Figure 11.4(a); $r = \Delta c/\Delta t$). The steeper the gradient is, the faster the rate. The initial rate is found by drawing the tangent to curve at time = 0 (Figure 11.4(b)). In this example, the rate of reaction is equal to the change in concentration/time with units of $mol\,dm^{-3}\,s^{-1}$.

# GRAPHICAL REPRESENTATIONS OF REACTION RATES

The rate of a reaction is the rate at which a product is formed or the rate at which a reactant is used up. Some chemical reactions occur very rapidly or almost instantaneously. Examples include precipitation and neutralization reactions (Chapter 5). Some chemical reactions occur very slowly. Examples include rusting (Chapter 8) and fermentation (Chapter 12). The most important factors that affect reaction rates are: temperature, concentrations of reactants (in solutions), pressure (for gases), surface area of solid reactants, catalysts, and light.

You may recall that any factor which increases the frequency of the collisions, the number of times molecules (or atoms or ions) meet one another, will increase the rate of the reaction (see Chapter 6). Collisions need to have enough combined kinetic energy to break the bonds between reactants apart and form a temporary high energy state called an '**activated complex**' (or **transition state**) before the products can be created. Not all collisions will result in a reaction.
In collisions with slow-moving molecules (low kinetic energy), the molecules bounce off each other and no reaction takes place (Figure 11.5).

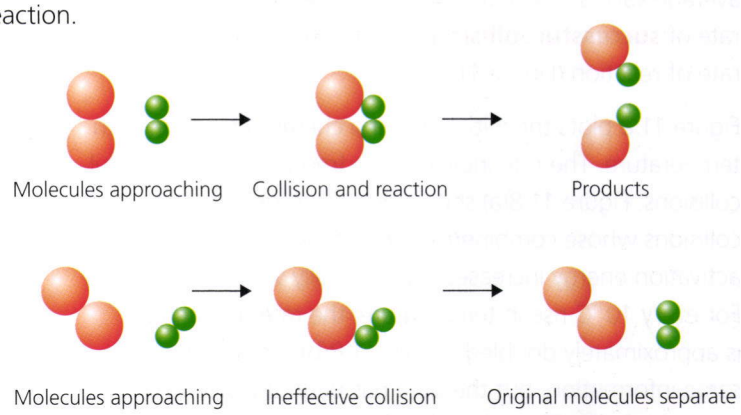



**Figure 11.5** Effective and ineffective collision of molecules

As an example, consider the synthesis reaction between hydrogen and oxygen gas molecules to form water (Figure 11.6). Before the reaction can take place, hydrogen and oxygen molecules have to collide. The bonds between the hydrogen atoms and the bonds between the oxygen atoms have to be broken, a process that requires energy, and is therefore endothermic. Then new O–H bonds forming water molecules have to be made, a process that is exothermic.

In many reactions between molecules, there is also a **steric effect**, that is, the molecules must collide in the correct relative positions or orientation. This is known as collision geometry. Steric effects arise from the fact that each atom within a molecule occupies a certain amount of space. If electron clouds (Chapter 4) are brought close together there will be repulsion between them. For atomic or molecular orbits to overlap and form products they must do so in the correct orientation.

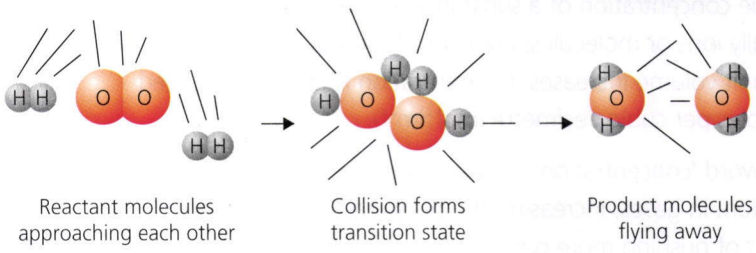



**Figure 11.6** The synthesis reaction of hydrogen and oxygen to form water ($2H_2(g) + O_2(g) \rightarrow 2H_2O(l)$)

# FACTORS AFFECTING COLLISIONS

## Temperature

When the temperature of the reaction mixture is increased, the reacting particles (molecules, ions or atoms) move around at higher average speeds and hence have higher average values of kinetic energy. This results in an increased rate of **successful collisions** and therefore an increased rate of reaction (Figure 11.7).

Figure 11.8 plots the initial rate of a chemical reaction with temperature. The rate indicates the frequency of successful collisions. Figure 11.8(a) shows that the proportion of collisions whose combined kinetic energy is greater than the activation energy increases exponentially with temperature. For every 10 °C rise in temperature, the rate of reaction is approximately doubled. Figure 11.8(b) presents the same information, but the data has been transformed mathematically. The *x*-axis shows the temperature as a reciprocal. The *y*-axis plots the natural log (ln) of the initial reaction rate.

## Concentration

As the concentration of a substance increases, the particles (usually ions or molecules) are closer together. The number per unit volume increases. Concentration is usually measured in moles per cubic decimetre ($mol\,dm^{-3}$).

The word 'concentration' is usually used to describe a solution. In gases, increasing the pressure has the same effect of pushing more particles together per unit volume. This produces an increased number of collisions and so the reaction rate increases. A gas at high pressure is more concentrated than a gas at low pressure.

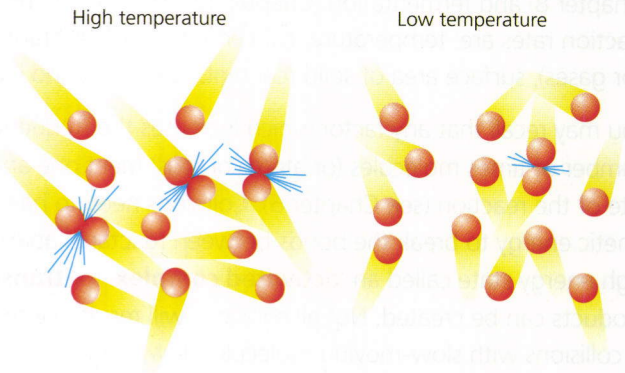



**Figure 11.7** Collision theory and the effect of temperature

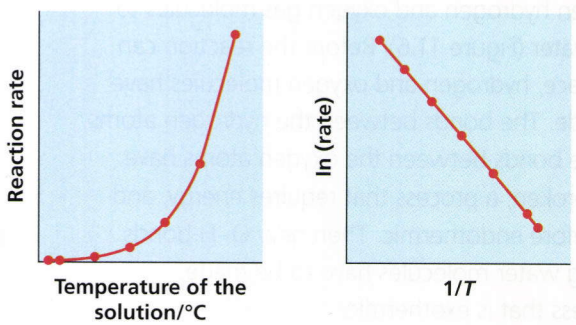



**Figure 11.8** The effect of temperature on the rate of a reaction

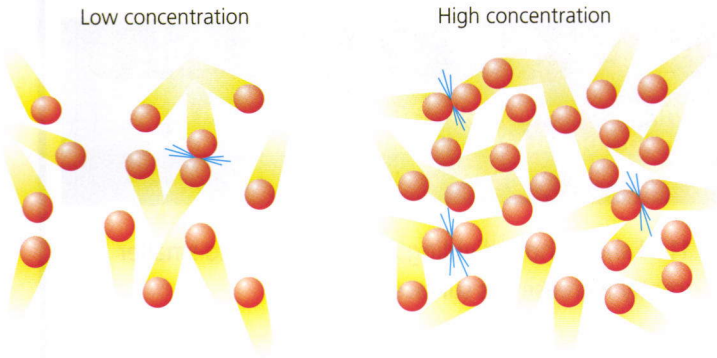



**Figure 11.9** Collision theory and the effect of concentration (on solutions or gases)

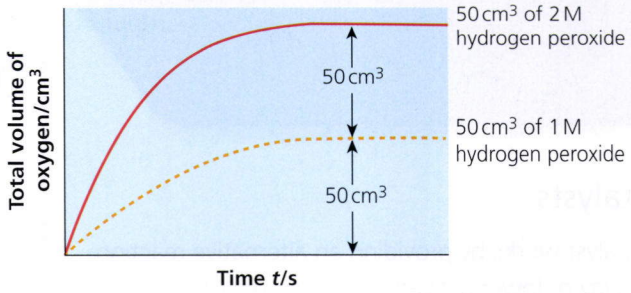



**Figure 11.10** The amount of oxygen gas produced from the decomposition of hydrogen peroxide at two different concentrations

Increasing the concentration affects the reaction rate because it increases the probability that a collision will occur (Figure 11.9). This principle is applied in petrol engines, when the mixture of petrol vapour and air is compressed before it is ignited by a sparking plug, to help it react very quickly – explosively.

Figure 11.10 compares the effect of concentration on the decomposition of two different concentrations of hydrogen peroxide to water and oxygen. The graph shows that the initial rate for this reaction, as well as the volume of oxygen gas produced, is exactly proportional to the concentration of the reactants.

## Surface area

Collisions take place at the surface of solids. With a larger surface area collisions are more frequent (Figure 11.11), and there is a greater chance of a 'successful' collision. In reactions involving solids, powders react much faster than lumps or granules, which react faster than lumps (all other variables kept constant).

Figure 11.12 compares the effect of surface area on the reaction between two equal masses of calcium carbonate and hydrochloric acid. Notice how initial reaction rate is very much faster for the powdered solid because the acid can attack the surface of the carbonate more easily. However, the outcome of the experiment is identical for both conditions; the same amount of carbon dioxide, $CO_2$ is eventually produced.

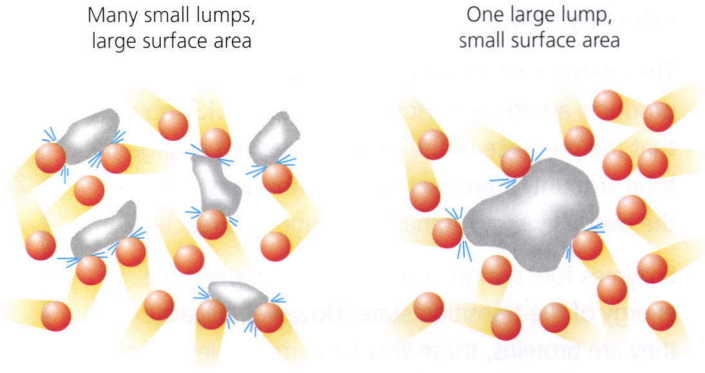



**Figure 11.11** Collision theory and the effect of surface area

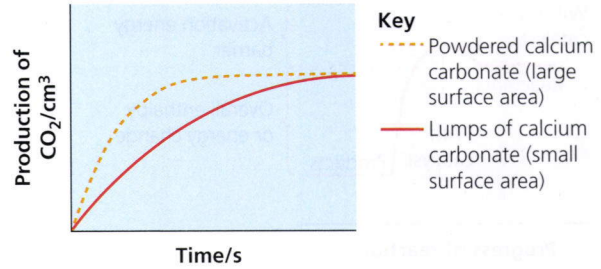



**Figure 11.12** The effect of surface area on the reaction rate between hydrochloric acid and two equal masses of calcium carbonate

## Catalysts

A catalyst works by providing an alternative reaction pathway or lower activation energy (see Chapter 10) needed for the transition state. This may be due to a steric effect (e.g. some enzymes hold the substrate in the correct orientation for reaction), but it could also be because the presence of the catalyst leads to a different reaction mechanism. Catalysts can also initiate reactions which would normally happen extremely slowly.

The alternative pathway increases the rate at which products are formed. However, Figure 11.13 shows that the presence of the catalyst does not change the total amount of product formed, nor does it affect the overall energy (enthalpy) change of a reaction.

Enzymes function the same way. They lower the energy of the transition state. However, because they are proteins, these very large molecules are also affected by intermolecular attractions. Most enzymes are adapted to function best in particular, narrow conditions, for example at a particular temperature or within narrow ranges of pH.

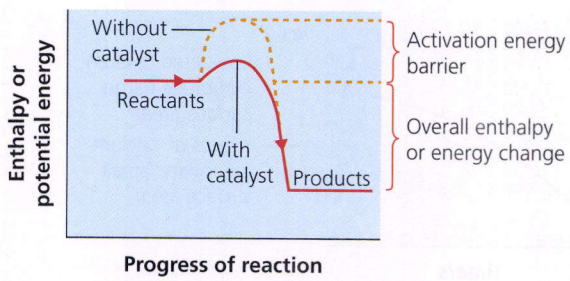



**Figure 11.13** A catalyst lowers the energy barrier and thus lowers the energy required to initiate a chemical reaction

## ACTIVITY: Investigating surface area of a solid

### ATL

- Information literacy skills: Present information in a variety of formats and platforms; process data and report results

Figure 11.14 shows how dividing a cubic lump into smaller cubes greatly increases its surface area.

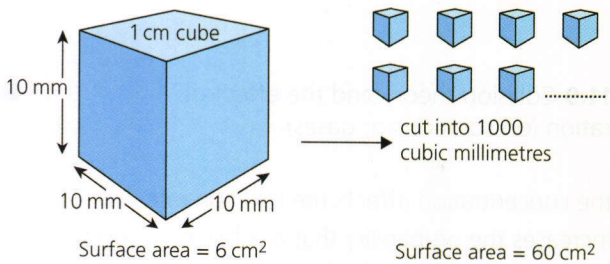



**Figure 11.14** How cutting a 1.0 cm cube ($1 \times 1 \times 6\,cm^2$) into $1000 \times 0.1$ cm cubes ($0.1 \times 0.1 \times 6 \times 1000\,cm^2$) increases the surface area of the solid ten times

1. **Investigate the relationship between surface area and the size of the cubes, for a given volume, using a spreadsheet.**
2. **Calculate the surface areas for the suggested divisions listed in the table below. Show the correct number of significant figures.**
3. **Plot for each set of cubes a to c, the relationship between the surface area and the number of divisions.**

| | Cube edge length | First division | Second division | ... |
|---|---|---|---|---|
| a | 10 mm | 8 × 5 mm cubes | 8 × 8 × 2.5 mm cubes | |
| b | 10 mm | 64 × 2.5 mm cubes | 64 × 64 × 1.25 mm cubes | |
| c | 10 mm | 1000 × 1 mm cubes | 1000 × 1000 × 0.1 mm cubes | |

4. **Describe how the number of divisions affects the relationship you observe, in each group of calculations.**

### Assessment opportunities

- In this activity you have practised skills that are assessed using Criterion A: Knowing and understanding.

# ACTIVITY: Interpreting reaction curves

## ATL

- Critical-thinking skills: Analyse complex concepts and projects into their constituent parts and synthesize with new understanding; interpret data

1 Figure 11.10 compares the reaction rates of the decomposition of two different concentrations of hydrogen peroxide to produce oxygen gas.
   a **Explain** what the horizontal part of the graph indicates.
   b **Present** a curve which represents a hydrogen peroxide concentration that is twice the concentration of the original solution by annotating a sketch of Figure 11.10.

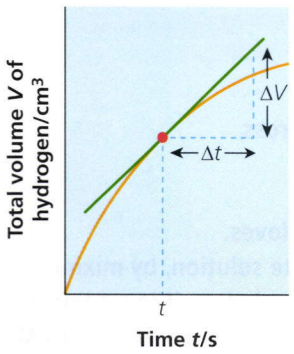



**Figure 11.15** Total volume of hydrogen gas plotted against time

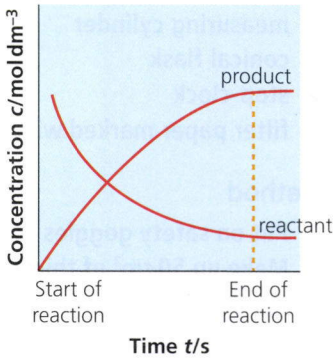



**Figure 11.16** The changing concentrations of a reactant and product during a reaction

2 Figure 11.15 shows the total amount of hydrogen gas produced when a known mass of magnesium ribbon (cleaned with sandpaper) reacted with hydrochloric acid (of a specific volume and concentration).

$$Mg(s) + 2HCl(aq) \rightarrow MgCl_2(aq) + H_2(g)$$

   a **State** the expression for calculating the rate of the reaction at any time.
   b **Explain** why the rate of the reaction (slope) is fastest at the beginning of the reaction.
   c **Predict** what will eventually happen to the slope.

3 Figure 11.16 shows data for the changing concentrations of reactants and products during a reaction.
   a **Describe** the changes in the slope of the graphs for the reactants and the products.
   b **Explain** the reason the curves become horizontal at the end of the reaction.
   c **Predict** how the curves might change if the concentrations of the two reactants are not the same.

4 Some reactions are photosensitive, that is, their rates are affected by light intensity. For example, photosynthesis is a chemical reaction whose first steps are dependent upon visible light.

Before the invention of digital cameras, photography relied on the decomposition of silver bromide to silver in film (Figure 11.17) exposed to light:

$$2AgBr(s) \rightarrow 2Ag(s) + Br_2(l)$$



**Figure 11.17** Photographic film

The development of the photographic film was controlled by the rate of the reduction of silver(I) ions. The table below lists the time required for development of the negative at different temperatures.

| Temperature/°C | Time/minutes |
|---|---|
| 18.5 | 11 |
| 19.0 | 10 |
| 20.0 | 9 |
| 21.0 | 8 |
| 22.6 | 7 |
| 24.0 | 6 |

   a **Plot** the relationship listed in the table.
   b **Estimate**, using the graph, the time required to develop the negative at 23 °C.

## Assessment opportunities

- In this activity you have practised skills that are assessed using Criterion A: Knowing and understanding.

# ACTIVITY: Data analysis for reactions

## ATL

- Transfer skills: change the context of an inquiry to gain different perspectives

**Safety:** You must wear safety glasses and carry out the experiment in a well-ventilated laboratory; do not breathe in the gas; do not perform the experiment if you suffer from asthma.

The reaction between sodium thiosulfate solution and dilute hydrochloric acid causes a yellow precipitate to form slowly:

$$S_2O_3^{2-}(aq) + 2H^+(aq) \rightarrow H_2O(l) + SO_2(g) + S(s)$$

If the reaction occurs in a conical flask placed on a filter paper that has been marked with a cross, the time for the cross to become obscured can be used to evaluate the rate of the reaction consistently (Figure 11.18). The value of this approach is that many variations are possible. The aim of this activity is to collect sufficient data to be able to analyse it graphically.

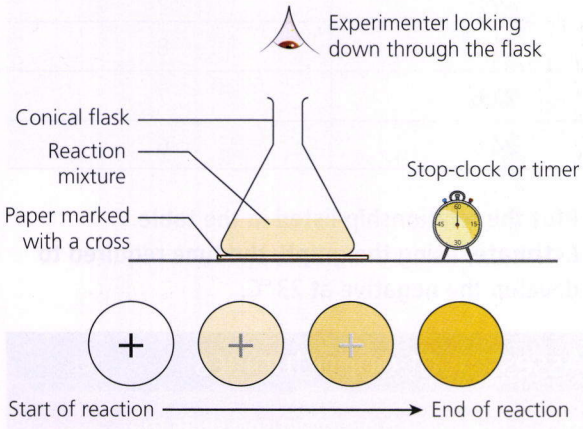



**Figure 11.18** Apparatus for investigating the rate of reaction between sodium thiosulfate solution and dilute acid

### Materials

- safety goggles and gloves
- 0.2 M sodium thiosulfate solution – hydrated sodium thiosulfate crystals have the formula $Na_2S_2O_3.5H_2O$, and a 0.2 mol $dm^{-3}$ solution contains approximately 50 g per cubic decimetre
- water to dilute
- 2.00 mol $dm^{-3}$ hydrochloric acid
- measuring cylinder
- conical flask
- stop-clock
- filter paper marked with a cross

### Method

1. Put on safety goggles and gloves.
2. Make up 50 $cm^3$ of thiosulfate solution, by mixing the 0.2 M stock with water and place it in a conical flask. (For example, a mixture of 40 $cm^3$ of the 0.2 M sodium thiosulfate and 10 $cm^3$ of water will give you a concentration of 0.16 M sodium thiosulfate.)
3. **Measure** 5 $cm^3$ of 2.00 mol $dm^{-3}$ hydrochloric acid in a small measuring cylinder. Place the conical flask onto the filter paper marked with a cross. Add the 5 $cm^3$ of hydrochloric acid, start a stop-clock immediately, swirl the contents of the flask, then allow the flask to remain still on the filter paper.
4. Look vertically down through the solution at the cross on the filter paper and stop the stop-clock when the cross just disappears. Rinse the flask immediately.

### Possible relationships to investigate

1. Effect of thiosulfate concentration on the rate of the reaction. A range of sodium thiosulfate concentrations below 0.2 M is recommended.
2. Effect of temperature on the rate of reaction between sodium thiosulfate and hydrochloric acid. You should warm the solutions carefully in a water bath before mixing them. A range of temperatures between 30 and 60 °C is recommended.

# Which conditions in reversible reactions at equilibrium will maximize yield?

### Analysing results

1. **State**, in this reaction, what caused the cross to disappear.
2. **Identify** why the method required the flask to be rinsed immediately after each experiment. (If you cannot think of a reason, repeat one of the experiments without rinsing the flask immediately.)
3. **Describe** the relationships between the factor you investigated as a graph of the reaction rate (on the *y*-axis) as a function of the concentration (on the *x*-axis).
4. **Explain** what the graph tells you about the rate of reaction, based on particle (molecular kinetic) theory.
5. **Identify** any sources of error in the experiment.

### Assessment opportunities

- In this activity you have practised skills that are assessed using Criterion A: Knowing and understanding.

## WHAT MAKES A REACTION REVERSIBLE?

You are probably very familiar with the reversibility of physical changes. For example, when water is cooled below 0 °C at STP, it freezes to form ice. When the ice is warmed to a temperature above 0 °C, it melts to form water. These two changes may be represented by a single equation:

$$H_2O(l) \rightleftharpoons H_2O(s)$$

In this equation, the symbol $\rightleftharpoons$ means that the change is reversible. A reversible change can go in either direction depending upon the conditions.

Many chemical changes are also reversible. If steam is passed through a heated tube containing iron filings, iron oxide with the formula $Fe_3O_4$ is formed. If hydrogen is then passed over this iron oxide, the reverse process takes place. These two chemical changes may be represented by a single chemical equation:

$$3Fe(s) + 4H_2O(g) \rightleftharpoons Fe_3O_4(s) + 4H_2(g)$$

**Thermal dissociation** refers to the reversible splitting up of a compound by heat to form products, which can recombine on cooling. Usually the mechanism involved is quite simple, in which a single bond is broken and hence thermal dissociation is a **reversible reaction**. Two examples of thermal dissociation are:

$$2NO_2(g) \rightleftharpoons 2NO(g) + O_2(g)$$

$$NH_4Cl(s) \rightleftharpoons NH_3(g) + HCl(g)$$

**Thermal decomposition** refers to the splitting up of a compound by heat to form products which do not recombine on cooling. Compared to thermal dissociation, more bonds are broken and/or rearranged and therefore these reactions are not so easily reversible. An example is:

$$2Pb(NO_3)_2(s) \rightarrow 2PbO(s) + 4NO_2(g) + O_2(g)$$

In a closed system, a reversible chemical change involves a mixture of products and reactants, both being converted to one another simultaneously. Compare the example of calcium carbonate (chalk or marble) being heated in an open container such as a crucible, with the same reaction occurring in a closed container.

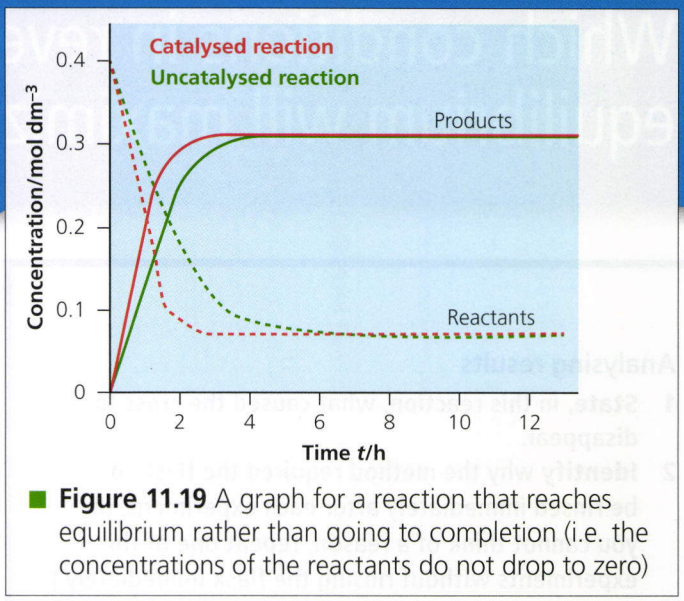



**Figure 11.19** A graph for a reaction that reaches equilibrium rather than going to completion (i.e. the concentrations of the reactants do not drop to zero)

# DYNAMIC EQUILIBRIUM

In the open container, the calcium carbonate decomposes and the product formed, carbon dioxide, escapes as a gas into the air. The reaction continues until all the calcium carbonate is converted to calcium oxide. In other words, the reaction goes completely to the right of the equation. It is said to go to **completion**.

In the closed container, the carbon dioxide recombines with the calcium oxide to form calcium carbonate. In this situation both forward and backward reactions occur together under the same conditions:

left-hand side → right-hand side (forward)

$CaCO_3(s) \rightleftharpoons CaO(s) + CO_2(g)$ (backward)

However, overall, the reaction to the right-hand side is faster than the backward reaction. As the calcium carbonate is used up, the forward reaction becomes slower. Eventually the rate of the forward reaction equals the rate of the backward reaction. At this point of balance, the reaction is said to be in **dynamic equilibrium**. Dynamic equilibrium is reached when the rate of the forward reaction equals the rate of the backward reaction.

## Changing the balance

What might happen to the dynamic equilibrium if the conditions of the closed system were changed? The Frenchman, Henri Le Chatelier (1850-1936), recognized that when a system in equilibrium is subjected as to a change, the position of equilibrium will alter in such a way as to counteract that change. The change can involve concentration, temperature or pressure, or removal or addition of a reactant or product. **Le Chatelier's principle** only suggests an outcome, it does not provide an explanation or predict a quantitative amount of either products or reactants.

Le Chatelier's principle applies to both physical and chemical changes (in closed systems). For example, when water boils the water is in equilibrium with water vapour:

$$H_2O(l) \rightleftharpoons H_2O(g)$$

If pressure is increased at a constant temperature, then volume decreases. Since liquid water has a smaller volume than steam, an increase in pressure results in an equilibrium shift from right to left. In reality, this means that boiling point rises with increasing pressure. Conversely, a reduction in pressure lowers boiling point (Chapter 1).

| Condition | Effect |
|---|---|
| Temperature | Increasing the temperature makes the reaction shift in the direction which absorbs energy (endothermic reaction).<br>Decreasing the temperature makes the reaction shift in the direction which releases heat (exothermic reaction). |
| Pressure | Increasing the pressure makes the reaction shift in the direction which produces less gas.<br>Decreasing the pressure makes the reaction shift in the direction which produces more gas. |
| Concentration | Increasing the concentration of one substance makes the equilibrium shift to decrease its concentration. |
| Catalyst | The presence of a catalyst does not affect the position of equilibrium, but means the rates of both forward and backward reactions are increased and thus brings a system to equilibrium more rapidly (see Figure 11.19). |

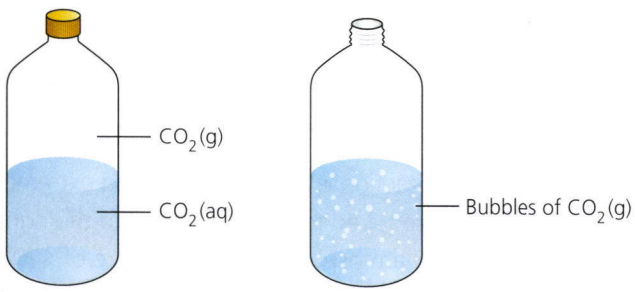
**Table 11.1** A summary of different changes on the position of equilibrium

# ACTIVITY: Le Chatelier's principle in context

## ATL

- Communication skills: read critically and for comprehension; use and interpret a range of discipline-specific terms and symbols

**1** **Fizzy drinks contain dissolved carbon dioxide, $CO_2(aq)$, and are made by dissolving carbon dioxide in the water under pressure. To keep the carbon dioxide dissolved, the pressure needs to be maintained by keeping the lid on the top of the bottle (Figure 11.20). The carbon dioxide is in equilibrium with carbonic acid, $H_2CO_3$, a weak acid.**




(a) At equilibrium (b) No longer at equilibrium

**Figure 11.20** The bottle with the lid on (a) is a closed system, but with the lid off (b), it is not

- **a** **Formulate an equilibrium equation to describe the reaction in the sealed bottle.**
- **b** **Predict, using Le Chatelier's principle, the effect of**
  - **i** **adding more carbon dioxide to the head space above a fizzy drink in a sealed bottle**
  - **ii** **opening the bottle on the pH of the fizzy drink.**
- **c** **Outline an experiment to determine whether the dissolving of carbon dioxide in water is an endothermic or exothermic process.**
- **d** **Outline how radioactive carbon-14 could be used to investigate a dynamic equilibrium in this chemical system.**

**2** **When bromine is added to water to form bromine water the following equilibrium is quickly established.**

$$\underset{\text{orange/red}}{Br_2(aq) + H_2O(l)} \underset{\text{acid}}{\overset{\text{alkali}}{\rightleftharpoons}} \underset{\text{colourless}}{H^+(aq) + Br^-(aq) + HOBr(aq)}$$

**At equilibrium, the concentrations of all five chemical species shown in the equation are constant, because the rates of the forward and backward reactions are the same. Dissolved bromine ($Br_2$) gives the solution an orange/red colour, but bromic(I) acid (HOBr) is colourless.**

**Predict, as a colour change, the effect on the dynamic equilibrium caused by adding**

- **a** **an alkali such as sodium hydroxide to the mixture**
- **b** **an acid such as hydrochloric acid to the mixture.**

**3** **Figure 11.21 shows two solutions with the following chemical equilibrium:**

$$2CrO_4^{2-}(aq) + 2H^+(aq) \rightleftharpoons Cr_2O_7^{2-}(aq) + H_2O(l)$$

**Predict the changes in colour that occur when an**

- **a** **acid is added**
- **b** **alkali is added.**

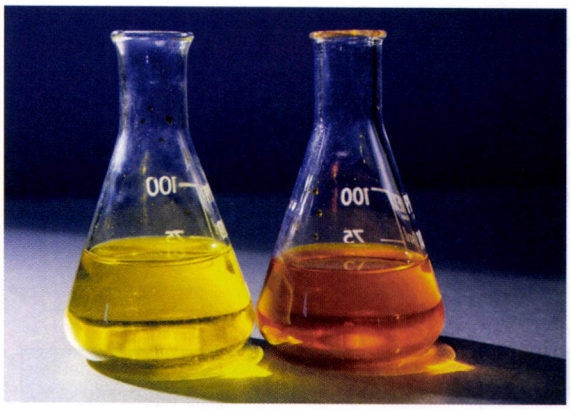



**Figure 11.21** The orange solution contains predominantly dichromate(VI) ions ($Cr_2O_7^{2-}$) and the yellow solution predominantly chromate(VI) ions ($CrO_4^{2-}$)

## Assessment opportunities

- In this activity you have practised skills that are assessed using Criterion A: Knowing and understanding.

# THE HABER PROCESS

For economic reasons, industrial processes aim to maximize the yield (concentration of the desired products) of the chemical reactions they involve. The design of optimal reaction conditions applies an understanding of reaction kinetics and Le Chatelier's principle.

The **Haber process** is a case study for the application of Le Chatelier's principle and reaction kinetics. Figure 11.22 outlines the industrial process, which involves reacting nitrogen and hydrogen to produce ammonia gas. Developed by the German scientist Fritz Haber in 1913, ammonia was initially used to manufacture explosives during the First World War. Today this process is the basis of the artificial fertilizer industry.

- The nitrogen needed in the Haber process is obtained from the atmosphere by distillation of liquid air (see Chapter 9).
- The hydrogen needed in the Haber process is usually obtained from the reaction between methane and steam:

  $CH_4(g) + H_2O(g) \rightleftharpoons CO(g) + 3H_2(g)$

  This process is known as steam reforming. As the reaction is reversible, to ensure that the reaction proceeds to the right (the forward reaction), and enable the maximum amount of hydrogen to be produced at an economic cost, the process is carried out at a temperature of 750 °C, at a pressure of 30 atmospheres with a catalyst of nickel. The carbon monoxide produced is then allowed to reduce some of the unreacted steam to produce more hydrogen gas.
- The key reaction of the Haber process involves the reaction of nitrogen with hydrogen to produce ammonia:

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

  This synthesis reaction is also reversible, and extreme conditions are required to help it proceed to the right: a pressure of 200 atmospheres, a temperature of 450 °C with a catalyst of iron. Under these conditions, about 25 per cent of the nitrogen and hydrogen are converted to ammonia. The hot gases from the converter are then cooled to liquefy the ammonia. The unreacted nitrogen and hydrogen gases are recycled.

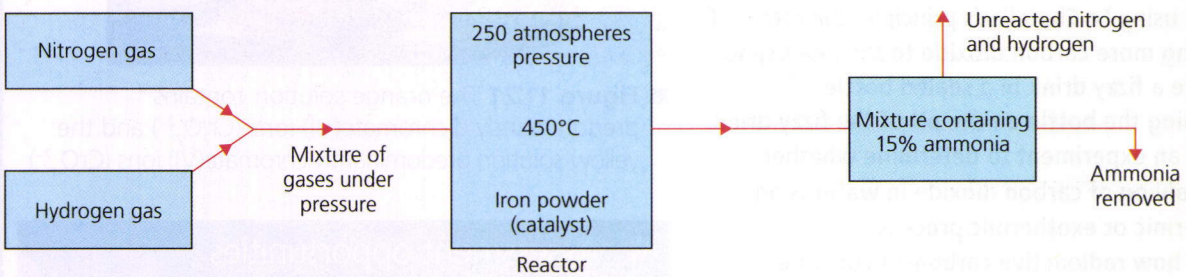



**Figure 11.22** Flow diagram of the Haber process

## ACTIVITY: Reflecting on the Haber process

### ATL

- Communication skills: Make inferences and draw conclusions

**1** **In the synthesis of ammonia, the forward reaction is exothermic.**

$$N_2(g) + 3H_2(g) \rightleftharpoons 2NH_3(g) \quad \Delta H = -92.4\,kJ\,mol^{-1}$$

(forward reaction: exothermic; reverse reaction: endothermic)

**Identify, with reference to Le Chatelier's principle, the reaction which will be favoured by an increase in temperature.**

**2** **Figure 11.23 shows the percentage yield of ammonia using different operating conditions of temperature and pressure.**

- **a** **Identify the effect of using an iron catalyst in this reaction.**
- **b** **Calculate the maximum mass of ammonia that could be made from 1 kg of nitrogen gas.**
- **c** **Describe, with reference to Le Chatelier's principle, how the yield of ammonia is affected by**
  - **i** **temperature**
  - **ii** **pressure.**
- **d** **The ammonia produced is separated from the unreacted gases as a liquid. Suggest why the unreacted gases are recycled.**
- **e** **Suggest why, in practice, a temperature of around 400 °C is chosen for this process, and why a temperature of 350 °C is not used.**
- **f** **Suggest why pressures above 300 atmospheres are rarely used in this process.**

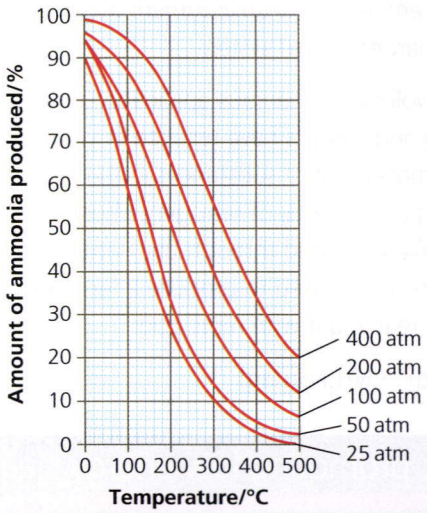



**Figure 11.23** Percentage yield of ammonia

### Assessment opportunities

- In this activity you have practised skills that are assessed using Criterion A: Knowing and understanding.

## EXTENSION

**Explore further:** What does the **fountain experiment** tell you about the properties of ammonia? **Explain** why the fountain is observed in this example: http://www.rsc.org/learn-chemistry/resource/res00000979 (or www.youtube.com/embed/X1BktOPsc7g which is direct to the video).

# To what extent is the Earth a chemical system in dynamic equilibrium?

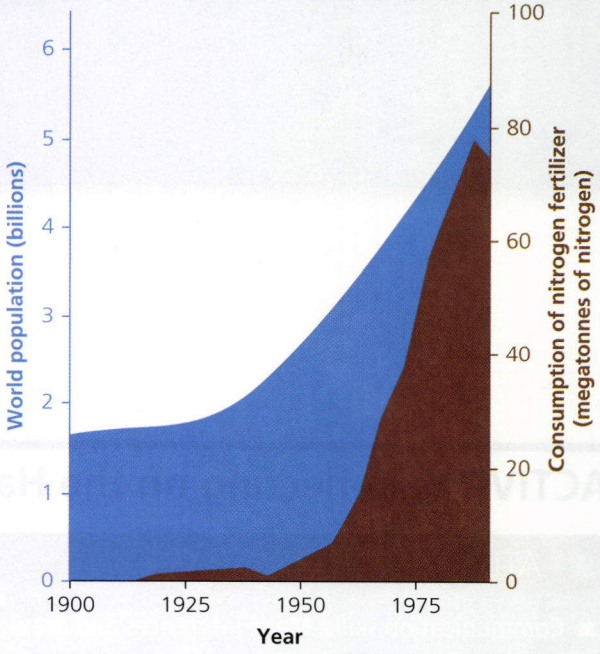



**Figure 11.24** The rate of increase in the use of nitrogen fertilizer (brown curve) from the early 1950s was matched by the growth of the human population (blue curve)

When tracking substances through a process, systems analysts do not just consider the balance of sources and sinks (Chapter 9), they also consider the rates of inputs and outputs, called a **flow**.

In this chapter, you have been introduced to the idea of a closed system. Earth's entire natural environment might be considered as a much larger, closed system.

Since the Industrial Revolution, ingenious applications of Le Chatelier's principle and kinetics have resulted in very large increases in the movement of substances in the environment, including compounds of nitrogen, phosphorus and sulfur. The ammonia produced through the Haber process, for example, could be used to produce a fertilizer, ammonium nitrate, by reacting it with nitric acid:

$$HNO_3(aq) + NH_3(aq) \rightarrow NH_4NO_3(aq)$$

After the Second World War, when the industrial use of ammonia shifted to agriculture, this boosted the availability of nitrogen to land plants by the bacterium *Rhizobia* in legumes (e.g. beans). The flow-on effects have included fertilizing the whole ecosystem, and boosting the world's population (Figure 11.24). It has been estimated that approximately half the world's population is alive today as a direct result of the Haber process!

## ! Take action: promoting low energy cleaning

### ATL

- Information literacy skills: Make connections between various sources of information; present information in a variety of formats and platforms; understand and implement intellectual property rights

! Bioremediation is the science of using 'extremophiles', naturally adapted organisms to clean contaminated environments. Examples include microbes (Archaea) and certain plants. Special enzymes in these organisms enable them to thrive in surroundings that are toxic for most organisms.

! **Design** an information leaflet or an Internet 'infomercial' of no more than 1200 words to campaign for investment in the use of bioremediation to repair environmental damage at low cost.

! In your leaflet or infomercial:

1. **Describe and explain how the extremophile you selected is able to use and improve the damaged environment, with reference to its special enzymes or transport proteins, and equations for the biochemical reactions.**
2. **Discuss and evaluate the implications of the commercial use of the extremophile on our planet.**

! Be sure to use scientific terminology accurately and **document** all your sources using a recognized referencing and citation standard.

### ◆ Assessment opportunities

◆ This activity can be assessed using Criterion D: Reflecting on the impacts of science.

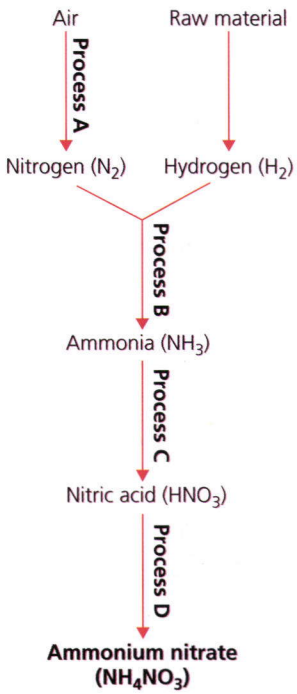
# SOME SUMMATIVE PROBLEMS TO TRY

Use these problems to apply and extend your learning in this chapter. The problems are designed so that you can evaluate your learning at different levels of achievement in Criterion A: Knowing and understanding.

A copy of a periodic table should be available for reference.

## THIS PROBLEM CAN BE USED TO EVALUATE YOUR LEARNING IN CRITERION A LEVEL 1–2

**1** The flow diagram refers to processes used in the manufacture of important nitrogen-containing compounds.




- **a** **State** the names of processes A, B and D.
- **b** **Identify** one source of hydrogen for process B.
- **c** **Suggest** how the following changes of conditions could affect process B:
  - **i** temperature is increased
  - **ii** pressure is decreased.

## THESE PROBLEMS CAN BE USED TO EVALUATE YOUR LEARNING IN CRITERION A TO LEVEL 3–4

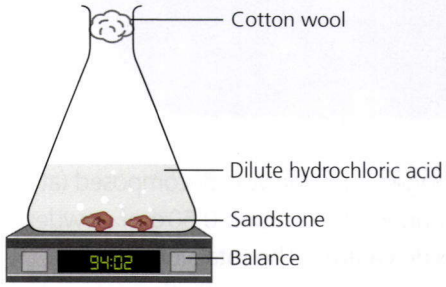
**2** Read the information below, to identify features about the experiment.

- **a** **Identify** the variables in this experiment and suggest how they were controlled.
- **b** **Outline**, using ideas about particles colliding, how the rate of reaction changed during the experiment.

Sandstone contains sand (mainly silicon dioxide) and calcium carbonate. Excess sandstone was reacted with dilute hydrochloric acid:

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

The rate of reaction was followed by measuring the mass lost during the reaction.




| Time *t*/minutes | Total mass lost/g |
|---|---|
| 0 | 0.00 |
| 4 | 0.18 |
| 8 | 0.30 |
| 12 | 0.38 |
| 16 | 0.44 |
| 20 | 0.48 |
| 24 | 0.51 |

**3** When carbon monoxide and steam are passed over a heated iron catalyst they react as follows:

$$CO(g) + H_2O(g) \rightleftharpoons CO_2(g) + H_2(g)$$

The forward reaction is exothermic; and the backward reaction in endothermic.

**Predict,** using the information about the experiment the effect on the yield of hydrogen caused by

- **a** increasing the quantity of steam
- **b** removing the carbon dioxide
- **c** decreasing the pressure
- **d** increasing the temperature.

## THESE PROBLEMS CAN BE USED TO EVALUATE YOUR LEARNING IN CRITERION A TO LEVEL 5–6

**4** **Describe** how the following variables affect reaction rate:

- **a** the surface area of a solid reactant
- **b** the concentration of a dissolved reactant
- **c** the pressure of a gas in a reaction
- **d** the temperature of the reactants
- **e** the presence of a catalyst.

5 A solution of hydrogen peroxide was decomposed (at a constant temperature of 25 °C) using 0.50 g of powdered manganese(IV) oxide catalyst. The total volume of oxygen formed was measured at regular time intervals using a gas syringe.

| Time/s | 0 | 10 | 20 | 30 | 40 | 50 |
|---|---|---|---|---|---|---|
| Total volume of oxygen/cm³ | 0.0 | 22.5 | 35.0 | 45.5 | 50.0 | 55.0 |
| Time/s | 60 | 70 | 80 | 90 | 100 | |
| Total volume of oxygen/cm³ | 60.0 | 63.5 | 64.0 | 65.0 | 65.0 | |

a **Plot** these results on a suitable graph.

b **Estimate** (from your graph) how much oxygen was formed after 25 seconds.

c **Calculate** the most rapid rate of decomposition of hydrogen peroxide.

d **Sketch** the shape of the graph showing the rate of decomposition of hydrogen peroxide solution with (i) twice (ii) half the concentration of the original. Assume all other variables are the same.

e **Outline** how you could determine whether copper(II) oxide catalyses this reaction.

6 When potassium chlorate(V) is heated strongly it breaks down, forming potassium chloride and oxygen.

Three test tubes were set up as described in the table and heated equally strongly. Every so often a glowing splint was held above the test tube to test for the production of oxygen. The time taken for a fixed volume of oxygen to be produced was measured.

a **Analyse** the information in the table and suggest a scientific reason for

i the time for the decomposition of potassium chlorate(V) in tube 2

ii the inclusion in this experiment of tube 3.

| Tube 1: potassium chlorate(V) | Tube 2: potassium chlorate(V) and manganese(IV) oxide | Tube 3: manganese(IV) oxide |
|---|---|---|
| 5.5 minutes | 2.5 minutes | No oxygen was produced |

Potassium chlorate(V) and potassium chloride are soluble in water. Manganese(IV) oxide is insoluble in water.

b **Suggest** how you could show that the manganese(IV) oxide

i was not used up in this reaction

ii could catalyse the same reaction again.

## THESE PROBLEMS CAN BE USED TO EVALUATE YOUR LEARNING IN CRITERION A TO LEVEL 7–8

7 **Explain**

a how an activated complex or transition state contributes to the 'success' of a chemical change

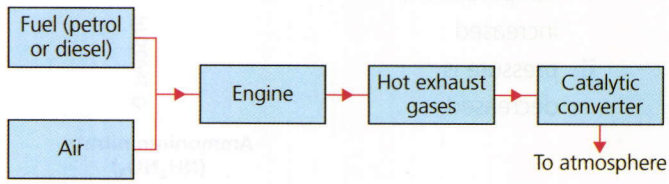
b how atomic orbits are thought to contribute to the 'steric' effect

c the difference between thermal dissociation and thermal decomposition

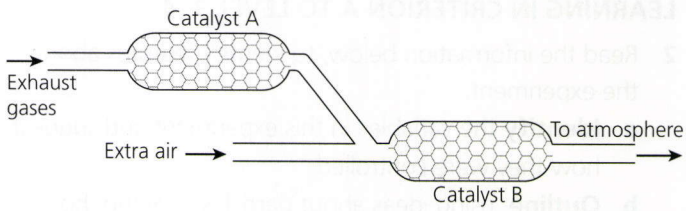
d how a closed system is necessary for a reversible reaction to reach equilibrium.

8 **Explain** why food cooks more quickly in a pressure cooker.

9 Car exhaust fumes contain additional pollutant gases including carbon monoxide, CO, and nitrogen monoxide, NO. Some cars are fitted with a catalytic converter ('cat converter'), which changes the exhaust gases into less toxic gases.




One design of catalytic converter is shown below.




Each of the catalysts only functions when at a high temperature, and increases the rate of one of the following reactions:

$2CO(g) + O_2(g) \rightarrow 2CO_2(g)$

$2NO(g) \rightarrow N_2(g) + O_2(g)$

**a** **Suggest** which of the gases is removed (converted) by catalyst B.

**b** If the volume of the nitrogen monoxide, NO, was much greater than volume of carbon monoxide, CO, this design could be modified. **Suggest and explain** which part of the catalytic converter could be removed.

**c** If the fuel was completely combusted in the hot engine, carbon monoxide would not form. This would require a large intake of oxygen into the sparking chamber. **Suggest** why this is not done. (Hint: many engine parts in contact with the very hot gases are made of iron.)

**10** The stomach contains gastric juice which contains hydrochloric acid with a pH between 1 and 2. The hydrochloric acid acts as an antiseptic and also converts an inactive form of the enzyme, pepsin, to an active form in which it can digest proteins. A normal person has about 1 $dm^3$ of 0.10 mol $dm^{-3}$ of hydrochloric acid in the stomach. Acid indigestion is caused by excess hydrochloric acid and can be relieved by taking antacid tablets.

Details of two brands of antacid tablets are compared below.

| Brand | A | B |
|---|---|---|
| Base | Sodium hydrogen-carbonate ($NaHCO_3$) | Magnesium hydroxide ($Mg(OH)_2$) |
| Mass active ingredient/mg | 250 | 250 |
| Contents | 10 tablets | 10 tablets |
| Price | \$2.40 | \$5.20 |

**Analyse** and **evaluate** this information to judge:

**a** whether it might be an advantage to take antacid medication with a meal, to avoid indigestion

**b** which of these antacid tablets would be most effective for relieving acid indigestion

**c** which brand is 'better value for money'

**d** whether diluting the stomach contents by drinking a litre (1 $dm^3$) of water would be equally effective.

# Reflection

In this chapter you explored how reactions might be manipulated and presented, as flow charts (the biochemistry of Lorenzo's story, the Haber process), and as graphs showing the formation of products or the rates of reactions. Le Chatelier described how in a reversible reaction, the dynamic equilibrium could be shifted to favour reactants or products. His principles are applied in a range of chemical industries. The increased availability of some of these substances, particularly nitrogen fertilizers, has caused profound changes in global cycles.

| **Use this table to reflect on your own learning in this chapter.** | | | | | | |
|---|---|---|---|---|---|---|
| Questions we asked | Answers we found | Any further questions now? | | | | |
| **Factual:** What factors affect reaction rates? Which conditions in reversible reactions at equilibrium will maximize yield? | | | | | | |
| **Conceptual:** How do catalysts make a difference to reactions? | | | | | | |
| **Debatable:** To what extent can the Earth be understood as a chemical system in dynamic equilibrium? | | | | | | |
| Approaches to learning you used in this chapter: | Description – what new skills did you learn? | How well did you master the skills? | | | | |
| | | Novice | Learner | Practitioner | Expert | |
| **Communication skills** | | | | | | |
| **Organization skills** | | | | | | |
| **Reflection skills** | | | | | | |
| **Information literacy skills** | | | | | | |
| **Critical-thinking skills** | | | | | | |
| **Transfer skills** | | | | | | |
| **Learner profile attribute(s)** | Reflect on the importance of balance for your learning in this chapter. | | | | | |
| Balanced | | | | | | |

# 12 Does organic chemistry mean we can make any substance we want?

The versatile bonding of carbon atoms has allowed humanity to **invent systems** of molecules of various **forms** to fulfil different **functions**.




**Figure 12.1** Why is the price of crude oil (petroleum) so important to the chemistry industry, geopolitics and the global economy?

## CONSIDER AND ANSWER THESE QUESTIONS:

**Factual:** What is an organic substance? What is special about the way carbon atoms form molecules?

**Conceptual:** How do functional groups affect the chemical properties of a molecule?

**Debatable:** To what extent can we live without organic materials (apart from food)? Could other elements form the building-blocks of life?

Now **share and compare** your thoughts and ideas with your partner, or with the whole class.

## IN THIS CHAPTER, WE WILL ...

- **Find out** why organic compounds are so versatile.
- **Explore**
  - the concepts of a homologous series and functional group;
  - the trends in physical properties of the members of a homologous series;
  - how the properties of organic compounds can be explained by covalent bonding and intermolecular forces;
  - the characteristic reactions of different homologous series and functional groups.
- **Take action** by creating an action plan to reduce plastic usage at home and at school.

## These Approaches to Learning (ATL) skills will be useful …

- Communication skills
- Organization skills
- Reflection skills
- Critical-thinking skills
- Creative-thinking skills
- Transfer skills

## We will reflect on this learner profile attribute …

- Knowledgeable – Understanding how science affects your life and recognizing how scientific knowledge connects with issues that have local and global significance. Knowing scientific concepts, and using them to understand other subjects. What is the difference between 'citizen science' where everyone has some scientific literacy, and having expertise in a scientific discipline?

## KEY WORDS

organic plastic saturated

## Assessment opportunities in this chapter …

- Criterion A: Knowing and understanding
- Criterion D: Reflecting on the impacts of science

# THINK–PUZZLE–EXPLORE

## ATL

- Communication skills: Make inferences and draw conclusions
- Critical-thinking skills: Consider ideas from multiple perspectives

### What do you *think* you know about organic chemistry?

You have already learnt that organic compounds contain carbon (Chapter 4). Brainstorm with your team what else you may know about this branch of chemistry.

### What questions or *puzzles* do you have?

A number of 'mystery materials' which contain carbon are available for you to observe in the classroom. As you handle or observe these samples, list any questions you have.

### Materials

- **plastic bags**
- **wood**
- **apple**
- **PVC slime**
- **limestone**
- **a sealed jar labelled '$CO_2$ (g)'**
- **vitamin C (ascorbic acid) tablets**
- **aspirin tablets**
- **paracetamol tablets**
- **coal**
- **bottle of oil**
- **jar of petroleum jelly**
- **roll of fishing line**
- **a stocking or pair of tights**

### How can you *explore* this topic?

What general approaches to learning may help you explore this subject? What science-specific approaches to learning may be useful?

You teacher will collate suggestions for questions and approaches, and you will review these at the end of the chapter.

# What is an organic substance?

## EXTENSION

**Explore further:** What was the role of Friedrich Wöhler (Figure 12.2) in disproving the idea of a 'vital force'?



■ **Figure 12.2** Friedrich Wöhler

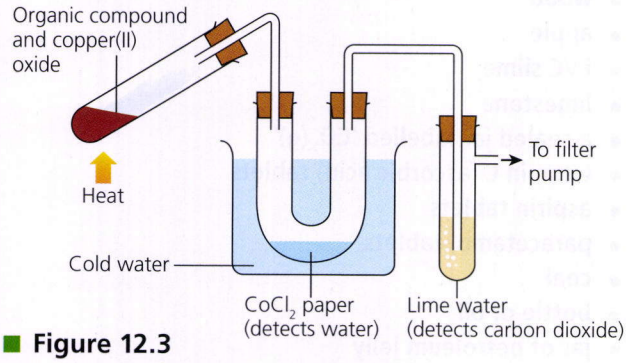
The study of the chemical elements and their compounds is divided into organic and **inorganic chemistry**. Many organic compounds also contain hydrogen and are known as **hydrocarbons**. Metal carbonates, oxides of carbon and allotropes of carbon are classified as inorganic compounds. The division of substances into organic and inorganic was suggested in 1807 by the Swedish chemist Jöns Jakob Berzelius (1779–1848). He believed that, because organic compounds were present in, or synthesized by, plants or animals, these chemicals could only be formed in living organisms via some type of mystical 'vital force'. In contrast, inorganic compounds could be obtained from minerals. At that time it was very difficult to extract organic chemicals in a pure enough form for analysis.

## ACTIVITY: Organic compounds

### ATL

■ Organization skills: Use appropriate strategies for assembling complex information

The presence of carbon and hydrogen in many organic compounds can be demonstrated using the apparatus in Figure 12.3.




■ **Figure 12.3**

**Safety:** Eye protection must be worn. Avoid handing cobalt(II) chloride paper directly; use forceps.

### Materials and equipment

- **safety goggles**
- **copper(II) oxide**
- **limewater (a saturated solution of calcium hydroxide)**
- **dry cobalt(II) chloride paper**
- **U-tube, beaker, test tubes and rubber bungs**
- **Bunsen burner**
- **filter pump**
- **test substances, e.g. cotton wool, wool, cotton, dried rice and marshmallows, crushed limestone and marble**

### Method

1. **Put on safety goggles. Place a crushed sample of the test substance with copper(II) oxide (see Figure 12.3).**
2. **Heat the material.**
3. **Any carbon from the compound forms carbon dioxide. When it bubbles though limewater (calcium hydroxide), a cloudy precipitate of calcium carbonate (chalk) is formed.**
4. **Any hydrogen combines with oxygen to form water. This can be detected by the cobalt(II) chloride paper when the colour changes from blue to pink.**

### Analysing results

1. **List compounds that contained carbon.**
2. **Identify further examples of organic materials in your home.**
3. **Define: limestone (a sedimentary rock formed from the skeletons of corals) and marble (metamorphosed limestone) using the**
   a. **modern definition of 'organic' or 'inorganic'**
   b. **Berzelius' ideas of 'organic' or 'inorganic'.**
4. **Evaluate whether the description *'organically grown'*, applied to some foods and materials like cotton, is a scientific claim or is based on other criteria.**

### ◆ Assessment opportunities

◆ In this activity you have practised skills that are assessed using Criterion A: Knowing and understanding.

# What is special about the way carbon atoms form molecules?

## WHY CARBON?

Carbon is the first member of IUPAC group 14 in the centre of the periodic table. It has four valence electrons (Figure 12.4). It could achieve a noble gas electron arrangement by losing or gaining four electrons; but the formation of carbon ions with charges of +4 or −4 requires too much energy to be feasible.

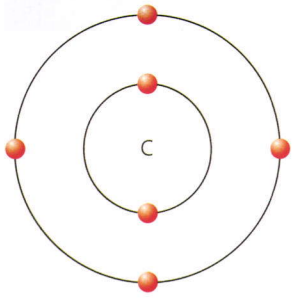



**Figure 12.4** The electron arrangement of a carbon atom

Therefore, the carbon atom achieves a noble gas configuration by sharing its outer electrons with other atoms. Nearly all organic compounds contain hydrogen. In methane (Figure 12.5) for example, four strong C–H bonds are formed. The C–H bonds formed are short and strong because carbon and hydrogen atoms are small. The bonds are also nearly non-polar because carbon and hydrogen have similar values of electronegativity. The shape of a methane molecule is tetrahedral.



**Figure 12.5** Covalent bonds in a methane molecule

Each carbon atom can form four single covalent bonds. Carbon atoms joined by strong carbon–carbon covalent bonds can form chains and rings. This property is called **catenation** and leads to a huge number of different organic structures, because the chains may be straight (linear) or branched and can have other atoms or groups of atoms (**functional groups**) **substituted** (replaced) in them.

By sharing two or three pairs of electrons, a carbon atom can also form double or triple bonds, not only with another carbon atom but also with other elements such as oxygen and nitrogen.

Over 90 per cent of all known compounds are organic: not only the proteins, carbohydrates and lipids (fats and oils) and nucleic acids in living organisms, but synthetics like plastics, dyes, pharmaceuticals, solvents and many explosives. Millions of organic compounds have been described and more are isolated or synthesized every day.

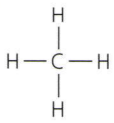
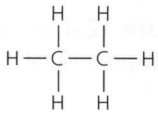
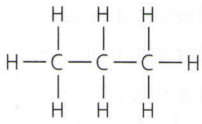
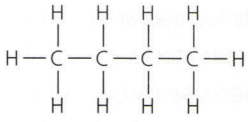
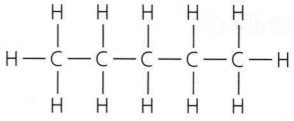
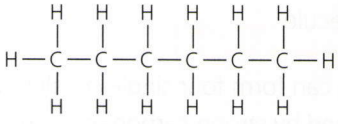
### Homologous series

Chemists classify organic compounds into 'families', known as **homologous series**. In each homologous series, the compounds have similar chemical properties. All organic compounds are named according to the homologous series to which they belong, and the number of carbon atoms they have.

## ALKANES

The simplest homologous series of organic compounds is the **alkanes**, consisting of chains of carbon atoms in which hydrogen atoms bond with the remaining unpaired electrons. These compounds are hydrocarbons, and because the carbon chains contain only single covalent bonds, they are **saturated** hydrocarbons. Alkanes have the general formula $C_nH_{2n+2}$, where $n$ is the number of carbon atoms in one molecule.

Table 12.1 lists the first six molecules in the alkane series and their formulas. Notice how the names of all alkanes end in *-ane*. The prefixes refer to the number of carbon atoms: *meth-* means one carbon atom, *eth-* means two carbon atoms and *prop-* means three carbon atoms, etc. The molecules are held together in the liquid and solid states by weak intermolecular forces that increase with the number of electrons.

| Number of carbon atoms in one molecule | Chemical name | Molecular formula | Relative molecular mass | Structural formula of one molecule | Boiling point/°C |
|---|---|---|---|---|---|
| 1 | Methane | $CH_4$ | 16 |  | −162 |
| 2 | Ethane | $C_2H_6$ | 30 |  | −89 |
| 3 | Propane | $C_3H_8$ | 44 |  | −42 |
| 4 | Butane | $C_4H_{10}$ | 58 |  | −0.5 |
| 5 | Pentane | $C_5H_{12}$ | 72 |  | 36 |
| 6 | Hexane | $C_6H_{14}$ | 86 |  | 69 |

■ **Table 12.1** Names and formulas of the first six alkanes

## Reactions and uses of alkanes

Alkanes are generally unreactive, but they can burn in air to form carbon dioxide and water. An example is the complete combustion of propane:

propane + oxygen → carbon dioxide + water

$C_3H_8(g) + 5O_2(g) \rightarrow 3CO_2(g) + 4H_2O(l)$

The main use of alkanes is in combustion (burning) to release thermal energy. Fuels such as bottled 'gas' for cooking, diesel fuel for cars and buses, petrol for cars and kerosene or paraffin fuel for jet aircraft are all alkanes. All of these fuels are obtained from **crude oil** (petroleum).

Alkanes are also found in animal products. One example is shark liver oil (Figure 12.6), which is approximately 14 per cent pristane, $C_{19}H_{40}$. The IUPAC name of this compound is 2,6,10,14-tetramethylpentadecane.

Methane is also produced in the guts of ruminants (animals like cows, goats and sheep) by the action of microbes (Archaea). The methane generated from ruminant digestion and manure is estimated to contribute about 10 per cent of the methane detected in the atmosphere (Chapter 9).

Solid, long-chain alkanes are produced by plants. Their surfaces, particularly their leaves, are protected by a firm layer of wax, called the cuticle. These waxes protect plants against water loss, damage by UV radiation, bacteria, fungi and harmful insects, and also prevent important minerals from being leached by rain.




■ **Figure 12.6** Shark liver oil

## ACTIVITY: Reflecting on the alkane series

### ■ ATL

■ Communication skills: Organize and depict information logically; use a variety of media to communicate with different audiences

1. **Present** models (e.g. with a molymod® kit) of three examples of alkanes from Table 12.1. **Describe** the nature of the spatial arrangement of the hydrogen atoms along the carbon chain.
2. **Plot** the relationship between the boiling points versus number of carbon atoms (in one molecule) of the alkane, and predict the boiling point of octane $C_8H_{18}$.
3. **Explain** why the boiling point of the alkane increases with the length of the carbon chain. (You may want to refer to Chapter 4.)
4. **Deduce** the formula of decane, an alkane containing ten carbon atoms, and **predict** the physical state of a sample of decane at standard temperature and pressure.
5. **Suggest** the source of the alkane composition of fossil fuels, based on the information about alkanes found in modern living organisms.

### ◆ Assessment opportunities

◆ In this activity you have practised skills that are assessed using Criterion A: Knowing and understanding.

## EXTENSION

**Explore further:** What is the occurrence of alkanes, such as methane and ethane, in the solar system; planets, moons (satellites) and comets?

# ALKENES

The **alkenes** are another homologous series of hydrocarbons. Simple alkenes with one carbon–carbon double bond have the general formula $C_nH_{2n}$, where $n$ is the number of carbon atoms in one molecule. Notice that all the names of alkenes end with *-ene*. The alkenes in Table 12.2 are all gases at standard temperature and pressure.

## Reactions and uses of alkenes

In air, alkenes burn like alkanes. An example is the combustion of ethene:

ethene + oxygen → carbon dioxide + water

$C_2H_4(g) + 3O_2(g) \rightarrow 2CO_2(g) + 2H_2O(l)$

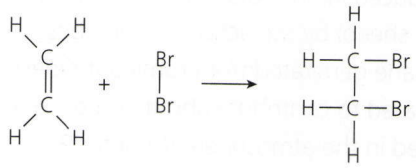
However, alkenes are usually not burnt because they are more reactive than alkanes and can be used to form a wide range of compounds for the chemical industry.

## Addition reactions

An addition reaction is one in which a molecule combines with the alkene to form one product. This is possible because of the reactive carbon–carbon double bond in an alkene. Bromine reacts with ethene in an addition reaction. The bromine molecule adds across the double bond of the ethene molecule:

ethene + bromine → 1,2-dibromoethane

$C_2H_4(g) + Br_2(g) \rightarrow C_2H_4Br_2(l)$



Many useful organic compounds are made from alkenes by addition reactions. For example, the 1,2-dibromoethane ($C_2H_4Br_2$) made from ethene was historically put into leaded petrol as an anti-knocking agent, and to reduce the build-up of lead residues by producing gaseous lead products.

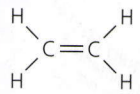
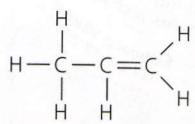
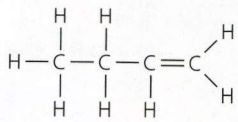
| Number of carbon atoms in one molecule | Chemical name | Molecular formula | Relative molecular mass | Structural formula of one molecule | Boiling point/°C |
|---|---|---|---|---|---|
| 2 | Ethene | $C_2H_4$ | 28 |  | −104 |
| 3 | Propene | $C_3H_6$ | 42 |  | −48 |
| 4 | But-1-ene | $C_4H_8$ | 56 |  | −6 |

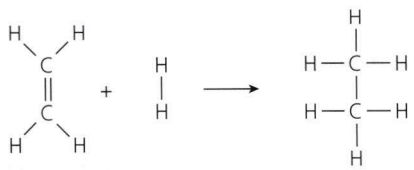
**Table 12.2** Names and formulas of some alkenes

## Addition of hydrogen

Alkenes react with hydrogen gas to produce alkanes. This reaction is reduction and also known as hydrogenation. A heated nickel catalyst must be used. An example is the reaction of ethene with hydrogen to form ethane:

ethene + hydrogen → ethane

$C_2H_4(g) + H_2(g) \rightarrow C_2H_6(g)$



## EXTENSION

How is **hydrogenation** used in the production of margarine (Figure 12.7)?




**Figure 12.7** Margarine

## ACTIVITY: Reflecting on the alkene series

### ATL

- Critical-thinking skills: Practise observing carefully in order to recognize problems; draw reasonable conclusions and generalizations; use models and simulations to explore complex systems and issues

1 **Present** models (e.g. with a molymod® kit) of the three examples of alkenes in Table 12.2.
   a **Describe** the nature of the spatial arrangement of the hydrogen atoms located near the double bond along the carbon chain.
   b A **structural isomer** is a compound with the same atoms but in a different spatial arrangement. **Calculate** how long a carbon chain needs to be before structural isomers become possible.
2 **Compare** the trends in boiling points of the homologous series of alkanes with the trends seen in the homologous series of alkenes.
   a **Identify** the apparent effect of having a double bond within a molecule. **Suggest** why this occurs.
   b **Predict** the boiling point of pent-1-ene, $C_5H_{10}$ (or 1-pentene). The '1' indicates the double bond is located between first and second carbon atoms in the chain. If the double bond was found between the 2nd and 3rd carbons, the molecule would be called pent-2-ene (or 2-pentene), and so on.
3 **Deduce** the name, molecular formula, relative molecular mass and structural formula of the next three members of the alkene homologous series.
4 Alkenes and organic compounds with carbon–carbon triple bonds, called **alkynes**, are considered **unsaturated**.
   a **Suggest** the meaning of 'unsaturated' in this context. Why is 'unsaturated margarine' considered a healthy choice?
   b **Predict** the names of the first six compounds in the alkyne homologous series.
   c **Deduce** the reactivity of alkynes compared with alkanes, given the following information: alkynes are not necessarily more reactive than alkenes with the same number of carbon atoms, but alkenes are more reactive than unsaturated hydrocarbons (alkanes) with the same number of carbon atoms.

### Assessment opportunities

- In this activity you have practised skills that are assessed using Criterion A: Knowing and understanding.

# How do functional groups affect the chemical properties of a molecule?

## FUNCTIONAL GROUPS

Many organic compounds contain a group of atoms, or a single atom (which is not hydrogen) known as a '**functional group**', a chemical structure that is responsible for many of its chemical and physical properties. Members of a homologous series (containing the same functional group) have similar chemical properties.

With familiarity, you will begin to recognize how the reactivity of functional groups can be used to create new organic molecules.

## ALCOHOLS

The hydroxyl functional group, –OH, results in a homologous series with the general formula $C_nH_{2n+1}OH$. The first molecules in this series are methanol and ethanol. Notice that the hydroxyl group attaches directly to a carbon atom in the alkane chain (Table 12.3). Alkanes with a hydroxyl group attached have the '*e*' ending of their name replaced with *-ol*.

The effect of the hydroxyl group is to give the end of the molecule polarity, which allows the molecule to dissolve in water and react with sodium (in a reaction similar to that of water).

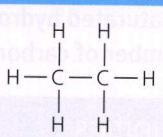
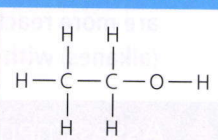
| 'Parent' alkane | Structural formula | Ethanol | Structural formula |
|---|---|---|---|
| Ethane, $C_2H_6$ |  | $C_2H_5OH$ |  |

**Table 12.3**

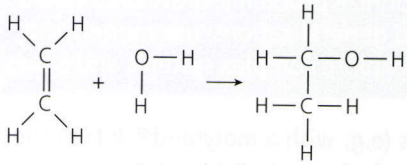
### Uses of alcohols

Alcohols are important solvents and chemicals in industry. They are used to make a range of different organic compounds.

### Making alcohols using an addition reaction of water to an alkene

Alkenes can react by addition with water to produce alcohols. A molecule of water is added across the carbon–carbon double bond of the alkene. This occurs when a mixture of the alkene and steam is passed over a catalyst, hot concentrated phosphoric(V) acid, ($H_3PO_4$):

ethene + water → ethanol



## ACTIVITY: Investigating the solubility of alcohols

### ATL

- Organization skills: Understand and use sensory learning preferences (learning styles)

Alcohols are often diluted to fulfil different functions – for example, as alcoholic drinks or in antifreeze in the cooling systems of engines. In this activity you will investigate how the form of an alcohol molecule affects its solubility.

**Safety:** Wear eye protection and goggles. Methanol is toxic; avoid contact with skin and inhaling fumes.

### Materials and equipment

- gloves and safety glasses
- disposable pipettes
- 150 $cm^3$ beakers
- a range of alcohols, for example: methanol, ethanol, propan-1-ol, butan-1-ol, pentan-1-ol, hexan-1-ol, octan-1-ol, decan-1-ol.

### Method

1. **Design** a table in which you list the alcohols you are testing, their formula, relative molecular mass, and a column to record your observations.
2. Put on safety glasses and gloves.
3. Fill the small beakers with tap water.
4. Add a *few drops* of each alcohol to each beaker, to test for solubility.

### Analysing results

1. **Identify** the alcohols that were miscible and immiscible in water.
2. **Suggest** how the length of the alkyl chain contributes to solubility.
3. **Suggest** a modification to the method that would help you detect droplets of immiscible alcohols on the surface of the water.

### Assessment opportunities

- In this activity you have practised skills that are assessed using Criterion C: Processing and evaluating.

## ACTIVITY: Reflecting on alcohols

### ATL

- Transfer skills: Apply skills and knowledge in unfamiliar situations; inquire into different contexts to gain a different perspective

1. **Suggest** why, when making ethanol using an addition reaction, a high temperature (300 °C) and a high pressure (70 atmospheres) are used during hydration (see Chapter 11).
2. Antifreeze, used in the radiators of cars in cold climates (Figure 12.8), contains ethylene glycol (1,2-ethane-diol), a kind of alcohol. **Suggest** why this compound is preferred to methanol ($CH_3OH$).




**Figure 12.8** Antifreeze is a type of alcohol.

### Assessment opportunities

- In this activity you have practised skills that are assessed using Criterion A: Knowing and understanding.



**Figure 12.9** Red wood ants squirting methanoic acid into the air from their nest against predators

# CARBOXYLIC ACIDS

The attachment of a **carboxylic acid** (carboxyl) functional group, –COOH, to an alkane results in another homologous series. The carboxylic acid homologous series has the general formula $C_nH_{2n+1}COOH$. A terminal (end) carbon is bonded to both a hydroxyl group and an oxygen atom (Table 12.4). Alkanes with a carboxyl group attached have the '*e*' ending of their name changed to *-oic acid*.

The effect of the carboxyl group is to give the end of the molecule polarity, and turns it into a typical weak acid (see Chapter 5) when dissolved in water. However, alkanes are non-polar and this means carboxylic acids with more than five carbon atoms (e.g. pentanoic acid) become increasingly immiscible in water as the non-polar hydrocarbon chain increases in length.

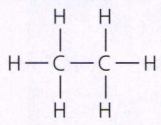
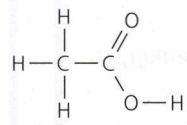
| 'Parent' alkane | Structural formula | Ethanoic acid | Structural formula |
|---|---|---|---|
| Ethane, $C_2H_6$ |  | $CH_3COOH$ |  |

**Table 12.4**

The first carboxylic acid in the series is methanoic acid, HCOOH. Many ants produce this compound (Figure 12.9), which explains why the common name for methanoic acid is 'formic acid', from the Latin word *formica*, meaning ant. It is also often used as a preservative and antibacterial agent on animal food, for tanning leather and dyeing textiles, and in the making of rubber.

You are likely to be familiar with the second carboxylic acid in the series, ethanoic acid, $CH_3COOH$. It is found in vinegar. Ethanoic acid is formed when ethanol is oxidized, for example by acetic acid bacteria (*Acetobacter*). The equation for the reaction is:

ethanol + oxygen → ethanoic acid + water

$$C_2H_5OH(aq) + O_2(g) \rightarrow CH_3COOH(aq) + H_2O(l)$$

## ACTIVITY: Reflecting on carboxylic acids

### ATL

- Critical-thinking skills: Interpret data; revise understanding of new information and evidence; identify trends and forecast possibilities

1. **List the first six compounds in the carboxylic acid homologous series.**
2. **Formulate equations to show the reactions between ethanoic acid ($CH_3COOH$) and magnesium, calcium oxide, sodium carbonate and sodium hydroxide.**
3. **During the 19th century, 'vinegar plants' were added to fermenting fruit in water or fruit juice to produce vinegar in the home. These organisms needed to be kept in the dark, and required oxygen. Identify the type of organism that a 'vinegar plant' actually was.**

### Assessment opportunities

- In this activity you have practised skills that are assessed using Criterion A: Knowing and understanding.

# A NOMENCLATURE FOR THE INCREDIBLE DIVERSITY OF ORGANIC COMPOUNDS

Your introduction to organic compounds has only begun to touch on their incredible variety. Each functional group can be represented by a general formula (Table 12.5). Each hydrogen atom along the parent chain can also be replaced with an **alkyl group**, or an alkane missing a hydrogen in the molecule, forming a branched chain, represented with an R symbol in the table. Common alkyl groups are the methyl ($-CH_3$), ethyl ($-CH_2CH_3$) and propyl ($-CH_2CH_2CH_3$) groups. If an organic compound has more than one alkyl group, these may be represented as $R_1$, $R_2$ and so on.

For example, a **haloalkane** (or halogenoalkane) may be shown as RX where R is the alkyl group and X represents the halogen, an atom in group 17 of the periodic table such as bromine, chlorine or iodine.

### Links to: Language acquisition

The IUPAC system for naming organic compounds is another 'language': once mastered, you have a tool for communicating with chemists everywhere.

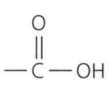
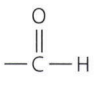
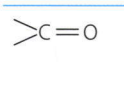
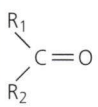
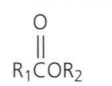
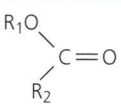
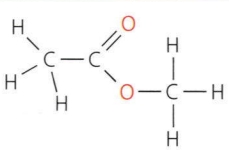
| Functional group | General formula | Name of homologous series | Example |
|---|---|---|---|
| –OH | ROH | Alcohols[1] | $CH_3OH$<br>Methanol |
|  | RCOOH | Carboxylic acids | $CH_3COOH$<br>Ethanoic acid |
| –Br, –Cl, –I, etc. | RX | Haloalkanes<br>(halogenoalkanes) | $CH_2BrCH_2Br$<br>1,2-dibromoethane[2] |
|  | RCHO | Alkanals (formerly aldehydes) | $CH_3CHO$<br>Ethanal |
|  |  | Alkanones[3] (formerly ketones) | $CH_3OCHCH_3$<br>Propanone |
|  |  | Esters[4] | <br>Methyl ethanoate |
| –O– | $R_1–O–R_2$ | Ethers[5] | $CH_3OC_2H_5$ or<br>$CH_3OCH_2CH_3$<br>Methoxyethane |
| $-NH_2$ | $RNH_2$ | Amines[6] | $CH_3NH_2$<br>Aminomethane<br>(methylamine) |

**Table 12.5** A reference table of functional groups. (Superscript numbers refer to the naming rules on the next page.)

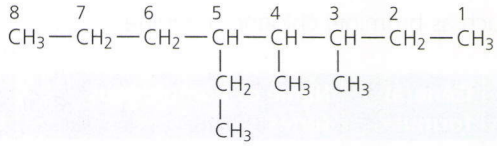
## Rules for naming functional groups

Refer to Table 12.5.

1. A hydroxyl, –OH, group can replace any hydrogen on a parent alkane. Its position can be indicated in the name by numbering the longest alkane chain and counting from the end which gives the lowest position for the hydroxyl group. For example, a propanol with a single hydroxyl group could be either propan-1-ol or propan-2-ol, but not propan-3-ol.
2. Notice the prefix *'di'* indicating that two halogens have been substituted. The numbers indicate precisely the carbon atoms in the longest unbranched chain to which the halogens have been attached. When more than one halogen is involved, they need to be listed in alphabetical order.
3. The oxygen atom is attached to one of the carbon atoms, and therefore the total number of atoms determining the length of the chain is (number of carbon atoms in $R_1$ + 1C + number of carbon atoms in $R_2$). The functional group (>C=O) is assigned the carbon with the lower number.
4. Name the alkyl group from the alcohol followed by the carboxylic acid group (the group with the double bonded oxygen). The *'ic'* of the acid is replaced by the suffix *'ate'*.
5. Select the longer alkyl group (-ethyl), which provides the parent name, in this case ethane. The shorter chain gets an *-oxy* suffix (not a prefix), in this case methoxy.
6. Amines are complicated to name because each hydrogen atom can also be substituted with an R group. Note that $–NH_2$ is a functional group of amino acids, used to synthesize proteins.

## IUPAC rules for naming branched-chain alkanes

Use this example to understand the process of naming these structures.




1. *Find the longest continuous chain* (the parent structure). In this example, the chain is eight carbons long, so it is an *octane*.
2. *Number the carbons in sequence, starting at the end which will give the substituent groups the smallest numbers.* In the example, this required numbering is from right to left, so the groups are attached to carbon atoms *3, 4 and 5 (total 12).* In the alternative direction, these numbers would have been 4, 5 and 6 (total 15).
3. *Add the numbers to the names of the substituent groups.* In this example: *3-methyl, 4-methyl* and *5-ethyl.*
4. *Use prefixes to indicate any groups that appear more than once*, using commas to separate the numbers. In this example, *3,4-dimethyl* will be part of the name.
5. *List the names of the alkyl groups in alphabetical order.* Note that the prefixes di, tri, penta and so on are ignored. Hyphens are used to separate numbers and words. In this example, *5-ethyl-3,4-dimethyl* will be part of the name.
6. *Apply the correct punctuation.* The name of the alkane is written as one word. Therefore, the IUPAC name for this example is: *5-ethyl-3,4-dimethyloctane.*

# ACTIVITY: Applying IUPAC nomenclature to organic compounds

## ATL

- Critical-thinking skills: Practise observing carefully in order to recognize problems; interpret data; test generalizations and conclusions

Work together or individually to respond to these questions.

1 **State** the name of a carboxylic acid that has an alkyl group, R, consisting of five carbon atoms.
2 **Present** structural formulas of the following compounds:
   a 3-ethyl-3-methylhexane
   b 2,4-dimethylhexane
   c 2,2,3,3-tetramethylpentane
   d 2,6,10,14-tetramethylpentadecane (also known as 'pristane').
3 The IUPAC name for the compound in Figure 12.10 is 1,1,1-trichloro-2,2-*bis*(4-chlorophenyl)ethane.

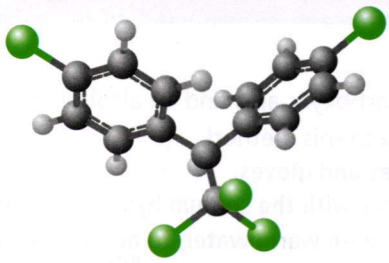


**Figure 12.10** A three-dimensional representation of a DDT molecule

**Suggest**, from the IUPAC formula:
   a the name of the 'parent alkane'
   b the carbon atom number to which the chlorine atoms are attached
   c how the carbon atoms are counted in the 'benzene' structure.
4 **Determine** the IUPAC names of branched-chain structures with less than 10 carbon atoms in the parent alkane that have been suggested (sketched) by your peers. Remember that you can count around corners; the chain does not have to be straight!

## Assessment opportunities

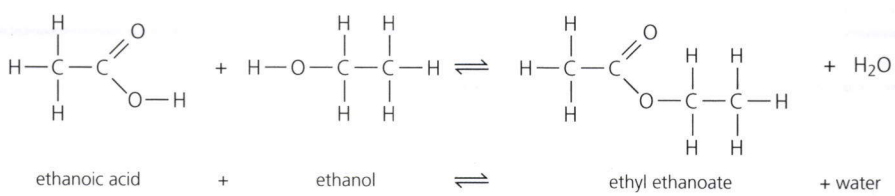
- In this activity you have practised skills that are assessed using Criterion A: Knowing and understanding.

# ACTIVITY: Making esters

## ATL

- Transfer skills: Apply skills and knowledge in unfamiliar situations; combine knowledge, understanding and skills to create products of solutions

**Esters** are often used as food flavouring or perfumes. They are formed when carboxylic acids react (reversibly) with alcohols, a reaction that also forms water. For example, ethanoic acid reacts with ethanol in the presence of concentrated sulfuric acid to form ethyl ethanoate and water. The sulfuric acid acts as a catalyst and dehydrating agent.



ethanoic acid + ethanol ⇌ ethyl ethanoate + water

The first part of the name comes from the alcohol (ROH), and the second part (ending in *-oate*) is modified from the carboxylic acid ($RCO_2H$).

**Safety:** Wear eye protection and goggles. Methanol is toxic so avoid contact with skin and inhaling fumes. Butanoic acid has a potent, disagreeable smell. It should be used only in a fume cupboard.

## Materials and equipment

- safety goggles and gloves
- a range of alcohols and organic acids, each with a dedicated pipette
- 2.0 M sulfuric acid
- 2 × 500 $cm^3$ beaker
- 1.0 M sodium hydrogencarbonate solution
- test tubes
- kettle (if warm tap water is not available)

## Method

Any combination of a carboxylic acid and an alcohol should result in the formation of an ester with this method.

1. **Put on safety goggles and gloves.**
2. **Fill the 500 $cm^3$ beaker with the sodium hydrogencarbonate solution.**
3. **Fill the other beaker with warm water, to act as a water bath.**
4. **Add a few drops of a carboxylic acid to a clean, dry test tube.**
5. **Add a similar amount of alcohol.**
6. **Your teacher will add a drop or two of concentrated sulfuric acid.**
7. **Warm the mixture gently in the beaker of warm water for 5–10 minutes.**
8. **Pour the mixture in the test tube into a beaker with the sodium hydrogencarbonate solution. The sodium hydrogencarbonate neutralizes the acid catalyst and any unreacted carboxylic acid.**
9. **You should get some drops of ester left on the surface which can be carefully smelled to appreciate the aroma of the ester.**
10. **Use different combinations of acids and alcohols to make five different esters. You may wish to try some of the examples listed in Table 12.6, or make your own combinations.**

| Carboxylic acid | Alcohol | Found in | Name of ester using IUPAC nomenclature |
|---|---|---|---|
| 1 g 2-hydroxybenzoic acid (salicylic acid) (s) | Methanol (l)* | Oil of wintergreen and in many plants; used in liniments | |
| Butanoic acid (l)* | Methanol (l)* | Rum, pineapple | |
| Ethanoic acid (l) | Ethanol (l) | Pear drops, apple | |
| Ethanoic acid (l) | Pentan-1-ol (l) | Banana | |
| Ethanoic acid (l) | Octan-1-ol (l) | Orange | |
| Butanoic acid (l)* | Ethanol (l) | Apricot, peaches | |
| Butanoic acid (l)* | Pentan-1-ol (l) | Apricot | |
| Heptanoic acid (l) | Ethanol (l) | Brandy | |
| 1 g benzoic acid (s) | Ethanol (l) | New mown hay | |
| 1 g benzoic acid (s) | Methanol (l)* | Feijoa | |

*Refer to safety box.

**Table 12.6** Combinations of carboxylic acids and alcohols

## Analysing results

1. **Formulate** IUPAC names for the esters and list them in the final column in Table 12.6.
2. **Formulate** balanced equilibrium equations for the esters you synthesized.
3. **Suggest** why several of the esters you have made don't usually smell exactly the same as a delicious, ripe example of the fruit in which they may be found.
4. **Explain** why esters are immiscible in water, although alcohols and carboxylic acids (with short length alkyl chains) tend to be water soluble.
5. **Analyse** the formula of an ester found in beeswax, to identify the formulas of the carboxylic acid and the alcohol reactants used to form it: $CH_3(CH_2)_{14}COO(CH_2)_{29}CH_3$.

### Assessment opportunities

- In this activity you have practised skills that are assessed using Criterion A: Knowing and understanding.

## EXTENSION

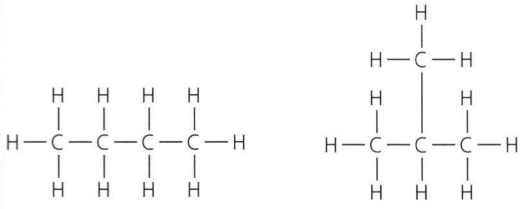
**Go further:** Discover common applications of **ethanol** ($C_2H_5OH$), **propanone** ($CH_3COCH_3$) and **ethyl ethanoate** ($CH_3COOC_2H_5$) used in the activity, above.

# THE SAME BUT NOT THE SAME: ISOMERS

By physically modelling alkanes and alkenes you may have realized the same carbon atoms could be bonded in very different ways. Compounds which have the same molecular formula but different structural formulas are called **isomers**. Isomerism is common in organic chemistry, because there are so many ways of bonding carbon atoms to other atoms.

## Structural isomers

The **molecular formula** of the two molecules in Figure 12.11 is $C_4H_{10}$, but their **structural formulas** are different. These two molecules are examples of structural isomers. They will tend to have similar chemical properties. The larger the molecule, the more isomers are possible.



**Butane**, $C_4H_{10}$
Colourless gas
Burns in air to form $CO_2 + H_2O$
Liquefies at 0 °C

**2-Methylpropane**, $C_4H_{10}$
Colourless gas
Burns in air to form $CO_2 + H_2O$
Liquefies at –16 °C

■ **Figure 12.11** Structural isomers with the formula $C_4H_{10}$. Both alkanes ($C_4H_{10}$) have four carbon atoms and 10 hydrogen atoms

## Equivalence: non-isomers

Single bonds may be able to rotate, but double and triple bonds cannot, resulting in the formation of **stereoisomers**. As atoms rotate to different positions, the same molecule may appear to be different. One way to recognize 'chemical equivalence' is to look for symmetry. If the two atoms you are comparing have symmetry between themselves on the molecule, they are probably chemically equivalent. Another way is to apply the IUPAC naming system.

## Geometric isomers

Double and triple bonds in unsaturated hydrocarbons cause rigidity, and this can result in differences in spatial arrangements, called **geometric isomerism**. *Trans* forms of a geometric isomers occur where chemical groups lie across the double bond; *cis* forms where chemical groups lie on the same side of the double bond (Figure 12.12).



*trans*-1,2-Dichloroethene

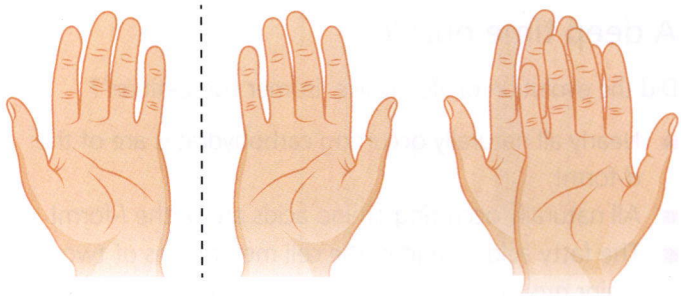


*cis*-1,2-Dichloroethene

■ **Figure 12.12** Two geometric isomers of 1,2-dichloroethene. The *trans* form has the substituent halogens on opposite sides of the double bond; in the *cis* form of the molecule these occur on the same side of the double bond

## Enantiomers

**Enantiomers** are non-superimposable mirror images (Figure 12.13). This also applies to molecular structures where single bonds connect four different chemical groups to a central, asymmetric carbon atom (Figure 12.14). These groups may be a hydrogen atom, halogens or alkyl groups.



■ **Figure 12.13** Two hands are examples of structures that are non-superimposable, mirror images, because they are asymmetric

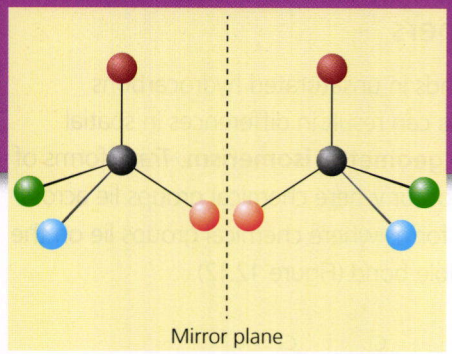



**Figure 12.14** An asymmetric carbon atom can bond with four different chemical groups, resulting in enantiomers, a type of stereoisomer in which the mirrors images are non-superimposable

Nearly all the chemical properties such as boiling point, density, refractive index and viscosity of carbon enantiomers are identical, but they do differ in one important way: they rotate plane **polarized light** in opposite directions. Polarized light has been 'filtered' so that its electromagnetic vibrations are limited to a single plane or direction. You may be familiar with this effect if you have ever reduced the glare of bright sunlight by using polarizing sunglasses. The *dextro*, *d* or + form of an enantiomer rotates polarized light clockwise, 'to the right' and the *laevo*, *l* or – form rotates it anticlockwise, 'to the left'. For this reason, enantiomers are also referred to as optical isomers.

## A deep time puzzle

Did the evolution of life involve 'isomer competition'?

- Nearly all naturally occurring carbohydrates are of the *d*-form!
- All naturally occurring amino acids are of the *l*-form!
- The fatty acids found in the cell membranes of two major groups of microbes, bacteria and Archaea, are optical isomers.

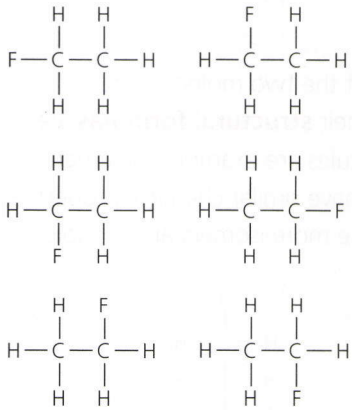
To date, no one really knows the reason for this observation! However, it is speculated that at some early stage of chemical evolution, maybe even before cellular life existed, molecular competition resulted in one type of stereoisomer becoming prevalent.

## ACTIVITY: Reflecting on isomers

### ATL

- Critical-thinking skills: Practise observing carefully in order to recognize problems; interpret data; revise understanding based on new information and evidence

1 **Identify** the number of different molecules shown below.



2 **Present** models (e.g. with a molymod® kit) of all the isomers (straight and branched) for pentane, hexane and heptane.

3 **Determine** the mathematical relationship between the number of carbon atoms and the number of isomers in these situations:
   a single bonded structural isomers
   b the effect of one double or triple bond in an unsaturated carbon chain 3, 5 or 7 carbons long.

4 **Suggest** how you could manufacture an ingredient to make sure that its stereoisomer property is compatible with human consumption.

### Assessment opportunities

- In this activity you have practised skills that are assessed using Criterion A: Knowing and understanding.

### Links to: Mathematics

Mathematics provides a tool with which to abstract numerical information to investigate patterns.

# Could other elements form the building blocks of life?

## ACTIVITY: Is life based on inorganic chemistry possible?

### ATL

- Creative-thinking skills: Consider multiple alternatives, including those which may be unlikely or impossible; make unexpected or unusual connections between objects and/or ideas; create original works and ideas; use existing works and ideas in new ways; generate metaphors or analogies

All the elements in IUPAC group 14 share to some extent carbon's chemical bonding properties based on four valence electrons. Imagine a world not based on carbon. This idea has often been used in science fiction. Could you match the creativity of some of these efforts?

Your 700–1200 word story should include:

- **a scientific explanation of the consequences of using a different element to form a system of molecules (e.g. chains, branches, rings and functional groups)**
- **a moral, ethical, social, economic, political, cultural or environmental factor, as found in all fine literature – including yours! For example, would recycling be possible with your alternative group 14 element or would, as a result of their chemistry, a logical response by your fictional characters provide moral or social insight into our own world?**

There are several possible presentations for this assignment, including as a cartoon strip.

All sources should be fully documented. This could be presented separately.

### Assessment opportunities

- In this activity you have practised skills that are assessed using Criterion D: Reflecting on the impacts of science.

### Links to: Language and Literature

A role of fiction is to provide insight into other possible worlds, and to discuss moral dilemmas objectively. Science fiction uses scientifically plausible contexts to explore the consequences of innovations and futuristic technologies.

## EXTENSION

Research **non-carbon based life** to find out about real life based on inorganic molecules and speculation by a famous scientist about this.

# To what extent can we live without organic materials (apart from food)?

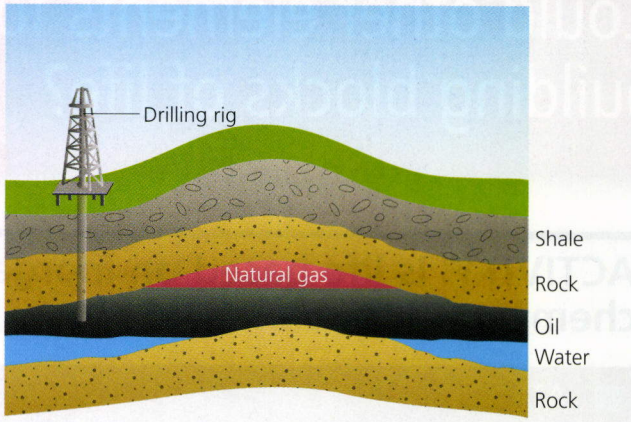



**Figure 12.15** The extraction of crude oil and natural gas

## CRUDE OIL IS A FOSSIL FUEL

Crude oil or petroleum (from the Latin *petra*, meaning rock, and *oleum*, meaning oil) is a dark, viscous (sticky) liquid found in the ground, especially under the sea, consisting of many different hydrocarbons. Although less than 10 per cent of crude oil is used in the chemical industry it is the most important raw material for the organic chemical industry.

About half of the world's crude oil is found in the Middle East. Crude oil and natural gas (methane) are often found together, held in between layers of non-porous rock in the ground. They are extracted by drilling a pipe through the rock (Figure 12.15).

### Separation and conversion of crude oil (petroleum)

Petroleum is a complex mixture of hydrocarbons, and every oil field has a different composition. However, the main components of petroleums are alkanes, and after the removal of impurities like sand and water, the refining process of any crude oil involves the same stages: **fractional distillation**, **cracking** and reforming.

#### Stage 1: Fractional distillation

Crude oil is heated and passed into a tall fractionating column (Figure 12.16) where it undergoes fractional distillation (see Chapter 2). The hydrocarbon molecules with the lowest boiling points pass to the top of the column, and those with the highest boiling points remain at the bottom. Intermediate fractions of increasing boiling points are also collected. The average relative molecular mass of the fractions increases with boiling point.

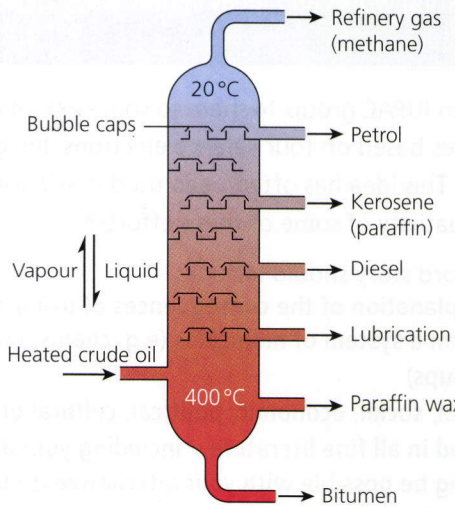



**Figure 12.16** A crude oil fractionating column

This results in about six fractions (apart from natural gas) which are purified and blended for use as petrol, diesel, kerosene (paraffin), solvents and oils (Table 12.7). The lighter fractions are used in the industrial production of organic chemicals. When used in this way, they are called chemical feedstocks.

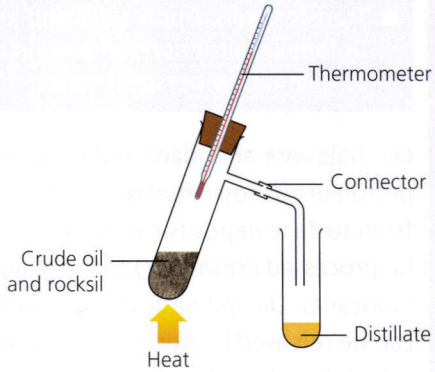
#### Laboratory distillation

Crude oil can be distilled using the apparatus shown in Figure 12.17. This process must be demonstrated by your teacher, in a fume cupboard. Alternatively, you can watch a brief video about the process and products here: **www.youtube.com/watch?v=26AN1LfbUPc**.

A more sophisticated arrangement for fractional distillation can be viewed here: **www.youtube.com/watch?v=0x2-8dedmE4&list=PLXl9I2_9q0tbbEQrVx9wmj3pAgLnGW1xd&index=7**.

| Name of fraction | Point range/°C | Number of carbon atoms in molecules | Uses |
|---|---|---|---|
| Natural gas | <20 | 1–4 | Fuel |
| Petrol | 20–205 | 5–10 | Solvent, motor fuel |
| Kerosene (paraffin) | 175–325 | 11–18 | Lighting fuel, fuel for tractor and jet engines |
| Diesel | >275 | 13–18 | Heating fuel, fuel for diesel engines, 'cracking stock' |
| Lubrication oil | Non-volatile solids | 18–22 | Lubricants, solvents, mild laxative pharmaceuticals |
| Paraffin wax | Non-volatile solids | 20–30 | Candle wax, waxed paper |
| Bitumen | Non-volatile solids | 30–40 | Roofing materials, road materials (asphalt and tar), petroleum coke (a waste product) |

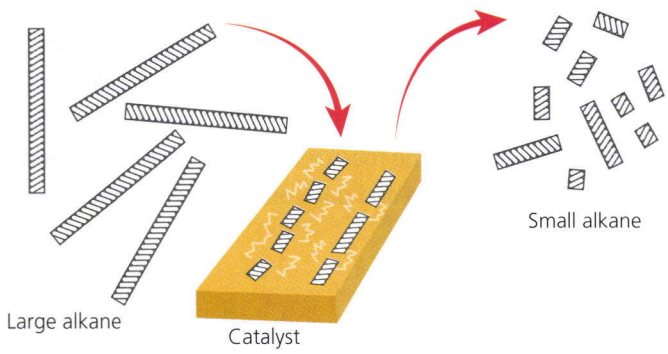
■ **Table 12.7** Properties of crude oil fractions and their uses




■ **Figure 12.17** Fractional distillation of crude oil (in the laboratory). Rocksil is a mineral wool that soaks up liquids

## Stage 2: Cracking

There is less demand for the more viscous fractions, made up of molecules with higher relative molecular masses and higher boiling points. The thicker liquids are therefore often 'cracked' (Figure 12.18). This means that the larger molecules are broken down (decomposed) into smaller ones suitable for making petrol, or for use in the chemical industry. This can be done in two ways: using a high temperature, or using a lower temperature and a solid catalyst.

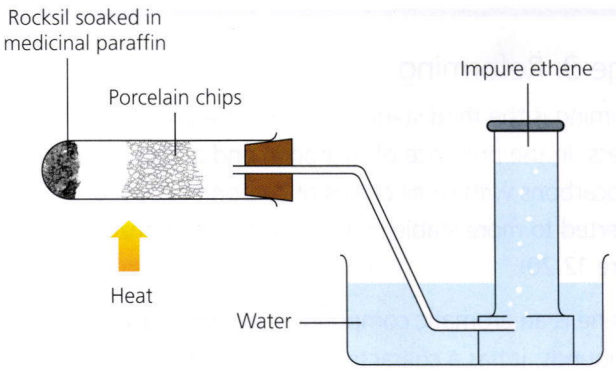



■ **Figure 12.18** The principle of cracking

### Laboratory cracking

For safety reasons, the cracking of crude oil may be demonstrated by your teacher in the laboratory using medicinal paraffin and the apparatus shown in Figure 12.19. Alternatively, you can watch a brief video of the process here: **www.youtube.com/watch?v=AajLtkJxPk0**.

A mixture of light hydrocarbon gases including ethene ($C_2H_4$) can be collected over water. The gaseous mixture is flammable and decolorizes bromine and potassium manganate(VII). A brief video of a test for the presence of an alkene can be found here: **www.youtube.com/watch?v=AajLtkJxPk0**.




■ **Figure 12.19** Cracking in the laboratory

## ACTIVITY: Reflecting on impacts of shale oil extraction or fracking

### ATL

- Transfer skills: Apply skills and knowledge in unfamiliar situations; inquire in different contexts to gain a new perspective

Oil shales are abundant and promise to replace petroleum as fossil fuel resources. Mined rocks from surface deposits can be burnt directly, or may be processed ('retorted') to make liquid fuels and lubricants. Oil and natural gas from deep deposits can be released by using pressurized water, a process called 'fracking'. Watch the video to understand how it works: www.youtube.com/watch?v=IB3FOJjpy7s

Use the Internet to investigate recent news stories about **shale oil fracking** or **mining**.

- **Reflect on how many of these stories are about economic, political, environmental and social impacts.**
- **Evaluate the pros and cons of these new methods of oil extraction, and whether we should exploit this resource.**
- **Present your findings induvidually as a written debate, or orally in teams leading to a conclusion based on the aspects you consider more persuasive. Be sure to acknowledge your sources.**

### Assessment opportunities

- In this activity you have practised skills that are assessed using Criterion D: Reflecting on the impacts of science.

## Stage 3: Reforming

Reforming is the third stage of the petroleum refining process. In the presence of hydrogen and a heated catalyst, hydrocarbons with small chains of carbon atoms are converted to more stable hydrocarbons with benzene rings (Figure 12.20).

Benzene is an aromatic compound. Like many **aromatic** compounds, it has a characteristic smell. Although their smell may be sweet and even attractive, many aromatics, including benzene, are very poisonous.

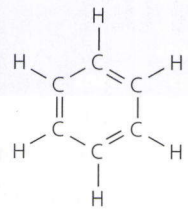


**Figure 12.20** Structure of benzene. It is a hydrocarbon since its molecule contains carbon and hydrogen atoms only

The molecules of an aromatic compound contain one or more fused benzene rings. For example, naphthalene, which is present in moth balls (Figure 12.21), is composed of two benzene rings joined together.



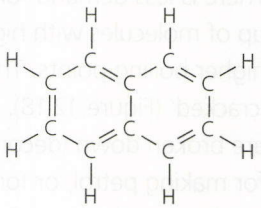



**Figure 12.21** Naphthalene, the chemical present in mothballs, contains two benzene rings

Aromatic compounds contain a high proportion of carbon and for this reason they often burn with luminous yellow flames producing black, sooty smoke. The benzene ring is a stable structure and some medicinal drugs contain a benzene ring, for example, aspirin and paracetamol (Figure 12.22).

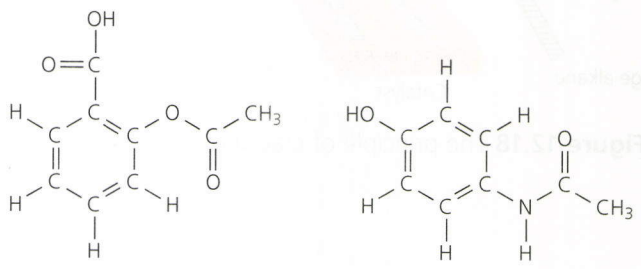


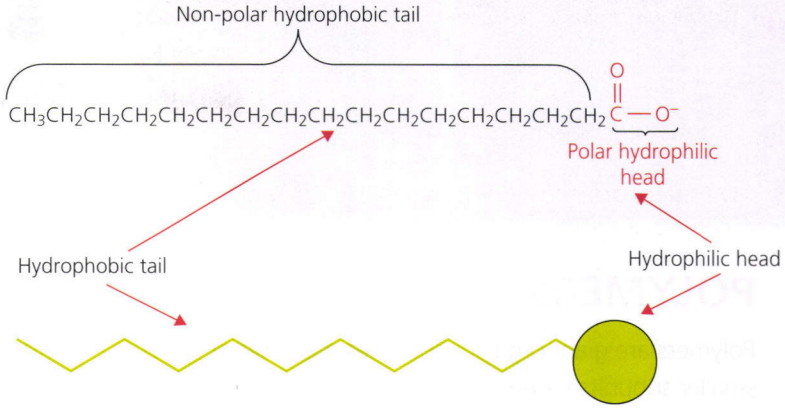

**Figure 12.22** Structure of (a) aspirin and (b) paracetamol. What formulas would these compounds have?

# ORGANIC MATERIALS IN USE

Carbon compounds may occur naturally or are made by humans from fossil fuels. In this section, you will consider the impact of some of these substances.

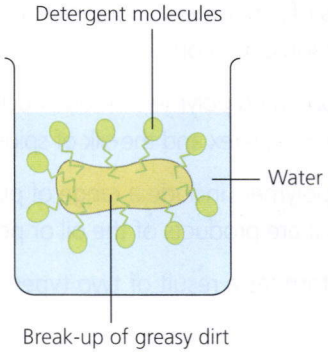
## Soaps and detergents

Soap and soapless detergent molecules are examples of emulsifiers (see Chapter 2). Their molecules have 'tadpole' structures, with different chemical properties. The long hydrocarbon chain 'tail' is hydrophobic (non-polar) and attracted to oils. The carboxylic acid group in the 'head' is hydrophilic and attracted to water (Figure 12.23).




■ **Figure 12.23** Generalized structure of soap molecule

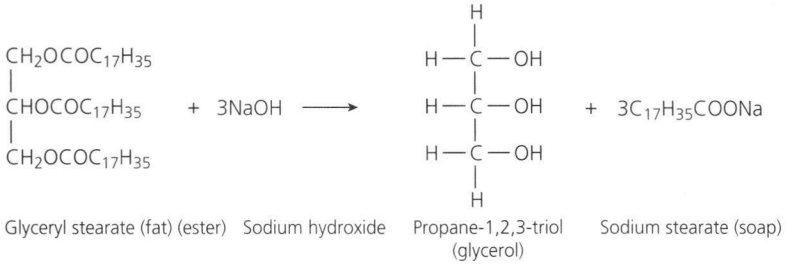
As the hydrophobic ends of the soap or detergent molecules mix with particles of grease, the hydrophilic heads remain in the water (Figure 12.24), which helps the grease form a suspension that can be rinsed away.




■ **Figure 12.24** Interaction between detergent molecules and grease and water

Soapless detergents are made from concentrated sulfuric acid and hydrocarbons obtained from petroleum refining. These synthetic detergents are more effective for dissolving oils, because they are more soluble than soap. They also do not react with the calcium ions found in 'hard' water, and therefore do not form a scum, bath rings being an example.

Soaps are made from renewable hydrocarbons, animal fats and vegetable oils (Figure 12.25). The fats are reacted with concentrated sodium hydroxide and then precipitated using a sodium chloride (NaCl) solution. The fats and oils contain esters and the process of making soap is called **saponification**. For example,






■ **Figure 12.25** Soap



**Figure 12.26** Spider silk (composed of proteins). How does a spider produce up to seven different types of silk?

# POLYMERS

Polymers are giant organic molecules made up of many smaller subunits called monomers, which may be chemically identical or have identical functional groups. 'Poly' means 'many' and a single polymer may contain many tens of thousands of monomers and consist of more than a hundred thousand atoms.

Naturally occurring polymers include nucleic acids, proteins, starch, cellulose, latex and the silk of spider webs (Figure 12.26).

Synthetic polymers include a range of plastics, nylon and fibres. Most are products of the oil or petrochemical industry.

Polymers form as a result of two types of reactions.

## Condensation polymerization

During **condensation polymerization**, each time two monomers react, a small molecule (usually water) is lost (eliminated). Nylon and Terylene are examples of plastics formed by condensation polymerization. Figures 12.27 and 12.28 show the reactions in a simplified form. In these schematic diagrams, the boxes represent carbon chains ($-CH_2-CH_2-CH_2-CH_2-$ units). The monomers used to make nylon (Figure 12.27) form **amide** linkages. Nylon is therefore called a polyamide. The monomers used to make Terylene (Figure 12.28) form ester linkages. Terylene is therefore a polyester. In both reactions, each time two monomers bond, a molecule of water is also formed.

Watch the formation of nylon here:
**www.youtube.com/watch?v=y479OXBzCBQ.**

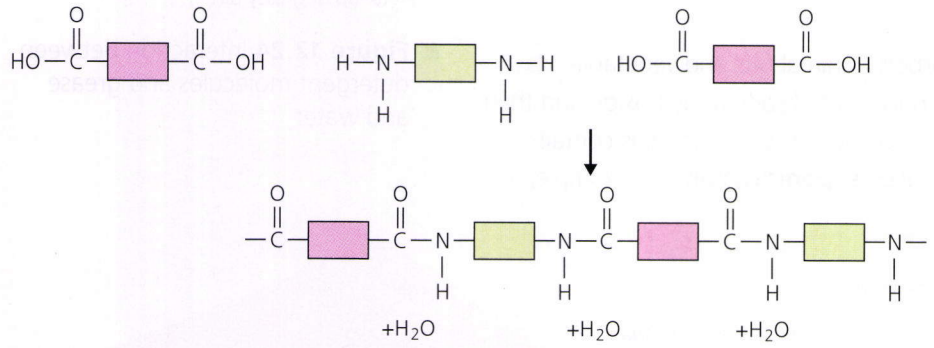



**Figure 12.27** Condensation polymerization to form nylon

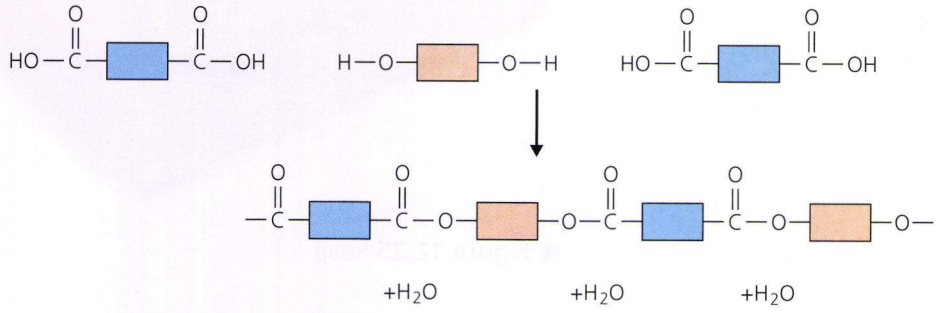



**Figure 12.28** Condensation polymerization to form Terylene. Notice how the dicarboxylic acid molecules alternate with diol molecules, forming ester linkages

| Polymer | Monomer |
|---|---|
| Protein | Amino acid |
| Cellulose, starch | Glucose |
| Nucleic acid (DNA, RNA) | Nucleotide |

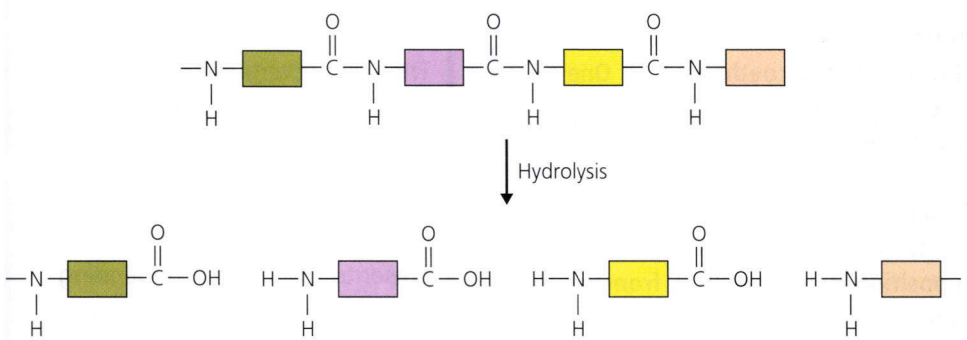
■ **Table 12.8** Natural condensation polymers, and their monomers

Condensation polymerization is also common in living tissues, where synthesis and breakdown of polymers is catalysed by enzymes (Table 12.8).

In proteins, the monomers consist of 20 different types of amino acid and the amide linkages are called peptide linkages. When a proteins is broken down into its component amino acids (for example, during digestion), the process is known as **hydrolysis**. Hydrolysis (Figure 12.29) is the reverse of condensation polymerization. The amino acids can be separated and identified using paper chromatography (see Chapter 2).

## Addition polymerization

Alkenes can also 'add on' to one another, over and over again. This process, in which many small unsaturated molecules add on to one another to form a large molecule, is known as **addition polymerization**.




■ **Figure 12.29** Hydrolysis of proteins into amino acids



■ **Figure 12.30** Polypropylene rope. What conditions determine high density and low density polyethene?

For example, when an ethene molecule breaks a bond, it can be added to itself, molecule by molecule, to form a poly(ethene) molecule or polythene. Each time the bond of the ethene molecule breaks, a new carbon–carbon bond is formed between the molecules. The arrows in the following equation show how (in a simplified way) this happens.

ethene ⟶ poly(ethene)

$$CH_2{=}CH_2 + CH_2{=}CH_2 + CH_2{=}CH_2 \longrightarrow -CH_2-CH_2-CH_2-CH_2-CH_2-CH_2-$$

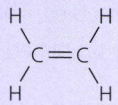
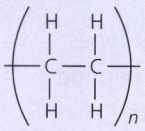
The different properties of polymers or plastics can be created by using different monomers. Any alkene or substituted hydrocarbon with a carbon–carbon double bond is able to act as a monomer for addition polymerization. As a result, plastics can be tailored for nearly every purpose. They are durable, lightweight and relatively inexpensive to produce. Examples include packaging materials and synthetic fibres (Figure 12.30).

## ACTIVITY: Reflecting on polymers

### ATL

- Critical-thinking skills: Interpret data; draw reasonable conclusions and generalizations

**1 Identify the structural formula, name and unit formula of each of the polymers in the table below.**

| Name of monomer | Structural formula of monomer | Name of polymer | Formula of repeating unit |
|---|---|---|---|
| Ethene |  | Poly(ethene) (polythene) |  |
| Propene | | | |
| Chloroethene (vinyl chloride) | | | |
| Phenylethene (styrene) | | | |
| Tetrafluoroethene | | | |
| Prop-2-enenitrile (acrylonitrile) | | | |
| Methyl 2-methylpropenoate (methyl methacrylate) | | | |

**2 Polytetrafluoroethene (PTFE or Teflon) is an addition polymer discovered in 1938 and prepared from tetrafluoroethene, $C_2F_4$. One of its first commercial uses was for storing uranium hexafluoride, $UF_6$, used to make atomic bombs. After the war it was used to make non-stick surfaces for frying pans.**

- **a Present the structural formula and shape of tetrafluoroethene.**
- **b Formulate a chemical equation to describe its polymerization.**
- **c Calculate the percentage composition by mass of PTFE from its empirical formula (repeating unit).**
- **d State further contexts where Teflon could be useful**
  - **i as a storage container**
  - **ii to reduce friction.**

### Assessment opportunities

- In this activity you have practised skills that are assessed using Criterion A: Knowing and understanding.

## ACTIVITY: Does organic chemistry mean we should synthesize any substance or molecules we want?

### ATL

- **Reflection skills:** Demonstrate flexibility in the selection and use of learning strategies; consider ethical, cultural and environmental implications

At the conclusion of this course, how can your chemical knowledge inform your opinions? Your 700–1200 word assignment should:

- **explain how a particular organic compound was created in order to address a specific problem or issue**
- **discuss and evaluate how the use of the compound interacts with one of the following factors: moral, ethical, social, economic, political, cultural or environmental and then use your understanding to express and justify your own opinion or verdict about its use.**

There are several possible presentations for this final assignment.

All sources should be fully documented. This could be presented separately, depending on your choice of communication format.

### Assessment opportunities

- This activity can be assessed using Criterion D: Reflecting on the impacts of science.



**Figure 12.31** The exposed gut of this dead seabird is filled with plastic flotsam, mistakenly consumed because birds confuse these coloured fragments with food like krill or shrimp

## A SEA OF PLASTIC

The first plastic was prepared in 1907. Today over a 100 million tonnes are used every year, representing about 8 per cent of global fossil fuel use. For all their convenience and versatility, synthetic polymers (plastics) pose a major problem: they persist in the environment, filling landfill and drifting in the oceans. It is now estimated that by 2050, all marine sea life will have ingested some plastic (Figure 12.31).

Every type of plastic can be recycled. However, the different types (Table 12.9) do need to be sorted.

| Resin code | Polymer name and abbreviation | Original uses | Recycled uses |
|---|---|---|---|
| 1 | Poly(ethene) terephthalate PETE or PET | Soft drink bottles<br>Mouthwash bottles<br>Peanut butter jars | Industrial strapping<br>Automotive bumpers<br>Luggage |
| 2 | High density poly(ethene) HDPE | Milk jugs<br>Retail bags<br>Yogurt containers | Playground equipment<br>Mailbox posts<br>Liquid laundry bottles |
| 3 | Polyvinyl chloride PVC or V | Shampoo bottles<br>Medical tubing<br>Window cleaner bottles | Binders/notebooks<br>Automotive mudflaps<br>Speed bumps |
| 4 | Low density poly(ethene) LDPE | Squeezable bottles<br>Dry cleaning bags<br>Frozen food bags | Garbage can liners<br>6-pack rings<br>Shipping envelopes |
| 5 | Polypropylene PP | Straws<br>Medicine bottles<br>Syrup bottles | Automotive ice scrapers<br>Bicycle racks<br>Lawn rakes |
| 6 | Polystyrene PS | Dinnerware<br>Egg cartons<br>Compact disc jackets | Light switch plates<br>Cafeteria trays<br>Video cassettes |
| 7 | Acrylic, nylon or fibreglass<br>Other or O | 3 and 5 gallon water bottles | Plastic lumber |

**Table 12.9** A recycling code for plastics

Source: **www.albany.edu/gogreen/11.recycling.shtml**

## ! Take action: Plastic – reduce and recycle

### ATL

- Reflection skills: Consider ethical, cultural and environmental implications

! Your aim is to **identify** the plastic involved in 10 examples of locally collected plastic waste.

**Safety:** Wear eye protection and gloves. Propanone is an irritant.

### Materials and equipment

- safety goggles and gloves
- propan-2-ol
- vegetable oil (e.g. peanut oil)
- propanone (acetone)
- small beakers
- scissors (to cut samples of each plastic)
- tweezers
- wooden peg
- copper wire
- Bunsen burner, lighter
- small beakers

### Method

1. **Put on safety goggles and gloves.**
2. **Cut a small sample of the plastic you intend to test.**
3. **Refer to the information in the dichotomous choice table overleaf. Each test will divide the samples into two classes. Only continue testing a sample if you have not yet been able to classify it.**
4. **Repeat for the remaining samples.**
5. **Dispose of your used plastic materials in the bin.** ➤

<table>
<tr><td rowspan="6">Water test<br>Does a small sample of the plastic sink or float on water?</td><td rowspan="3">YES<br>Alcohol test<br>Does a small sample of the plastic sink or float on propan-2-ol?</td><td>YES<br>Oil test<br>Does a small sample of the plastic sink or float on vegetable oil?</td><td>YES<br>It is PP</td><td rowspan="4"></td></tr>
<tr><td></td><td>NO<br>It is LDPE</td></tr>
<tr><td>NO<br>It is HDPE</td><td rowspan="2"></td></tr>
<tr><td rowspan="3">NO<br>Copper wire test<br>1 Use the wooden peg to hold the wire in the blue flame of the Bunsen burner<br>2 Touch the hot wire to the plastic so a little sticks to the wire<br>3 Return the wire to the Bunsen burner flame and note the colour of the flame</td><td>GREEN FLAME<br>It is PVC</td></tr>
<tr><td>ORANGE FLAME<br>Acetone test<br>Test a small sample of the plastic in approximately 30 cm$^3$ of acetone for 20 seconds</td><td>SOFTENS, BECOMES STICKY<br>It is PS</td></tr>
<tr><td>NO REACTION<br>Heat test<br>Hold the sample in a beaker of boiling water for approximately 20 seconds</td><td>SOFTENS<br>It is PET</td></tr>
</table>

Acknowledgement: This table has been re-drawn using information developed by QUT – Queensland University of Technology Faculty of Science.

■ **Table 12.10** Dichotomous choices are possible using this key to identify six types of plastic

## Analysing results

1. **State the type of plastic that was the most common.**
2. **Identify any plastics you were unable to classify.**
3. **Suggest why it was important to dislodge any adhering bubbles in the density tests.**
4. **Estimate, based on your observations during this activity, the approximate density of the propan-2-ol solution.**

! Question 5 refers to the following information:

> The effect that heat has on plastics is a crucial difference. Thermoplastics (or thermosoftening plastics) change shape when they are heated and can be re-melted and re-shaped. These polymers may be forced into moulds under pressure (injection moulding) or can be forced through small holes (extrusion). Thermosets cannot be re-melted and have to be moulded in manufacture.

5. **Identify which type of plastic**
   - **a would be easier to recycle**
   - **b is likely to have more covalently bonded cross-links between the polymer strands. These are stronger but generally have a similar effect to the borate cross-links that stiffened slime (see Chapter 4).**

! At least a third of plastics are used for packaging. What alternatives could be used to reduce the volume of plastic to be recycled?




■ **Figure 12.32** A plastic windmill kit for a model railway

! Imagine you are a scientist commissioned by a local authority to review plastic use and recycling in the locality. With reference to your scientific research in this activity, write a report for the local authority **outlining** how plastic waste could be reduced, and how plastic recycling could be made more efficient.

! **Summarize** the societal, economic and environmental impact of your proposals.

! Make sure to document all your sources appropriately.

### ◆ Assessment opportunities

◆ In this activity you have practised skills that are assessed using Criterion A: Knowledge and understanding and Criterion D: Reflecting on the impacts of science.

# SOME SUMMATIVE PROBLEMS TO TRY

Use these problems to apply and extend your learning in this chapter. The problems are designed so that you can evaluate your learning at different levels of achievement in Criterion A: Knowing and understanding.

A copy of a periodic table should be available for reference.

## THESE PROBLEMS CAN BE USED TO EVALUATE YOUR LEARNING IN CRITERION A TO LEVEL 1–2

1 **State** the name of the functional group in each of the following compounds:

**a** $(CH_3)_2CHCHO$

**b** $CH_3CH_2OCH_2CH_3$

**c** $C_{17}H_{35}COOH$

**d** $C_6H_{13}OH$

2 Complete the word equations to **suggest solutions** for the following **familiar examples** of esterification:

**a** ethanoic acid + pentan-1-ol ⇌ _____ + water

**b** methanoic acid + octan-1-ol ⇌ _____ + water

**c** butanoic acid + ethanol ⇌ _____ + water

**d** pentanoic acid + pentan-1-ol ⇌ _____ + water

3 **Identify** the organic compounds that are unsaturated in the list below:

$H_2CCH_2$; $C_2H_2$; $CH_3CH_2CH_3$; $CH_3COOH$; $CH_3OH$

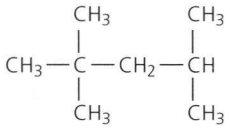
## THESE PROBLEMS CAN BE USED TO EVALUATE YOUR LEARNING IN CRITERION A TO LEVEL 3–4

4 **Outline** an experimental approach that could demonstrate that the complete combustion of hydrocarbons results in the formation of carbon dioxide and water.

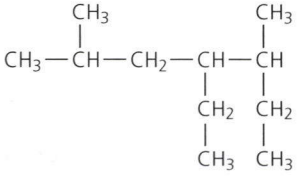
5 **a** Haloalkanes contain the functional group C–X where X is a halogen. **Present** all the possible structural isomers of a substituted alkane with the molecular formula $C_3H_6Cl_2$. **State** the IUPAC name of the compounds you have presented.

**b** **Apply** the IUPAC system to **deduce** the names of the following branched chain alkanes:

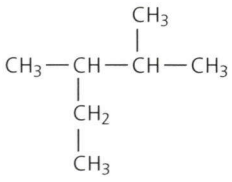
**i**



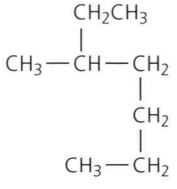
**ii**



**iii**



**iv**



6 Consider the following melting point data for the first ten alkanes:

| Alkane name | Molecular formula | Melting point (°C) |
|---|---|---|
| Methane | $CH_4$ | −182 |
| Ethane | $C_2H_6$ | −183 |
| Propane | $C_3H_8$ | −188 |
| Butane | $C_4H_{10}$ | −140 |
| Pentane | $C_5H_{12}$ | −130 |
| Hexane | $C_6H_{14}$ | −95 |
| Heptane | $C_7H_{16}$ | −91 |
| Octane | $C_8H_{18}$ | −57 |
| Nonane | $C_9H_{20}$ | −51 |
| Decane | $C_{10}H_{22}$ | −30 |

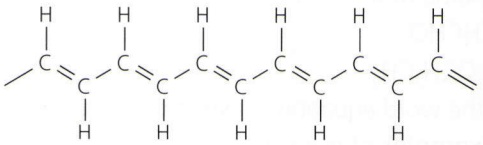
**Identify**, with reference to the information in the data table:

- **a** how many degrees colder than ice, which melts at 0 °C, is the melting point of methane
- **b** how many degrees colder than ice is the melting point of decane
- **c** the relationship between the length of the alkane chain and its melting point
- **d** what you can **deduce** about intermolecular attractions in decane compared with those in methane.

## THESE PROBLEMS CAN BE USED TO EVALUATE YOUR LEARNING IN CRITERION A TO LEVEL 5–6

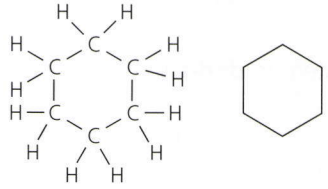
7 **Describe,** with two examples, how functional groups change the chemical properties of an organic molecule.

8 Polyethyne is a conducting polymer whose structure is shown below. The electrical conductivity is due to the presence of carbon atoms with alternating single and double bonds between them. It is prepared by polymerizing ethyne (acetylene), $C_2H_2$.



- **a** **Present** the structure of ethyne and **explain** whether the molecule is saturated or unsaturated.
- **b** **Identify** the formula of the repeating unit of polyethyne.
- **c** **Identify** the type of polymerization involved in the production of polyethyne.
- **d** **Suggest** how the reactivity of polyethyne is likely to compare to polyethene. **Explain** your answer.

9 The alkanes discussed in the text are either straight-chain or branched. However, there is a homologous series of alkanes known as the cycloalkanes. The structure of cyclohexane ($C_6H_{12}$) is shown below as a structural formula and a skeletal formula. Cyclohexane is a liquid at room temperature.



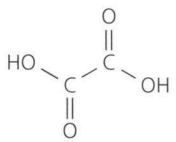
- **a** **Formulate** molecular formulas and **present** the structural and skeletal formulas for cyclopropane, cyclobutane and cyclopentane.
- **b** **Deduce** the general formula for the cycloalkanes and use it to predict the formulas for cycloheptane and cyclooctane.
- **c** On an industrial scale cyclohexane is prepared by the hydrogenation of benzene ($C_6H_6(l)$). **Formulate** an equation summarizing this reaction.

## THESE PROBLEMS CAN BE USED TO EVALUATE YOUR LEARNING IN CRITERION A TO LEVEL 7–8

**10 a** **Explain** why methanol, ethanol, propan-1-ol and butan-1-ol are all highly soluble in water, but pentan-1-ol is far less soluble and decan-1-ol is almost insoluble at 25 °C.

**b** A fresh ball of cotton wool is dipped into each of the alcohols listed in part (a) and rubbed across a piece of dark paper to produce a series of six 'wet marks'. Predict, with reasons, the order in which the marks will evaporate to dryness.

**11** Ethanedioic acid (commonly known as oxalic acid) is a poisonous substance found in rhubarb leaves. It has the following structural formula:




**a** **Suggest** why ethanedioic acid is described as a dibasic acid in aqueous solution.

**b** **Deduce** the molecular and empirical formulas of ethanedioic acid.

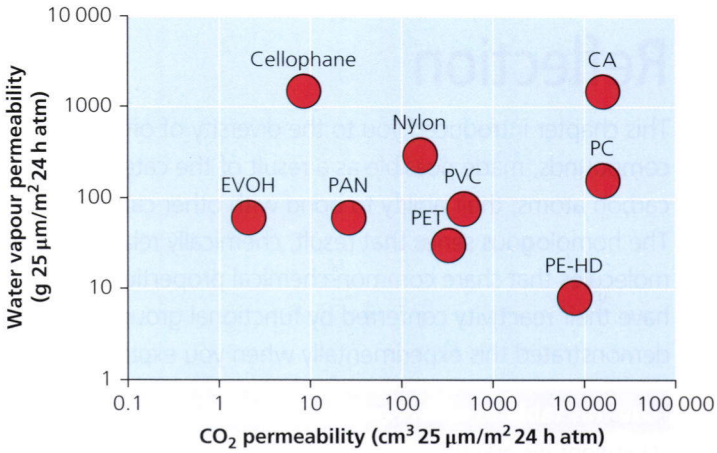
**c** **Formulate** an equation showing its neutralization by barium hydroxide solution.

**d** Ethanedioic acid reacts with ethanol (in the presence of concentrated sulfuric acid) in a 1 : 2 molar ratio to form an ester. **Determine** the structural formula of the ester.

**e** **Suggest** why aluminium saucepans become shiny and clean after stewing with rhubarb leaves.

**f** **Suggest** a name for the salt formed between ethanedioic acid and potassium carbonate. **Formulate** the equation for the reaction.

**12** The graph below describes the permeability properties of a range of plastics. Codes shown are for: cellulose acetate (CA); poly(ethylene-co-vinyl alcohol) (EVOH); polyacrylonitrile (PAN); poly(vinyl chloride) (PVC); polycarbonate (PC); poly(ethylene terephthalate) (PET), and high density polyethylene (PE-HD).




**a** **Suggest** and **explain** which

**i** of the polymers is the most suitable as a barrier sprayed inside food packaging

**ii** polymer might be suitable for dialysis tubing (dialysis is used to treat patients with kidney failure).

**b** Cellulose acetate is a hard, transparent plastic used to make eyeglasses, film and fibre. **Suggest** whether this plastic is also suitable for

**i** packaging carbonated soda (soft) drinks

**ii** recycling.

**c** Low density polyethylene (PE-LD) is used to make squeezable bottles and bags for frozen food and dry cleaning. **Suggest** how its permeability properties are likely to compare with PE-HD, shown on the graph.

# Reflection

This chapter introduced you to the diversity of organic compounds, made possible as a result of the catenation of carbon atoms, their ability to bond with other carbon atoms. The homologous series that result, chemically related organic molecules that share common chemical properties, often have their reactivity conferred by functional groups. You demonstrated this experimentally when you explored the formation of esters. Many of these raw materials for organic chemistry come from fossil fuels, particularly crude oil that is refined by fractional distillation. Plastics, an important group of synthetic polymers, are useful materials but harm the environment. You have only just begun this journey into organic chemistry. What else do you want to explore?

| **Use this table to reflect on your own learning in this chapter.** | | | | | |
|---|---|---|---|---|---|
| Questions we asked | Answers we found | Any further questions now? | | | |
| **Factual:** What is an organic substance? What is special about the way carbon atoms form molecules? | | | | | |
| **Conceptual:** How do functional groups affect the chemical properties of a molecule? | | | | | |
| **Debatable:** To what extent can we live without organic materials (apart from food)? Could other elements form the building-blocks of life? | | | | | |
| Approaches to learning you used in this chapter: | Description – what new skills did you learn? | How well did you master the skills? | | | |
| | | Novice | Learner | Practitioner | Expert |
| **Communication skills** | | | | | |
| **Organization skills** | | | | | |
| **Reflection skills** | | | | | |
| **Critical-thinking skills** | | | | | |
| **Creative-thinking skills** | | | | | |
| **Transfer skills** | | | | | |
| **Learner profile attribute(s)** | Reflect on the importance of being knowledgeable for your learning in this chapter. | | | | |
| **Knowledgeable** | | | | | |

# Glossary

**acids** All acids form hydrogen ions ($H^+$) in solution. An acid dissolves in water to give a pH value less than 7. When an acid and a base react, a salt and water are formed

**actinides** A group of 15 metallic, radioactive chemical elements with atomic numbers from 89 (actinium) to 103 (lawrencium); named from the first metal in the series

**activated complex (transition state)** A temporary high energy state during a collision between reactants, before the products can be formed

**activation energy** The minimum amount of total kinetic energy a colliding pair of ions, atoms or molecules require for a chemical reaction to occur

**activity series** An order of reactivity, giving the most reactive metal first, based on results from a range of experiments involving metals reacting with oxygen, water and steam, dilute aqueous acids and metal salt solutions

**addition polymerization** A type of polymerization involving monomers bonding together, via rearrangement of bonds without the loss of any atom or molecule, to form a single molecule

**adhesion** The attraction of dissimilar particles to each other

**alcohols** A homologous series of organic compounds containing the functional group –OH with the general formula $C_nH_{2n+1}OH$

**alkali** A water-soluble base

**alkali metal** Elements in group 1 of the periodic table: lithium, sodium, potassium, rubidium, caesium and francium. They are very reactive, electropositive, monovalent metals forming strongly alkaline hydroxides

**alkaline earth metals** Elements in group 2 of the periodic table: beryllium, magnesium, calcium, strontium, barium and radium. They are reactive, electropositive, divalent metals, and form basic oxides which react with water to form comparatively insoluble hydroxides. $Ba(OH)_2$ is a strong alkali and very soluble

**alkanes** A homologous series of hydrocarbons with the general formula $C_nH_{2n+2}$; they have only single bonds between carbon atoms in their structures

**alkenes** Unsaturated hydrocarbons with a carbon–carbon double bond and with the general formula $C_nH_{2n}$

**alkyl group** A piece of an organic molecule with the general formula $C_nH_{2n+1}$. An example is a methyl ($-CH_3$) group

**alkynes** Unsaturated hydrocarbons with a carbon–carbon triple bond and with the general formula $C_nH_{2n-2}$

**allotrope** Different structural bonding arrangements of an element; e.g. diamond, graphite and fullerene-60 are examples of allotropes of carbon, and oxygen gas ($O_2$) and ozone ($O_3$) are allotropes of oxygen

**alpha (α) decay** The spontaneous emission of an alpha particle from a nucleus

**alpha (α) particle** A particle of ionizing radiation consisting of 2 protons and 2 neutrons (an energetic helium-4 nucleus)

**amide** An organic compound with a linkage between two alkyl groups of the form $R_1–CO–NR_2$

**amorphous** A solid which does not have a crystalline structure. While there may be local ordering of the particles, no long-range lattice is present

**amphiprotic** A substance that can donate or accept a proton ($H^+$)

**amphoteric** A substance which reacts with both acids and bases, e.g. $Al_2O_3$

**anion** A negatively charged ion which moves to the anode during electrolysis

**anode** An electrode where oxidation occurs (electrons are lost) from a substance during an electrochemical process

**antacid** A medicine which neutralizes excess hydrochloric acid in gastric juice in the stomach. Antacids are weak bases and are metal oxides, metal carbonates or metal hydroxides

**anthropogenic** Phenomenon created by human activity

**aqueous** A solution in which the solvent is water

**aromatic** An organic molecule that incorporates a benzene ring (an unsaturated 6-carbon ring) in its structure

**atmosphere** The layers of gases held by a planet's gravitational force

**atom** Smallest particle of matter comprising an element

**atomic number** The number of an element in the periodic table, corresponding to its proton number ($Z$)

**Avogadro's constant** Avogadro's constant ($6.02 \times 10^{23}$ $mol^{-1}$) is the number of particles (atoms, ions, molecules or electrons) in one mole of a particular substance

**background radiation** Level of naturally occurring ionizing radiation, originating from radioactive materials in rocks, soil and building materials as well as cosmic radiation from outer space

**balanced equation** A chemical reaction represented by the formulas of reactants and products, showing the same number of each type of atom before and after the reaction

**base (alkali)** All bases form hydroxide ions ($OH^-$) in solution. A base dissolves in water to give a pH value more than 7. When an acid and a base react, a salt and water are formed

**beta (β) decay** The spontaneous emission of a beta particle from a nucleus. During beta emission, a neutron decays into a proton (increasing the atomic number by one) and an electron

**beta (β) particles** Fast-moving electrons emitted by radioactive nuclei and formed when a neutron inside a nucleus changes to form a proton and a fast-moving electron

**biosphere** The biological component of Earth systems (living and dead)

**blast furnace** A furnace allowing continuous production of iron from iron oxide using carbon monoxide as the active reducing agent

**Bohr model** A model of the atom that explains emission and absorption of radiation as involving transitions of electrons between energy levels

**bond energy** The amount of energy (in kilojoules) required to break one mole of a particular covalent bond in molecules in the gaseous state into gaseous atoms

**Brønsted–Lowry theory** Describes an acid as a proton or hydrogen ion donor, and a base as a proton or hydrogen ion acceptor

**Brownian motion** The movement of tiny particles of a solid, suspended in a liquid or gas, when observed under a microscope. The overall random motion is caused by bombardment of the particles by molecules and atoms present in the surrounding medium

**carbon cycle** Processes including photosynthesis, combustion and respiration (including that in decomposition), by which carbon in its compounds transfers between the atmosphere, oceans, and living organisms

**carboxylic acid** A homologous series of organic compounds with the general formula $C_nH_{2n}O_2$

**catalyst** A substance which, when present in small amounts, increases the rate of a chemical reaction but remains chemically unchanged at the end of the reaction. The function of a catalyst is to provide a new reaction pathway with a lower activation energy. A catalyst has no effect on the enthalpy change of a reaction

**catalytic converter** A honeycomb structure coated with rare earth metal catalysts, used in a car's exhaust to reduce air pollution

**catenation** The linkage of atoms of the same element (such as carbon) into longer chains or rings

**cathode** The electrode where reduction occurs (a substance gains electrons) during an electrochemical process

**cation** A positively charged ion which moves to the cathode during electrolysis

**causal link** When one variable directly causes a change in another

**changes of state** The interconversion of a substance between the solid, liquid and gaseous states

**chemical bonds** The attractive electrostatic forces that hold atoms together in elements, or hold atoms or ions together in compounds

**chemical energy** Energy is required to break the chemical bonds and intermolecular forces operating between particles, and released when new bonds form

**chemical reaction** A transformation of matter caused by the breaking and formation of bonds to create new substances

**chromatography** A separation technique for complex mixtures that relies on the differential movement of components in the mixture (liquid or gas) through a stationary medium

**closed system** A system from which the products of reactions taking place within the system cannot escape. A closed system can, however, exchange energy with its surroundings

**cohesion** The attraction of similar particles to each other

**coke** The solid material formed when volatile chemicals in coal have been removed by heating. It contains a high percentage of carbon and is used as a reducing agent and fuel

**collision theory** A simple model to account for changes in the rate of reaction with temperature and concentration. It regards atoms, ions or molecules to be hard spheres that react with each other when they collide with sufficient kinetic energy

**combustion** The burning of a substance in air or oxygen to produce oxides

**complete combustion** The burning or combustion of carbon or a carbon-containing fuel in excess oxygen to produce carbon dioxide and water

**(to) completion** The reaction goes completely to the right of the equation; the reactants are all used up

**compound** A pure substance composed of two or more chemical elements which are chemically bonded together. The proportions of the different elements in a compound are fixed by mass

**compound ion** An ion which consists of two or more different atoms bonded together covalently and carrying an overall negative or positive charge

**condensation polymerization** A type of polymerization which involves the elimination of a small molecule such as water or HCl

**condensing** The change of state when a gas is cooled to form a liquid (at the same temperature). Heat energy is released during this process

**conductors** Materials and substances that readily allow the transfer of heat and electricity. The presence of free electrons makes a substance a good conductor

**contaminant** Any substance found in the environment as a result of human activity (it may be harmless or harmful)

**core electrons** The electrons in an atom that are not valence electrons and therefore do not participate in bonding

**correlation** A mathematical connection or relationship between two variables, or the process of establishing such a relationship

**corrosion** A reaction with oxygen, water or acid that results in the disintegration of the material under attack

**corrosive** A reactive substance that damages living tissue and other materials

**counter-current flow** Transfer or exchange system involving two fluids, usually liquids or solutions, flowing in opposite directions

**covalent bond** A chemical bond formed by the sharing of one or more pairs of electrons, usually between two non-metallic atoms

**covalent molecular substance** A substance in which atoms of individual molecules are joined by strong covalent bonds, and the separate molecules are attracted by intermolecular forces which are weaker and give such substances comparatively low melting points and boiling points

**covalent network solid** A chemical compound (or element) in which the atoms are bonded by covalent bonds in a continuous network extending throughout the material

**cracking** The decomposition of long-chain alkanes into smaller alkenes and alkanes

**crude oil** A liquid formed predominantly from sea organisms and plants that died millions of years ago. It contains a mixture of hydrocarbons and is the raw material for many fuels and plastics

**crystalline** A solid form of a substance consisting of crystals

**daughter (nucleus)** The nucleus that was formed during a radioactive decay process

**decay** A change that leads to a degeneration to a substance of lower mass or energy, such as in a radioactive process

**decay constant** A value related to the probability that the radioactive nucleus will decay

**decay curve** A graph of the number of undecayed nuclei against time. The decay curve graph may also be drawn to show the count rate (number of decays per second) against time

**decay product** The daughter nucleus or other particles produced in a decay process

**decay series (also called decay chain or decay sequence)** A series of radioactive decay processes in which the decay of one radioactive element creates a new element that may itself be radioactive, and continuing until the sequence ends with stable, non-radioactive atoms

**decomposition reaction** The separation of a chemical compound into elements or simpler compounds. It is sometimes defined as the exact opposite of a chemical synthesis. This can occur via heat or electricity

**delocalized electrons** Electrons that are not associated with one particular atom

**density** Mass per unit volume

**deuterium** The isotope of hydrogen ($^{2}_{1}H$) having a single neutron in the nucleus

**dialysate** The fluid and solutes in a dialysis process that do not pass through the semi-permeable membrane, and are discarded

**dialysis** Transfer of solute (dissolved solids) across a semi-permeable membrane

**diatomic** Molecules are composed of two atoms

**dichotomous choices** A tool that allows the user to determine the identity of items by making a series of either/or choices

**diffusion** The net movement of a substance (e.g. atoms, ions or molecules) from a region of high concentration to a region of low concentration. This is also referred to as the movement of a substance down a concentration gradient

**dilution** The process of adding more solvent to a solution to lower the concentration. (A serial dilution dilutes a volume by a factor greater than 1, resulting in a series of concentrations descending in geometric progression.)

**dipole** A pair of separated equal and opposite electrical charges located on a pair of atoms within a molecule

**dispersion forces** The weakest kind of intermolecular attraction, also called London forces or weak van der Waals' forces, caused by the random motion of electrons within atoms or molecules leading to the formation of temporary dipoles

**(single) displacement reaction (of metals)** A redox reaction in which a more reactive metal displaces a less reactive metal from a solution of its ions or salt, often in aqueous solution or during a reaction involving powdered solids

**distillate** Product of distillation formed by condensing vapours to form liquids

**dot-and-cross diagram** A diagram illustrating the bonding in a molecule or ion pair using dots and crosses to represent outer electrons

**double bond** A covalent bond in which two pairs of bonding electrons are shared by a pair of adjacent atoms

**double displacement** A chemical reaction in which two ionic compounds react in solution, and the positive ions (cations) and the negative ions (anions) of the two reactants switch places, forming two new ionic compounds

**ductile** A ductile material can be drawn out into wire

**dynamic equilibrium** The position reached by a reversible reaction in a closed system when the rate of the forward reaction is the same as the rate of the reverse reaction

**electrolysis** The chemical decomposition of an ionic substance, known as the electrolyte, by an electric current

**electron** A subatomic particle with a negative charge. Electrons are located in shells, or energy levels, outside the nucleus

**electron arrangement** The electron arrangement shows how many electrons there are in an atom or ion and their distribution in shells

**electron shells** The regions around the nucleus where the electrons are located. Each shell can hold up to a maximum number of electrons

**electronegativity** A measure of the ability of an atom in a molecule to attract a pair of electrons (in a covalent bond)

**element** A pure chemical substance that consists of one kind of atom or its isotopes

**emission spectrum** The range of wavelengths or frequencies emitted by an atom in the gas phase stimulated by either heat or voltage. Emission spectra are unique to each element.

**empirical formula** The formula with the lowest whole number ratio of atoms in a compound

**emulsifier** A substance that changes the surface tension between colloidal droplets, keeping them in suspension. Emulsifier molecules combine water-soluble and oil-soluble properties

**emulsion** A stable dispersion of one liquid in a second, immiscible liquid

**enantiomer** A type of stereoisomer in which molecules are non-superimposable mirror images of each other

**end point** The point where the indicator changes colour suddenly during a chemical reaction, e.g. in an acid–base titration

**endothermic** a chemical reaction in which the system (chemicals) absorbs energy from its surroundings in the form of heat

**energy level diagram** A diagram that shows changes in the potential energy (or enthalpy) of a chemical reaction or physical change during the course of the process

**energy levels** The allowed energies of electrons in an atom which correspond to the shells. Electrons fill the energy levels, or shells, starting with the one closest to the nucleus

**enthalpy (*H*)** A quantity equivalent to the total heat content of a system. Its change is equal to the heat added to or leaving the system at constant pressure

**enthalpy change ($\Delta H$)** The change in potential energy as a result of changes in the bonds between particles during a chemical or physical reaction

**enthalpy of combustion** The enthalpy (energy) change when one mole of a compound is completely burnt in oxygen gas at 298 K and 100 kPa pressure

**enthalpy of fusion ($\Delta H_{fusion}$)** The enthalpy (energy) change involved when a solid melts to liquid at the same temperature. The temperature at which this occurs is the melting point of the substance

**enthalpy of neutralization** The enthalpy (energy) change when one equivalent of acid reacts with one equivalent of alkali to form one mole of water

**enthalpy of vaporization ($\Delta H_{vaporisation}$)** The enthalpy (energy) change involved when liquid evaporates to gas at a given pressure. The temperature at which this occurs is the boiling point of the substance

**entropy (*S*)** A measure of how energy is dispersed among (or within) particles. A measure of disorder or randomness

**entropy change ($\Delta S$)** The change in entropy associated with a physical or chemical change

**enzyme** Protein produced by a living cells which acts as a catalyst for a reaction

**ester** An organic molecule that results from reaction between a carboxylic acid and an alcohol to form an ester and water. The reaction is reversible and catalysed by hydrogen ions from concentrated sulfuric acid

**evaporating** A process that occurs at the surface of a liquid and involves a liquid changing into a gas at a temperature below its boiling point

**excess** A reactant is present in excess when after the reaction is complete, some of that reactant remains unreacted. The reactant is in excess when it is present in a molar ratio that is greater than the value in the balanced equation

**exothermic** A chemical process in which thermal energy is released

**fermentation** The conversion of sugars to ethanol and carbon dioxide by yeast under anaerobic conditions

**filtration** The act or process of filtering

**fission (nuclear)** Process by which nuclei are split into smaller nuclei (by neutrons), releasing energy

**flame test** A small sample of a metal salt is introduced into a hot Bunsen flame. The flame vaporizes part of the sample. This excites some of the atoms which emit light at wavelengths characteristic of the metal atom

**flash point** The lowest temperature at which there is enough vapour (gas) for the fuel to ignite

**flow** The rate of inputs or outputs in a system

**fractional distillation** A method of distillation using a fractionating column; it is used to separate liquids with different boiling points

**frequency** The number of waves produced every second by the source. It is measured in units of hertz (Hz) or $s^{-1}$ (per second). It is given the symbol *f* or $\nu$

**fuel (chemical)** A substance, e.g. methane, that can be burnt (combined with oxygen) to produce heat energy by combustion

**fuel cell** A device which converts chemical energy into electrical energy. A gaseous fuel, usually hydrogen or a hydrocarbon, and oxygen are passed over porous electrodes where the redox process occurs and an electric current is produced

**functional group** An atom or group of atoms that gives the chemical properties of a homologous series of organic compounds

**fuse (chemistry)** 1. To melt. 2. Join or blend two materials by melting together

**fusion (nuclear)** Process by which smaller nuclei are forcibly combined to produce larger nuclei, with a release of binding energy

**galvanizing** Placing a thin layer of zinc on iron or steel to protect the surface from corrosion

**gamma ($\gamma$) decay** Gamma decay occurs when a nuclide is produced in an excited state, gamma emission occurring by transition to a lower energy state. It can occur together with alpha decay and beta decay

**gamma ($\gamma$) radiation** Electromagnetic radiation of very short wavelength which is released as a result of energy changes within the nuclei of atoms

**gas** A fluid state of matter which expands freely to fill any space available, irrespective of its volume. Gas particles move quickly and are separated by wide distances

**Geiger counter** Device that detects ionizing radiations through the change of conductivity of a gas caused by ionization

**gel** A colloid in which the dispersed phase has combined with the dispersion medium to produce a semi-solid, e.g. jelly

**geometric isomerism** Molecules that differ only in the geometry (spatial positions) of their groups, as a result of having bonds that do not allow the molecule to rotate, such as carbon–carbon double bonds

**Gibbs free energy ($\Delta G$)** The energy available to do work (at constant pressure)

**global warming** The increase in the average temperature of the Earth's atmosphere since the Industrial Revolution due to rising levels of greenhouse gases

**greenhouse effect** Process of atmospheric absorption of infrared radiation then re-emission towards the ground, leading to the trapping of heat energy in the atmosphere

**greenhouse gases** Gases that contribute to the greenhouse effect and global warming by absorbing infrared energy emitted or reflected from the surface of the Earth

**group (also known as a family)** A column of elements in the periodic table. Elements within a group share similar chemistry

**Haber process** The industrial manufacture of ammonia from nitrogen and hydrogen

**half-cell** An electrode in contact with a solution of ions where the oxidation or reduction half-reaction occurs. Two half-cells can be connected via a salt bridge to make an electrochemical cell

**half-equation** The two parts of a redox reaction, one describing the oxidation and the other the reduction

**half-life** The time taken for half of the atoms (or half of the mass) in a substance to decay

**halide** An ion or ionic compound of the halogens, group 17

**halogenated hydrocarbon (haloalkanes, halogenoalkanes)** A hydrocarbon in which one or more hydrogen atom is replaced by atoms of the elements bromine, chlorine, fluorine or iodine (called halogens)

**halogens** Elements in group 17 of the periodic table: fluorine, chlorine, bromine, iodine and astatine. They are reactive non-metallic elements which form acidic compounds with hydrogen from which simple salts can be made

**heat** The mode of energy transfer between two objects due to a temperature difference between them

**heavy metal** Toxic metals with a relatively high atomic mass. Often act as enzyme inhibitors

**hertz** A unit of frequency equal to one cycle per second

**heterogeneous** A sample of matter consisting of more than one pure substance and more than one phase

**homogeneous** A sample of matter consisting of more than one pure substance with properties that do not vary within the sample

**homologous series** A group of organic compounds that follow a regular structural pattern and have the same general molecular formula, differing only by the addition of $-CH_2-$ groups

**hydrate** Typically, salts containing a fixed amount of water within the crystal. This water is called water of crystallization and can be removed by gentle heating

**hydrocarbons** Compounds that are composed of only carbon and hydrogen

**hydrogen bond** A relatively strong intermolecular force in which a hydrogen atom which is covalently bonded to a very small and electronegative atom (nitrogen, oxygen or fluorine) is also bonded more weakly to an unshared electron pair of an electronegative atom in the same molecule, or one nearby

**hydrolysis** A chemical reaction between a substance and water

**hydronium** A compound ion with the formula $H_3O^+$ that is present in aqueous solutions and acids

**hydrosphere** The Earth system consisting of liquid water, and therefore described by oceans, seas, lakes, ponds, rivers and streams

**ignition temperature** The lowest temperature at which the fuel will spontaneously burn

**immiscible** Liquids are said to be immiscible when they do not mix, for example oil and water

**incomplete combustion** Incomplete combustion of a hydrocarbon occurs when there is insufficient oxygen, resulting in the formation of carbon monoxide and/or soot (unburnt carbon)

**indicator (acid–base)** A substance that changes colour at a significant point in a chemical process. An acid–base indicator is a specific example of this

**inert** Chemically unreactive

**inorganic chemistry** The study of the synthesis, reactions, structures and properties of compounds that do not include organic carbon. Carbonates are usually included

**insoluble** Incapable of being dissolved; incapable of forming a solution, especially in water

**intermolecular (forces)** Attractive forces operating between the molecules present in a solid or liquid

**intramolecular (forces)** Any force that holds together the atoms making up a molecule

**ion** An atom or group of atoms that has gained (anion, having a negative charge) or lost (cation, having a positive charge) electrons

**ionic bond** A bond formed when electron(s) are transferred from a metal atom to one or more non-metal atoms. It is the result of electrostatic forces of attraction between oppositely charged ions

**ionic equation** The simplified equation for a reaction involving ionic substances. Only those ions that actually participate in the reaction are included in the ionic equation; spectator ions are not included

**ionic solid** A compound composed of positive and negative ions, arranged into a lattice

**isolated closed system** A system that does not allow the transfer of heat or matter between the closed system and its surroundings

**isomers** Compounds with the same molecular formula but different molecular structures

**isotopes** Atoms with the same proton number but different numbers of neutrons, having the same chemical properties

**iterative** Involving repetition, particularly relating to procedures

**kinetic energy (of particles in a gas)** The energy due to the movement of gas particles; it depends on the mass of the gas particle and the square of its speed

**kinetic molecular theory** The theory that explains the physical properties of matter and changes of state in terms of the movement and arrangement of its constituent particles

**kinetic theory** Bernoulli's explanation that gas pressure was the result of millions of tiny collisions between ball-like particles

**lanthanides (rare earth elements)** Metallic elements with atomic numbers 57 (lanthanum) to 71 (lutetium)

**lattice** A regular arrangement of particles in a solid, whether these are atoms, ions or molecules

**law of conservation of mass** Mass is not lost or gained during a chemical reaction – the total mass of the reactants equals the total mass of the products. Atoms cannot be created or destroyed

**Le Chatelier's principle** An observation that systems at equilibrium respond to change by shifting in such a way to counteract that change

**limiting reactant** The reactant that is completely used up in a reaction, and thus determines when the reaction stops

**liquid** A fluid phase of matter which is nearly incompressible because the particles are closely packed. Liquids therefore have a defined volume

**lithosphere** Earth's crust and upper mantle

**London dispersion forces** The force of attraction of protons in the nucleus of an atom for electrons in a neighbouring atom. Also known as dispersion force or weak van der Waals' force

**lone pairs (non-bonding valence electrons)** Paired electrons in the valence orbits that are not covalently bonded

**lustre** The way light interacts with the surface of a metal, crystal, rock or mineral, resulting in 'shine'

**magic number** Any of the numbers, 2, 8, 20, 28, 50, 82 or 126, that represent the number of neutrons or protons in strongly bound and exceptionally stable atomic nuclei

**magnetic** Having the properties of a magnet; i.e. of attracting iron or steel. Magnetic materials include iron, nickel, cobalt, some alloys of rare earth metals, and some naturally occurring minerals such as lodestone (mixed oxides of iron)

**malleable** The ability of metals to be beaten into thin sheets without breaking or cracking

**mass number** The sum of the numbers of protons and neutrons in the nucleus of an atom or ion

**mass spectrometer** An instrument which can measure the masses and relative abundances of atoms and molecules. It makes use of the magnetic force on a moving charged particle

**matter** A substance that takes up space and has mass

**Maxwell–Boltzmann distribution curve** A graph showing the distribution of kinetic energies among the molecules of a gas in thermal equilibrium

**meniscus** The curve in the upper surface of a liquid close to the surface of the container, caused by surface tension and adhesion

**metallic bond** The attraction of delocalized electrons for positively charged metal ions in metals and alloys of metals

**metalloids (semi-metals)** Elements with properties of both metals and non-metals, or semi-conductors (e.g. arsenic, antimony or tin)

**metals** A type of matter that is usually solid at room temperature; typical properties are lustre, malleability, ductility, good conductivity and the ability to form positive ions

**mineral** A naturally occurring solid that consists entirely of a single element or compound

**molar mass (also referred to as formula mass)** The mass in grams of one mole of molecules or the formula mass of an ionic compound. It is numerically equal to the relative molecular or atomic mass of a substance, but has units of $g\,mol^{-1}$

**molar volume (of gas)** One mole of a gas occupies 22.7 cubic decimetres (litres) at 0 °C (273.15 K) and 1 bar pressure or $10^5$ Pa (100 kPa)

**molarity** The number of moles of solute per cubic decimetre of solution

**mole** The measure of the amount of a substance. One mole of a substance has a mass equal to its formula mass in grams. One mole of a substance contains $6.02 \times 10^{23}$ (Avogadro's constant) of atoms, ions or molecules

**molecular formula** A chemical formula which shows the actual number of atoms of each element present in a molecule of a covalent compound

**molecular gastronomy** A food science that seeks to investigate the physical and chemical transformations of ingredients that occur in cooking

**monatomic** An element consisting of single atoms

**neutral (acid–base)** When neither hydrogen nor hydroxide ions in a solution are present in excess

**neutral (electrical)** Having no overall electric charge. Atoms, molecules and neutrons are electrically neutral

**neutralization** This happens when adding an acid to a base until neither is in excess. It involves a reaction between hydrogen ions and hydroxide ions to form water molecules

**neutron** A neutral particle found in the nucleus of all atoms (except that of the most abundant isotope of hydrogen). It has approximately the same mass as the proton

**nitrogen cycle** A description of how nitrogen circulates through Earth's systems

**noble gases** Elements in group 18 of the periodic table: helium, neon, argon, krypton, xenon and radon. They are all monatomic gases and almost totally unreactive (though compounds of xenon, krypton, radon and argon are known)

**non-metals** A group of chemical elements that are typically poor conductors of heat and electricity. They tend to form negative ions and covalent compounds with each other and are found on the right hand side of the Periodic Table

**non-redox** A reaction that does not involve a change of oxidation state

**non-renewable (resource)** Matter that does not renew itself in a natural timeframe for sustainable economic extraction. Examples include metals and fossil fuels

**nucleon** A particle in a nucleus, either a neutron or proton

**nucleon number (*A*)** The total number of nucleons (protons and neutrons) in a nucleus

**nuclide** The general term for a unique nucleus

**octet** A set of eight electrons in the valence shell of an atom or ion

**octet rule** Atoms (for elements atomic number 6–20) fill their valence or outer electron shell with eight electrons (an octet) when they form compounds

**orbit** In the Rutherford–Bohr model of an atom, this term applied to the circular path of an electron as it travels round the nucleus of an atom

**ore** An impure mineral from which a metal can be profitably mined or extracted

**organic chemistry** The study of carbon-containing compounds, with the exception of the allotropes of elemental carbon and its oxides

**osmosis** Diffusion of water molecules through a semi-permeable membrane from a solution of high water potential (low solute concentration) to low water potential (high solute concentration)

**oxidation** Reactions that involve the gain of oxygen, the loss of hydrogen, the loss of electrons or an increase in oxidation number. It is brought about by oxidizing agents

**oxidation number (or state)** The number of electrons over which an atom has 'gained' or 'lost control' as a result of its relative electronegativity value. It indicates whether an element has been reduced or oxidized during a redox reaction

**oxidizing agent (also known as an oxidant)** A reactant that causes oxidation; it accepts electrons from the reactant or one of the reactants. In the reaction the oxidizing agent itself is reduced

**oxygen catastrophe or Great Oxygenation Event (GOE)** The appearance of oxygen gas in Earth's atmosphere, as a result of photosynthesis, and the consequences on the ecosystem

**ozone** A gaseous allotrope of oxygen, a molecule with three oxygen atoms ($O_3$)

**ozone depletion** The production of a region of lower concentration (a 'hole') in the ozone layer by the action of chlorine atoms released from chlorofluorocarbons (CFCs)

**ozone layer** A layer containing ozone ($O_3$) in the stratosphere (between 15 and 30 kilometres) which prevents harmful ultraviolet radiation from reaching the Earth's surface. The concentration is only a few ppm

**parallax error** A displacement or difference in the apparent position of an object (such as a pointer on a dial, or the level of a liquid) viewed along two different lines of sight

**patina** A film on the surface of bronze or similar metals, produced by oxidation over a long period

**period** A row in the periodic table. Across a period from left to right, the atoms of all the elements have the same number of electron shells, but an increasing number of electrons in their outer shell

**periodic table** A table of the chemical elements arranged in order of increasing atomic number to show patterns in the chemical and physical behaviour of chemical elements because of related electron configurations

**pH** A scale that measures the acidity or alkalinity of a solution, related to the concentration of hydrogen (hydronium) ions in solution. The pH number is related to the molarity of hydrogen ions

**phase** A region of space throughout which all physical properties of a material are essentially uniform. Examples include miscible states of matter and various homogeneous, miscible mixtures, including solutions

**photolysis** Chemical decomposition of a molecule, usually caused by ultraviolet radiation

**Planck's constant (*h*)** A constant that, when multiplied by the frequency of radiation, gives the quantity of energy contained in one quantum. $h = 6.63 \times 10^{-34}$ J s

**polar** Having a dipole, e.g. a *polar bond* between atoms caused by a difference of electronegativity; the resultant may be a *polar molecule*

**polarized light** Light in which all the vibrations occur in a single plane

**pollutant** Any substance that produces a harmful effect on the environment

**polyatomic ions (compound ions)** Ions which consist of two or more different atoms bonded together covalently and carrying an overall negative or positive charge

**polymer** A compound containing very large molecules composed of repeating units called monomers

**precipitate** An insoluble substance formed by a chemical reaction in solution. There is an argument that precipitation represents a phase change from aqueous to solid, and is hence a physical process only

**precision** Refers to the closeness of two or more measurements to each other. Precision is independent of accuracy and level of sensitivity

**product** A substance produced during a chemical reaction

**protium** A hydrogen isotope with no neutrons: $^{1}_{1}H$

**proton** A positively charged sub-atomic particle located in the nucleus of an atom

**proton number (*Z*)** Number of protons in a nucleus

**quantitative** The measurable quantity/amount of something rather than its quality/effect

**quantum** A discrete quantity of energy proportional in magnitude to the frequency of the radiation it represents

**radioactive** Referring to any substance that is capable of radioactive decay

**react** To interact and undergo a chemical or physical change

**reactant** A chemical that is used up during a chemical reaction

**reactivity** A comparison of how quickly an element reacts with another substance compared to another element of the group in the same reaction

**redox reaction** A reaction involving reduction and oxidation (and which results in one or more electrons being transferred)

**reducing agent** A chemical substance that brings about reduction; it donates electrons to one of the reactants. In the reaction the reducing agent itself is oxidized

**reduction** Chemical reactions in which oxygen is lost from a compound, electrons are gained by a compound, a compound gains hydrogen or there is a decrease in oxidation number. It is caused by reducing agents

**refining** The processes which separate, convert and purify chemicals from crude oil, or the removal of impurities from metals

**reliability** Repeatability of a result – extent to which the same result can be achieved through repeated measurement are found on the right hand side of the Periodic Table

**renewable resource** A category of matter that is replenished over time through naturally recurring processes, such as biological growth or through geological cycles

**reversible reaction** A reaction that can go either backwards or forwards depending on the conditions

**$R_f$ (retardation factor, or retention factor)** The distance travelled by the compound divided by the distance travelled by the solvent during chromatography, calculated from the following expression: $R_f$ = *distance moved by the compound* ÷ *distance moved by the solvent*

**rotation** A rolling and spinning motion

**rusting** The corrosion of iron or steel by oxygen and water

**sacrificial metal (sacrificial protection)** A method used to prevent iron from rusting by attaching a more reactive metal, which oxidizes and passes into solution in preference to the iron

**salt** An ionic compound formed by the reaction of an acid with a base, in which the hydrogen ion of the acid has been replaced by a metal ion

**salt bridge** A connection made between two half-cells that allows ions to flow while preventing the two solutions from mixing. It prevents a build-up of charge which would stop the flow of current

**saponification** The process that produces soap, involving the reaction of triglycerides with sodium or potassium hydroxide to produce glycerol and a fatty acid salt, called 'soap'

**saturated** Organic molecules that contain only carbon–carbon single bonds

**saturated vapour pressure** The pressure at which the molecules from an evaporating liquid are at a maximum concentration for the temperature

**scientific notation** A mathematical expression used to represent numbers as a decimal between 1 and 10 multiplied by a power of 10, so that very large and very small numbers can be represented using fewer digits

**semi-conductor** A material with an electrical conductivity that is intermediate between that of an insulator and a conductor

**semi-permeable** Permeable only to certain molecules

**significant figures** The digits that are known with certainty, and the last digit (which is uncertain). The following three examples are all expressed to three significant figures: 432 (all numbers to the left of the decimal point), 40.2 and 0.0402 (all non-zero digits to the right of the decimal point), and $4.32 \times 10^2$

**single bond** A covalent bond formed by the sharing of one pair of electrons

**sink** The destination of a component, such as a gas or a pollutant, in a system

**smelting** To extract metal from its ore by a process involving heating and melting, usually using carbon as a reducing agent

**snowball Earths** Past geological events during which the Earth is thought to have been nearly entirely covered with ice (including glaciers at the equator)

**solid** A state of matter whose particles are vibrating in fixed positions and are not able to move from one location to another. The particles are held in a lattice by chemical bonds or intermolecular forces

**solubility** The amount of solute required to form a saturated solution in a given volume of solvent

**solute** The solid, liquid or gas that has been dissolved to form a solution

**solvent** A liquid that dissolves solids, liquids or gases to form a solution

**source** The origin of a component, such as a gas or contaminant, in a system

**specific heat capacity** The amount of heat energy required to raise the temperature of 1 gram of substance by 1 degree Celsius

**spectator ions** Ions present in solution that do not participate directly in a reaction

**standard electrode potentials** The voltage generated when a half-cell (under standard conditions) is connected to a standard hydrogen electrode by a salt bridge and an external circuit

**standard hydrogen electrode** A reference half-cell used to measure standard electrode potentials. It consists of hydrogen gas (100 kPa) bubbled over a platinum electrode in a 1 M solution of HCl (aq)

**standard temperature and pressure (STP)** Under standard conditions of 0°C (or 273 K) and 100 kPa pressure

**states** Solid, liquid and gas are the three most common states of matter in which all substances can exist, depending on the conditions of temperature and pressure

**stereoisomers** Compounds differing only in the spatial arrangement of their atoms

**steric effect** The contribution of the relative positions or orientation of molecules involved in a collision

**strong acid** An acid that is completely dissociated or ionized when dissolved in water

**strong base** A base that is completely dissociated or ionized when dissolved in water

**structural formula** A structural formula shows the arrangement of atoms in the molecule of a compound

**structural isomers** Molecules with the same molecular formula but different bonding arrangements of the atoms

**substituted** When an atom or group of atoms (the substituent) takes the place of a hydrogen atom on the parent chain of a hydrocarbon

**substitution reaction** A reaction in which an atom or a group of atoms in an organic molecule is replaced by another atom or group of atoms

**successful (effective) collisions** Collision between molecules, ions or atoms resulting in a reaction; one in which the particles collide with the correct alignment and enough kinetic energy to react

**supramolecular chemistry** A branch of chemistry that focuses on the chemical systems made up of molecular subunits or components

**surface chemistry** A branch of chemistry concerned with the processes occurring at interfaces between phases, especially that between liquid or solid and gas

**suspension** A fine dispersion of solid particles in a liquid which slowly settle on standing

**synthesis reaction** A reaction in which a compound is formed from its elements

**taxonomy** A classification system

**theory** In science, a general system of ideas that explains a substantial group of observations in nature and has been confirmed by a very large number of experiments and observations

**thermal decomposition** The chemical decomposition of a substance into simpler substances at high temperatures; it involves the breaking and/or rearrangement of more bonds than thermal dissociation and hence is not so easily reversible

**thermal dissociation** A reversible thermal decomposition, usually involving a simple mechanism in which a single bond is broken and hence the process is reversible

**thermochemical equation** A balanced stoichiometric chemical equation that includes the enthalpy change, $\Delta H$

**titration (acid–base)** A procedure that is used to find out the exact concentration of a particular solution (an acid or an alkali) or to prepare salts formed between the reaction of an acid and alkali

**transition metals/elements** A block of metals from the central region of the periodic table between groups 1 and 13; including scandium, and the actinides and lanthanides ('d-block elements'). They are hard, strong, dense metals that form compounds which are often coloured and able to act as catalysts. They often form more than one stable cation

**translational (motion)** The motion of a body which moves from one point to another

**transuranium elements** All elements beyond uranium on the periodic table. The transuranium elements are all radioactive and are produced by nuclear reactions

**triple bond** A covalent bond in which three pairs of bonding electrons are shared by a pair of atoms

**unsaturated** A molecule containing one or more double or triple (multiple) bonds

**valence electrons** The electrons in the outermost shell of an atom or ion. They are involved in bond formation

**valence shell** The outermost shell of an atom

**valency** The number of atoms of hydrogen with which an atom will combine, or for which it can be substituted

**validity** The extent to which a measurement supports a hypothesis

**van der Waals' forces** The sum of the attractive or repulsive forces between molecules (or between parts of the same molecule) other than those due to covalent bonds, or the electrostatic interaction of ions

**vaporizing** Slow evaporation of a solvent usually from the surface of the liquid phase

**vapour** A substance in the gas state (vapour)

**vapour pressure** The pressure due to its vapour when the liquid and vapour are in dynamic equilibrium at a fixed temperature

**vibration (vibrational motion, vibrational energy)** A movement back and forth, without changing average position

**volatile** A substance in the solid or liquid state which needs very little heat to form a vapour, having a high vapour pressure and low boiling point

**voltaic cell** An arrangement of two electrodes contained in separate half-cells containing an electrolyte, with a salt bridge completing the circuit. A voltaic cell produces an electromotive force (e.m.f.) by the chemical reactions at the electrodes

**water cycle** A description of how water circulates around the Earth

**wavelength** The distance between corresponding points, for example, the distance between two peaks or two troughs, on two successive waves. It is denoted by the Greek letter lambda ($\lambda$)

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# Index


**acids 108–9**
- domestic products 114
- in the periodic table 116
- reaction with metal carbonates 113

**activation energy 230–1**

**addition polymerization 297**

**addition reactions, alkenes 280–1**

**alcohols 282–3**

**alkali metals 52–3**

**alkaline earth metals 54**

**alkalis 114**

**alkanes 277–9**

**alkenes 280–1**

**allotropes 83**

**alloys 52**

**alpha (α) decay 153, 159**

**aromatic compounds 294**

**Arrhenius, Svante 108**

**atmosphere 207**
- carbon dioxide sources and sinks 208–9
- changes in composition 203
- contribution of living organisms 205
- demonstration of water vapour in 206
- formation of 202, 204
- fractional distillation of liquid air 204–5
- pollutants 212–13, 233, 234

**atomic radius 174**

**atomic structure**
- discovery of 172
- electron arrangements 174–5

**atoms 49**
- discovery of subatomic particles 63
- discovery of the nucleus 161

**Avogadro's constant 133**

**bases 108–9, 116**

**batik-style dying 97**

**Bernoulli, Daniel 5**

**beta (β) decay 153, 159**

**boiling 124**

**bond energies 243**

**bonding**
- relationship to properties 74–6
- trends across the periodic table 77–80

**Brønsted, Johannes 108**

**Brownian motion 128–9**

**calorimeters 238, 244**

**carbon 277**
- allotropes of 83

**carbon cycle 208–9**

**carbon footprints 210**

**carboxylic acids 284**

**catalysts 255–8, 262**

**CFCs (chlorofluorocarbons) 219, 220**

**change, chemical and physical 18**

**chemical symbols 60**

**chromatography 42–3, 45**

**colloidal systems 30–1**

**combustion 227–8, 238**

**combustion products 229**

**communication of scientific ideas 20, 131**

**compounds 27**

**concentration, effect on reaction rates 260–1**

**concept maps 28**

**condensation polymerization 296–7**

**corrosion 187–91**

**cosmetic products 33**

**covalent substances 79**

**cracking 293–4**

**crude oil 292–4**

**Dalton, John 6**

**Daniell cell 240–3**

**density 10**

**dialysis 39**

**diffusion 124, 129**

**dilutions, serial 112**

**dipole–dipole forces 83–5**

**dispersion forces 82–3**

**displacement reactions 100, 185, 239**

**distillation 40**

**dot-and-cross diagrams 177**

**dynamic equilibrium 266–7**
- and Earth systems 270
- and the Haber process 268–9

**electrolysis 54, 59**
- decomposition of water 136–7
- metal extraction 194

**electron arrangements 174–5**
- dot-and-cross diagrams 177
- Lewis dot notation 179–81

**electronegativity 82, 175**

**electrons 63**

**elements 27**
- discovery of 63
- groups of 50
- names of 60–1
- origin of 162–3

**emission spectra 53**
**emulsions 31, 32, 33–4**
**enantiomers 289–90**
**endothermic reactions 140–1**
**energy consumption 234, 249**
**energy level diagrams 231, 237, 246**
**enthalpy 140–1, 231**
of fusion and vaporization 246–7
of neutralization 245
**enthalpy changes 236–9**
calculation from bond energy 243–4
calculation from experimental data 244
**entropy 140–1**
**enzymes 255–6**
**equations 100–1**
balancing them 103–5
**equilibrium *see* dynamic equilibrium**
**esters 287–8**
**estimation 135**
**evaporation 38**
**exothermic reactions 140–1**
**explosives 248**
**fertilizers 270**
**filtration 38**
**fire triangle 231**
**flame tests 170–1**
**flash points 228–9**
**forces**
cohesive and adhesive 3–4
intermolecular 82–5
**formulas of compounds 89**
**fractional distillation of crude oil 292–3**
**Franklin, Benjamin 12**
**'fruit batteries' 242**
**fuel cells 235**
**fuels 232–3**
**functional groups 282, 285–6**
**fusion reactions 162–3**
**gamma (γ) decay 153, 159**
**gas pressure 134**
**Geiger counters 155–6**
**Gibbs free energy 242–3, 246**
**glass 25–6**
**global warming 208, 209–10**
**green chemistry 220**
**greenhouse effect 207–8**
**greenhouse gases 210**
**Haber process 217, 268–9**
**half-lives 157, 158**
**halogens 55**
**hand warmers 248–9**
**heavy metal water pollution 106**
**homologous series 277**
*see also* alcohols; alkanes; alkenes; carboxylic acids
**hydrogen bonds 84–5**
**hypothesizing 8**
**indicators 110–11**
**inquiry cycles 16**
**intermolecular forces 82–5**
**ionic bonding 78, 82**
**ionic compounds 91**
solubility 100, 102, 114
**ionization energies 175, 176**
**ions 49**
**isomers 289–90**
**isotopes 147–50, 154**
stability of 151–2
uses of 155, 160
**isotope signatures 152**
**kinetic theory 126–7, 259–62**
**Le Chatelier's principle 266–9**
**Lewis dot notation 179–81**
**Lowry, Thomas 108**
**Mars 211**
**mass spectrometers 149–50**
**matter**
cultural uses of 29
flowchart of 26–7
historical ideas about 5–6
**Maxwell–Boltzmann distribution curve 126–7**
**measurement 135, 136–9**
**Mendeleev, Dmitri 6, 62, 65**
**meniscus 3–4**
**metallic bonding 77–8**
**metals 51–2**
corrosion 187–91
extraction of 192–4
reactivity series 184–6, 188
recycling 195
*see also* alkali metals; alkaline earth metals; rare earth elements
**Milley–Urey experiment 202**
**mixtures 4, 16, 27**
colloidal systems 30–1
cultural uses of 29
emulsions 33–4
phases 30
separation of 37–8, 40–1, 44–5
**modelling 157–9, 161, 178**
**molecular gastronomy 36**
**moles 133–4**
**naming elements 60–1**
**naming inorganic compounds 87–8**
**naming organic compounds 285–7**
**neutralization reactions 113, 138–9, 245**
**neutrons 63**

**Newton, Isaac 5**

**nitrogen cycle 216–17**

**noble gases 58**

**octet rule 174, 176**

**organic compounds 276**
- aromatic 294
- crude oil 292–4
- esters 287–8
- functional groups 282
- homologous series 277
- isomers 289–90
- nomenclature 285–7
- polymers 296–8
- soaps and detergents 295
- *see also* alcohols; alkanes; alkenes; carboxylic acids

**osmosis 39**

**oxides 117**

**ozone layer 207, 219–20**

**particle motion 123–9**

**particle size estimation 13**

**patinas 189**

**periodic table 6, 64–5**
- acids and bases 116
- alternative representations 66–7
- bonding relationships 77–80
- electronegativity patterns 82
- online resources 173
- origins of 62–3

**phlogiston theory 227**

**phosphorus cycle 218**

**pH scale 111–12**

**plastics, recycling 299–300**

**polar bonds 83**

**pollution 201, 212–15, 233–4**

**polymers 296–8**

**precipitation reactions 100, 101**

**preservatives 32, 33**

**Priestly, Joseph 5–6**

**properties of matter 14**
- relationship to bonding 74–6

**protons 63**

**purity 15–16, 27**

**quality assurance 135**

**quantitative chemistry 136–9**

**radioactive decay 151, 153–6**
- models of 157, 159

**rare earth elements 56–7**

**reaction curves, interpretation of 263**

**reaction rates 258–9**
- influencing factors 260–2

**reactivity series (activity series) 182, 184–6**
- implications of 188

**recycling 195, 299–300**

**redox reactions 117**
- application of 191
- Lewis dot notation 181

**relative atomic mass 148, 151**

**report writing 17**

**resources 11, 115**

**reversible reactions 265**

**$R_f$ values 42–3**

**risk management 107**

**Rutherford, Ernest, gold foil experiment 161**

**scents, extraction from flowers 41**

**scientific notation 12**

**scientific roles 115**

**separation**
- chromatography 42–3, 45
- of liquids 40–1
- osmosis and dialysis 39
- of solids 37, 44–5
- of solids from liquids 38

**sherbet 131**

**slimes 92**

**smelting 192–3**

**smoke alarms 160**

**soaps 295**

**solids, structure of 26**

**solubility 100, 102, 114**

**spontaneity of reactions 246**

**spreadsheets 173**

**standard electrode potentials 186**

**standardization 10, 12**

**states of matter 9**

**static electrical charge 81**

**surface area 262**
- effect on chemical change 131
- effect on reaction rates 261

**sustainability 234**

**synthetic chemistry 86**

**systems of the Earth 204**

**temperature 8**
- effect on chemical change 130
- effect on reaction rates 260

**thermal energy calculations 237–9, 243–5**

**titration 138–9**

**toiletries 35**

**Torricelli, Evangelista 5, 6**

**transuranium elements 154**

**valency 90, 175**

**vapour pressure 127**

**voltaic cells 185–6, 240**

**volume measurement 3–4**

**waste disposal 99**

**water**
- bottled mineral water 216
- electrolytic decomposition of 136–7
- heavy metal pollution 106
- molecular dipole 84–5, 100

**water cycle 214**

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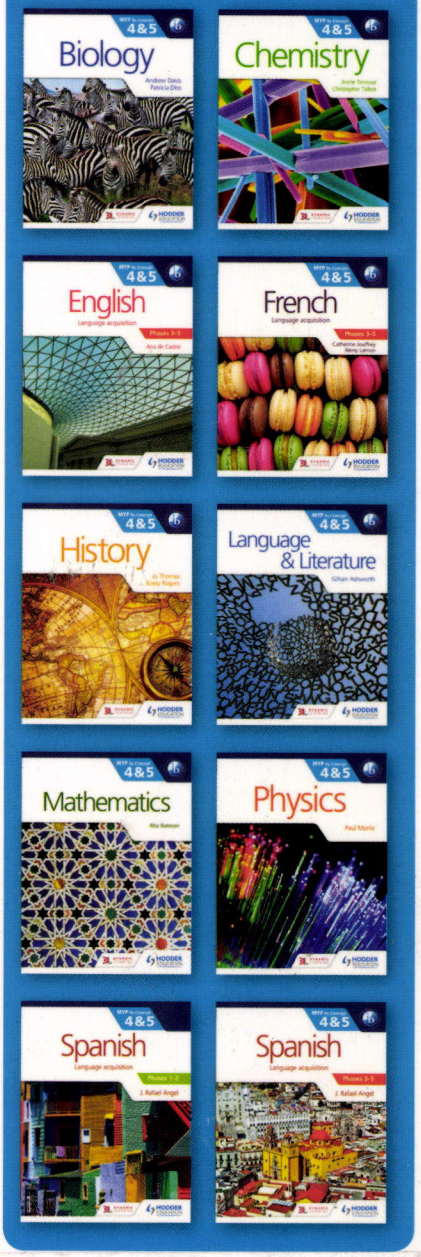


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