Heinemann CHEMISTRY 1

5TH EDITION

VCE Units 1 & 2

Written for the VCE Chemistry Study Design 2016–2021

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Heinemann
CHEMISTRY 1
5TH EDITION

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The Chemistry Education Association was formed in 1977 by a group of chemistry teachers from secondary and tertiary institutions. It aims to promote the teaching of chemistry, particularly in secondary schools. The CEA has established a tradition of providing up-to-date text and electronic material and support resources for both students and teachers and professional development opportunities for teachers.

CEA offers scholarships and bursaries to students and teachers to further their interest in chemistry. CEA supports STAV with sponsorship for the Chemistry Conference, Science Drama Awards and The Science Talent Search.

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Unit 2: What makes water such a unique chemical?

AREA OF STUDY 1
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How are substances in water measured and analysed?

AREA OF STUDY 3
Practical investigation

How to use this book

Heinemann Chemistry 1 5th edition

Heinemann Chemistry 1 5th Edition has been written to the new VCE Chemistry Study Design 2016–2021. The book covers Units 1 and 2 in an easy-to-use resource. Explore how to use this book below.

Extension

Extension material goes beyond the core content of the Study Design. It is intended for students who wish to expand their depth of understanding.

Highlight

Focus on important information such as key definitions, formulas and summary points.


CHAPTER 04 Ionic bonding

Rocks, plates, molten lava and electrical insulators belong to a group of substances called ionic compounds. At the end of this chapter, you will be able to explain the structure and properties of these compounds.

Ionic compounds are made by the chemical combination of metallic and non-metallic elements. You will see that the properties of ionic compounds are a direct result of the bonding between the particles within these compounds.

The writing of chemical formulas and naming ionic compounds are other important skills that you will learn in this chapter.

Key knowledge

- Common properties of ionic compounds (brittleness, hardness, high melting point, difference in electrical conductivity in solid and liquid states) with reference to their formation, nature of ionic bonding and crystal structure, including limitations of representations. Experimental determination of the factors affecting crystal formation of ionic compounds
- The uses of ionic compounds

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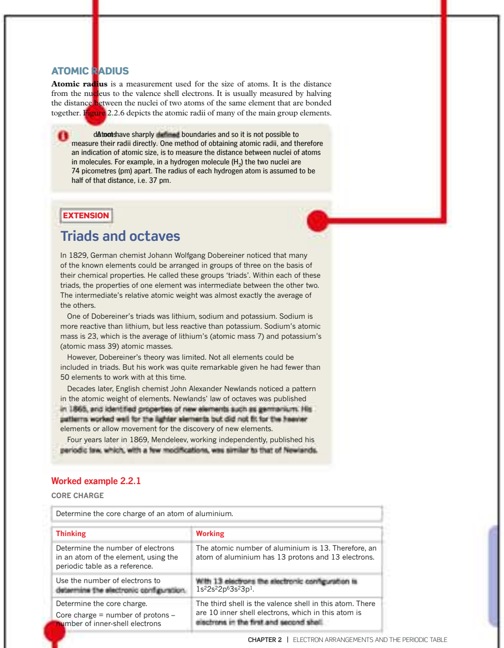
Chapter opener

Chapter opening pages link the Study Design to the chapter content. Key knowledge addressed in the chapter is clearly listed.


ATOMIC RADIUS

Atomic radius is a measurement used for the size of atoms. It is the distance from the nucleus to the valence shell electrons. It is usually measured by halving the distance between the nuclei of two atoms of the same element that are bonded together. Figure 2.2.6 depicts the atomic radii of many of the main group elements.

dAtomts have sharply defined boundaries and so it is not possible to measure their radii directly. One method of obtaining atomic radii, and therefore an indication of atomic size, is to measure the distance between nuclei of atoms in molecules. For example, in a hydrogen molecule (H_2) the two nuclei are 74 picometres (pm) apart. The radius of each hydrogen atom is assumed to be half of that distance, i.e. 37 pm.

EXTENSION

Triads and octaves

In 1829, German chemist Johann Wolfgang Dobereiner noticed that many of the known elements could be arranged in groups of three on the basis of their chemical properties. He called these groups 'triads'. Within each of these triads, the properties of one element was intermediate between the other two. The intermediate's relative atomic weight was almost exactly the average of the others.

One of Dobereiner's triads was lithium, sodium and potassium. Sodium is more reactive than lithium, but less reactive than potassium. Sodium's atomic mass is 23, which is the average of lithium's (atomic mass 7) and potassium's (atomic mass 39) atomic masses.

However, Dobereiner's theory was limited. Not all elements could be included in triads. But his work was quite remarkable given he had fewer than 50 elements to work with at this time.

Decades later, English chemist John Alexander Newlands noticed a pattern in the atomic weight of elements. Newlands' law of octaves was published in 1865, and identified properties of new elements such as germanium. His patterns worked well for the lighter elements but did not fit for the heavier elements or allow movement for the discovery of new elements.

Four years later in 1869, Mendeleev, working independently, published his periodic law, which, with a few modifications, was similar to that of Newlands.

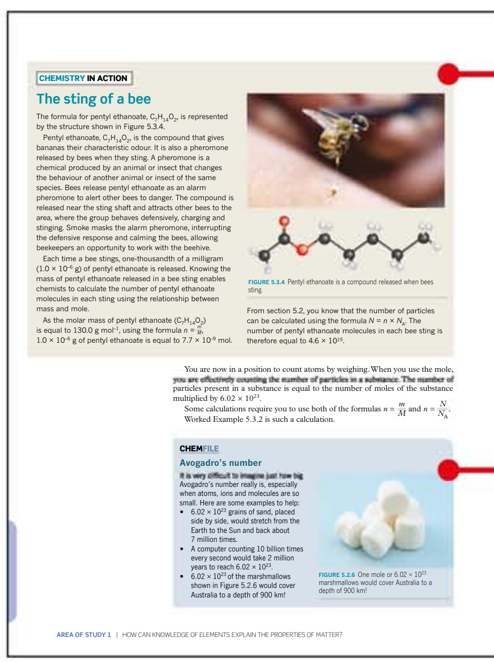
Worked example 2.2.1

CORE CHARGE

Determine the core charge of an atom of aluminium.

Thinking	Working
Determine the number of electrons in an atom of the element, using the periodic table as a reference.	The atomic number of aluminium is 13. Therefore, an atom of aluminium has 13 protons and 13 electrons.
Use the number of electrons to determine the electronic configuration.	With 13 electrons the electronic configuration is $1s^2 2s^2 2p^6 3s^2 3p^1$.
Determine the core charge. Core charge = number of protons – number of inner-shell electrons	The third shell is the valence shell in this atom. There are 10 inner shell electrons, which in this atom is electrons in the first and second shell.

CHAPTER 2 | ELECTRON ARRANGEMENTS AND THE PERIODIC TABLE


CHEMISTRY IN ACTION

The sting of a bee

The formula for pentyl ethanoate, $C_7H_{14}O_2$, is represented by the structure shown in Figure 5.3.4.

Pentyl ethanoate, $C_7H_{14}O_2$, is the compound that gives bananas their characteristic odour. It is also a pheromone released by bees when they sting. A pheromone is a chemical produced by an animal or insect that changes the behaviour of another animal or insect of the same species. Bees release pentyl ethanoate as an alarm pheromone to alert other bees to danger. The compound is released near the sting shaft and attracts other bees to the area, where the group behaves defensively, charging and stinging. Smoke masks the alarm pheromone, interrupting the defensive response and calming the bees, allowing beekeepers an opportunity to work with the beehive.

Each time a bee stings, one-thousandth of a milligram (1.0×10^{-6} g) of pentyl ethanoate is released. Knowing the mass of pentyl ethanoate released in a bee sting enables chemists to calculate the number of pentyl ethanoate molecules in each sting using the relationship between mass and mole.

As the molar mass of pentyl ethanoate ($C_7H_{14}O_2$) is equal to 130.0 g mol^{-1}, using the formula $n = \frac{m}{M}$, 1.0×10^{-6} g of pentyl ethanoate is equal to 7.7×10^{-9} mol.

FIGURE 5.3.4 Pentyl ethanoate is a compound released when bees sting.

From section 5.2, you know that the number of particles can be calculated using the formula $N = n \times N_A$. The number of pentyl ethanoate molecules in each bee sting is therefore equal to 4.6×10^{15}.

You are now in a position to count atoms by weighing. When you use the mole, you are effectively counting the number of particles in a substance. The number of particles present in a substance is equal to the number of moles of the substance multiplied by 6.02×10^{23}.

Some calculations require you to use both of the formulas $n = \frac{m}{M}$ and $n = \frac{N}{N_A}$. Worked Example 5.3.2 is such a calculation.

CHEMFILE

Avogadro's number

It is very difficult to imagine just how big Avogadro's number really is, especially when atoms, ions and molecules are so small. Here are some examples to help:

- 6.02×10^{23} grains of sand, placed side by side, would stretch from the Earth to the Sun and back about 7 million times.
- A computer counting 10 billion times every second would take 2 million years to reach 6.02×10^{23}.
- 6.02×10^{23} of the marshmallows shown in Figure 5.2.6 would cover Australia to a depth of 900 km!

FIGURE 5.2.6 One mole or 6.02×10^{23} marshmallows would cover Australia to a depth of 900 km!

AREA OF STUDY 1 | HOW CAN KNOWLEDGE OF ELEMENTS EXPLAIN THE PROPERTIES OF MATTER?

Chemistry in Action

Chemistry in Action place chemistry in an applied situation or relevant context. These refer to the nature and practice of chemistry, applications of chemistry and the associated issues and the historical development of concepts and ideas.

ChemFile

ChemFiles include a range of interesting information and real-world examples.

Worked examples

Worked examples are set out in steps that show thinking and working. This enhances student understanding by linking underlying logic to the relevant calculations.

Each Worked example is followed by a Try Yourself: Worked example. This mirror problem allows students to immediately test their understanding.

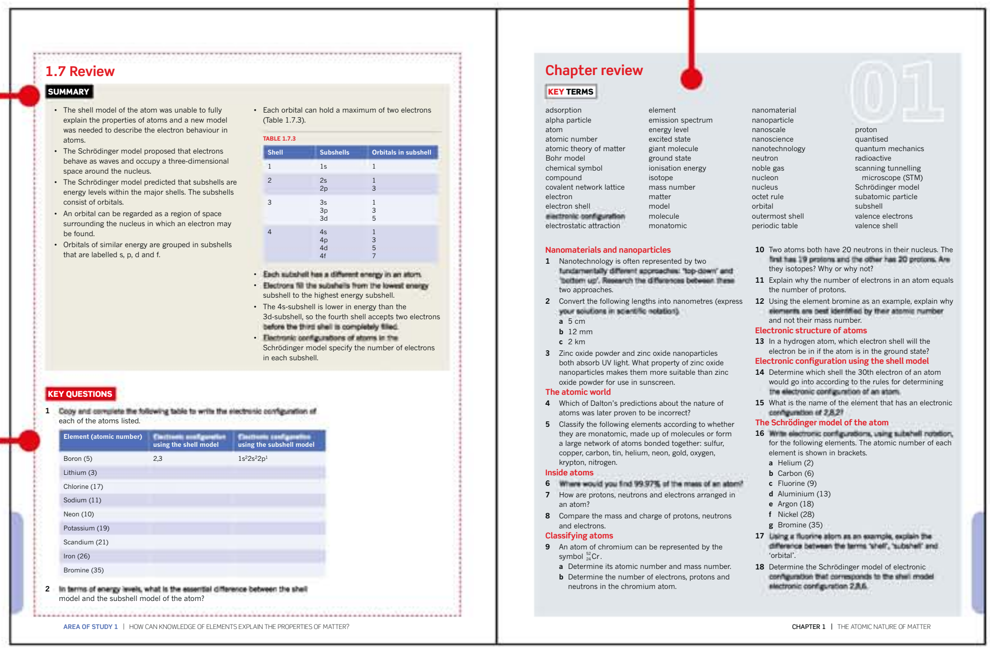
Fully worked solutions to all Try Yourself: Worked examples are available on *Heinemann Chemistry 5th Edition ProductLink*.

Chapter review

Each chapter finishes with a set of higher order questions to test students' ability to apply the knowledge gained from the chapter.

Section summary

Each section includes a summary to assist students consolidate key points and concepts.

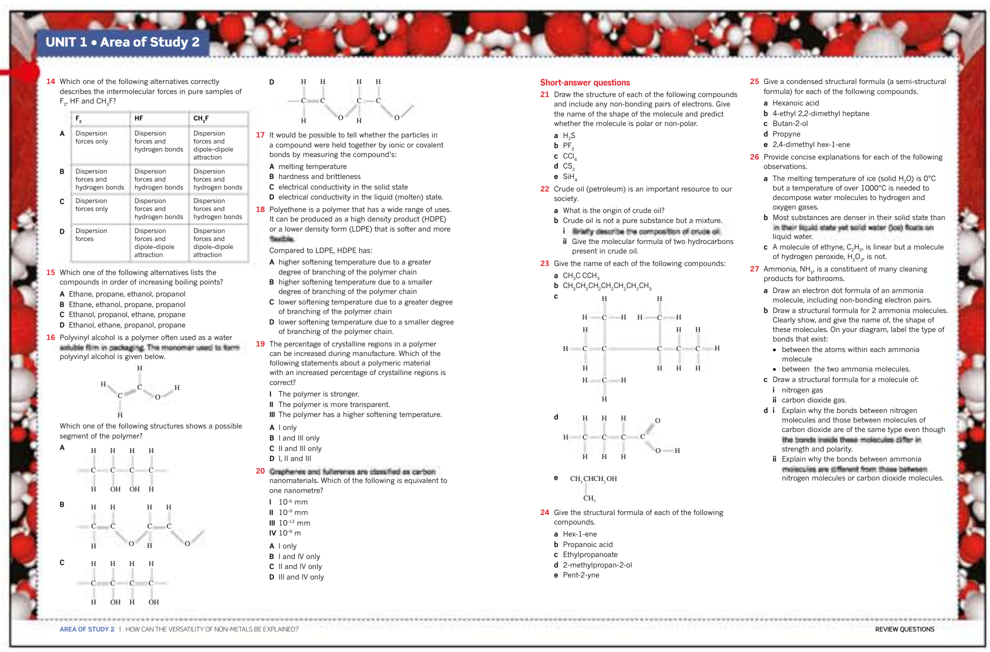


Section review

Each section finishes with questions to test students' understanding and ability to recall the key concepts of the section.

Area of Study review

Each Area of Study finishes with a comprehensive set of exam-style questions, including multiple choice and extended response, that assist students to draw together their knowledge and understanding and apply it to this style of questions.



Answers

Numerical answers and key short response answers are included at the back of the book. Comprehensive answers and fully worked solutions for all section review questions, Try Yourself: Worked examples, chapter review questions and Area of Study review questions are provided via *Heinemann Chemistry 5th Edition ProductLink.*

Glossary

Key terms are shown in bold and listed at the end of each chapter. A comprehensive glossary at the end of the book includes and defines all key terms.

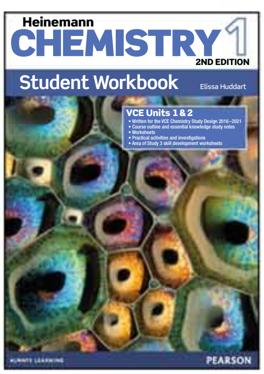
Heinemann Chemistry 1
5th edition

Student Book

Heinemann Chemistry 1 5th Edition has been written to fully align with the VCE Chemistry Study Design 2016–2021. The series includes the very latest developments and applications of Chemistry and incorporates best practice literacy and instructional design to ensure the content and concepts are fully accessible to all students.

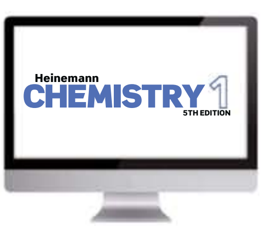
Pearson eBook 3.0

Pearson eBook 3.0 is the digital version of the student book. It retains the integrity of the printed page and is available online or offline on any device—PC/Mac, Android tablet, iPad.



Student Workbook

Heinemann Chemistry 1 Student Workbook 2nd edition will give students the edge in preparing for all forms of assessment. New content has been written to ensure the workbook is fully aligned to the 2016–2021 Chemistry Study Design. Key features include study notes, worksheets, practical activities and guidance, and assessment practice and opportunities.



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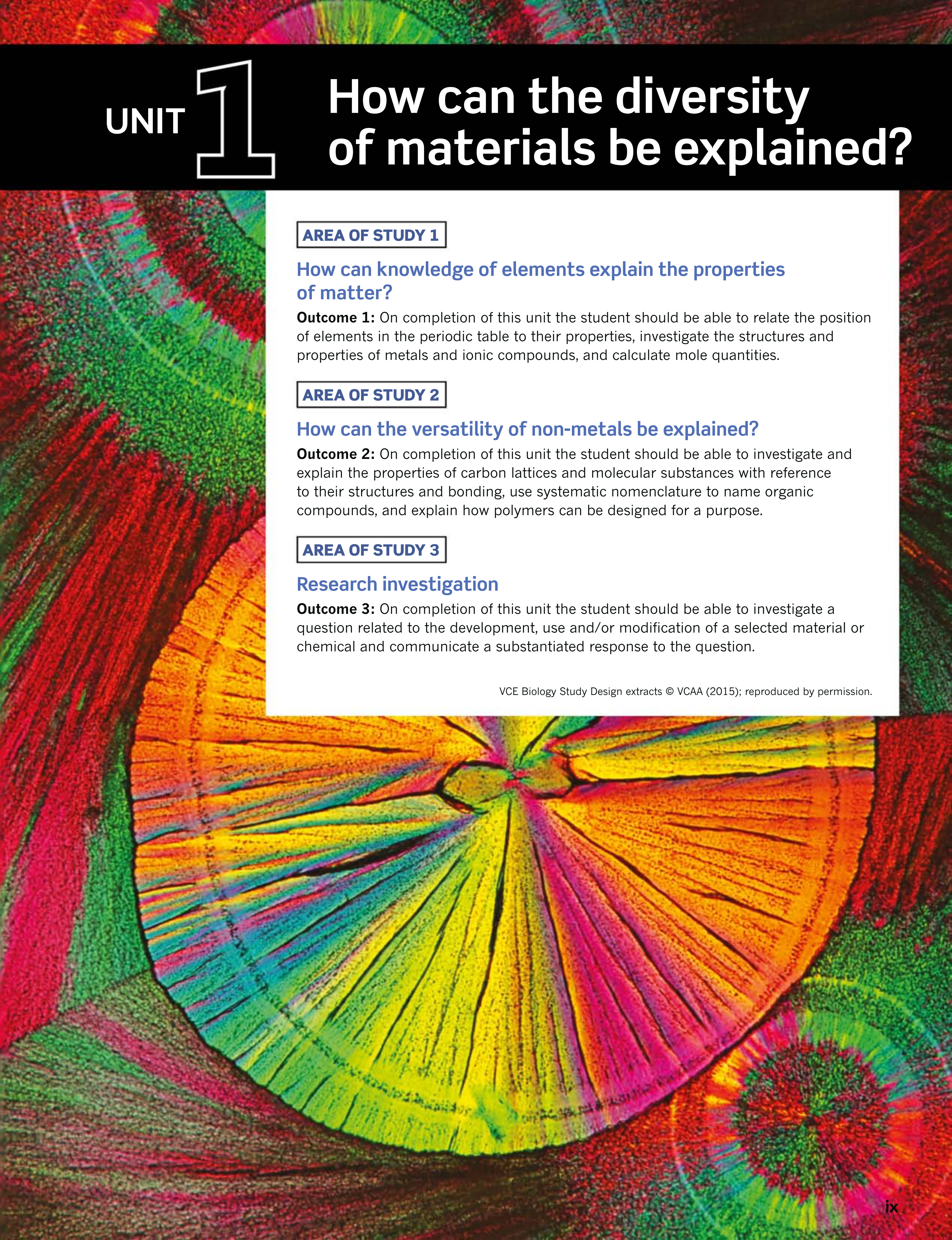


UNIT 1 How can the diversity of materials be explained?

AREA OF STUDY 1

How can knowledge of elements explain the properties of matter?

Outcome 1: On completion of this unit the student should be able to relate the position of elements in the periodic table to their properties, investigate the structures and properties of metals and ionic compounds, and calculate mole quantities.

AREA OF STUDY 2

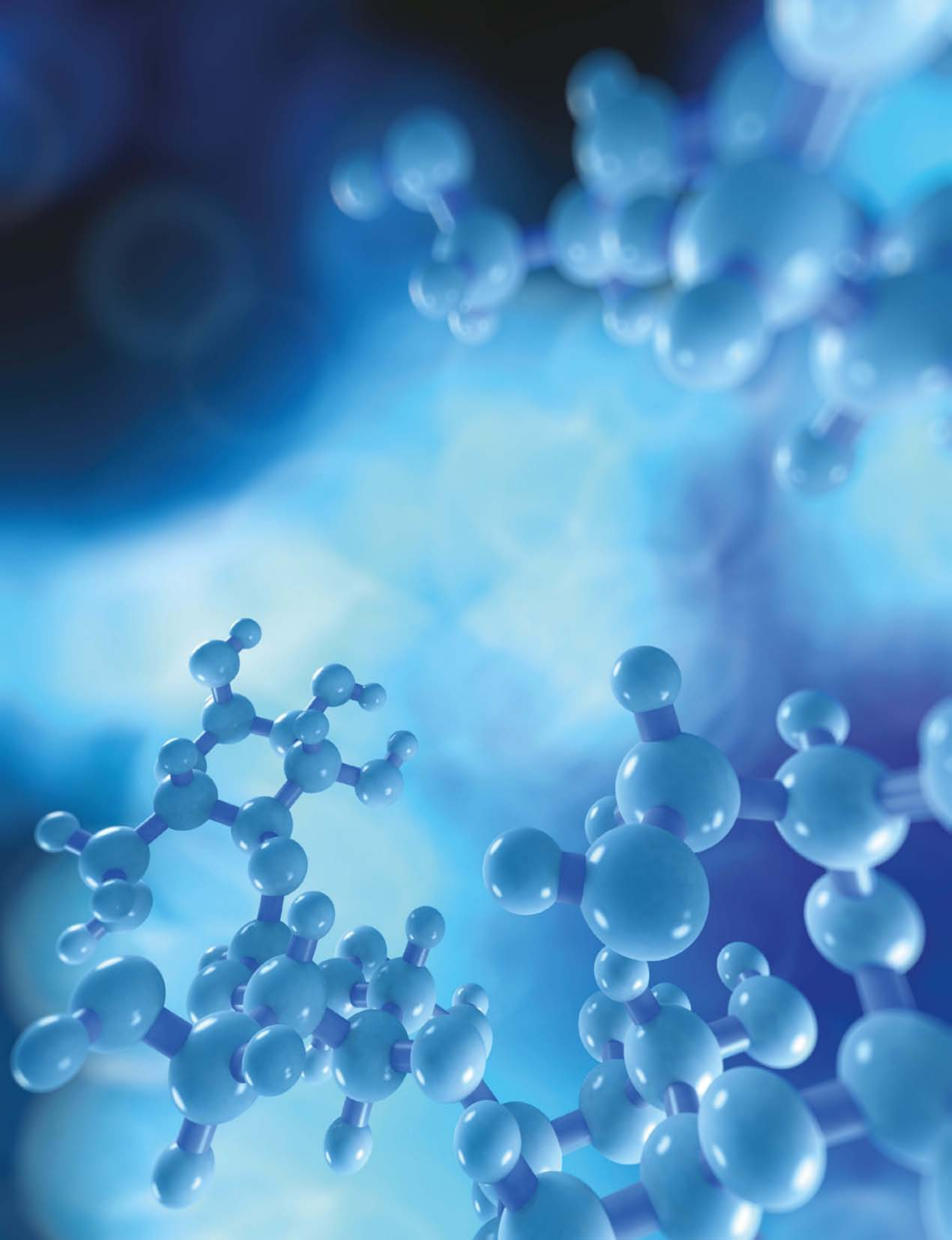
How can the versatility of non-metals be explained?

Outcome 2: On completion of this unit the student should be able to investigate and explain the properties of carbon lattices and molecular substances with reference to their structures and bonding, use systematic nomenclature to name organic compounds, and explain how polymers can be designed for a purpose.

AREA OF STUDY 3

Research investigation

Outcome 3: On completion of this unit the student should be able to investigate a question related to the development, use and/or modification of a selected material or chemical and communicate a substantiated response to the question.



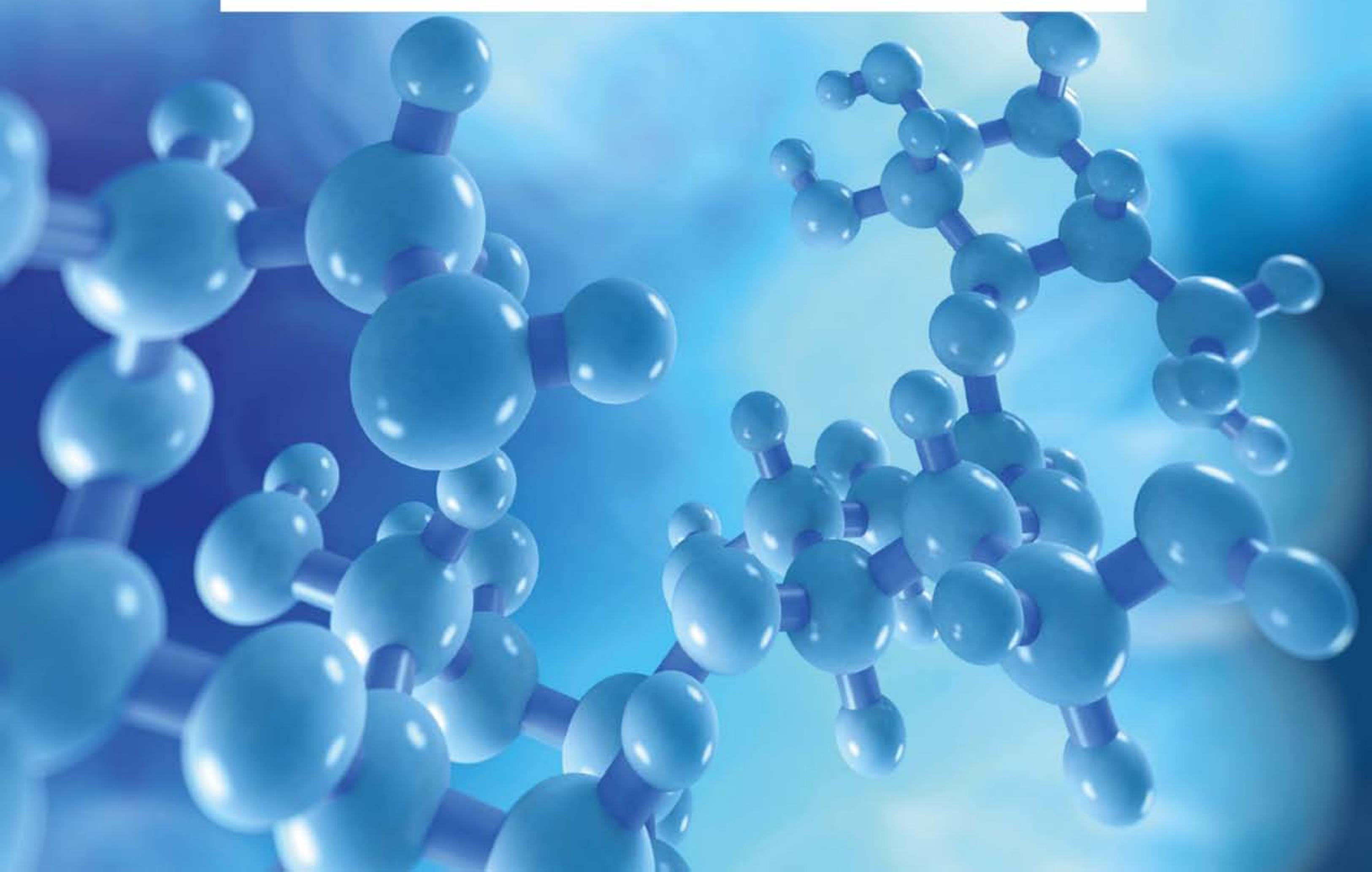
CHAPTER 01

The atomic nature of matter

In this chapter, you will begin by examining how material science can create advanced materials by controlling matter on the atomic scale. Nanoparticles contain just a few hundred or thousands of atoms. You will then develop a detailed picture of the structure of atoms, which is the foundation for all chemistry.

Key knowledge

- Relative and absolute sizes of particles that are visible and invisible to the unaided eye: small and giant molecules and lattices; atoms and subatomic particles; nanoparticles and nanostructures
- The definition of an element with reference to atomic number and mass number
- Isotopic forms of an element using appropriate notation
- Spectral evidence for the Bohr model and for its refinement as the Schrödinger model
- Electronic configurations of elements 1 to 36 using the Schrödinger model of the atom, including s, p, d and f notations (with copper and chromium exceptions)



1.1 Nanomaterials and nanoparticles

One of the most significant advances in materials science this century has been in the area of nanoscience. Nanoscience looks at materials at a very small scale—the nanoscale. The nanoscale is larger than the atomic scale, but is still far too small to be seen with the naked eye. By modifying and engineering materials at the nanoscale, scientists can fundamentally change the properties of the materials and therefore create new technologies.

Nanoscience is the study of nanoparticles and nanotechnology. **Nanotechnology** is the use of technologies that manipulate and investigate the properties of materials on the nanoscale.

Materials engineered on the nanoscale are already an important part of your everyday life. For example, microchips in computers and phones are made up of nanoscale transistors that process information at billions of bits per second. Lasers and light-emitting diodes (LEDs) also use materials engineered on the nanoscale. Even some sunscreens are made of nanoparticles designed specifically to absorb ultraviolet radiation.

'Nanotechnology' is no longer just a term used in science fiction. It is here today, and it has fundamentally changed the world you live in.

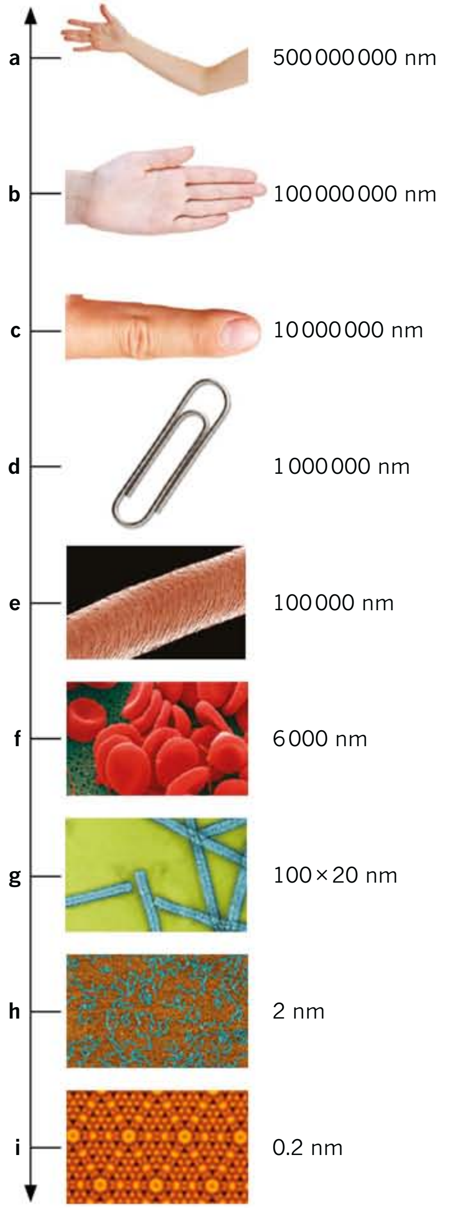


FIGURE 1.1.1 This scale compares the sizes of objects down to the nanometre size.
(a) The length of the average human arm is 0.5 m (500 000 000 nm).
(b) The width of the average hand is 10 cm (100 000 000 nm).
(c) The width of a finger is about 1 cm (10 000 000 nm).
(d) The width of a paperclip wire is approximately 1 mm (1 000 000 nm).
(e) The width of a human hair is approximately 100 000 nm.
(f) The diameter of red blood cells is 6000 nm.
(g) Tobacco mosaic virus is 100 nm long and 20 nm wide.
(h) DNA strands are about 2 nm wide.
(i) Silicon atoms are 0.2 nm across.

THE NANOSCALE

The prefix nano- refers to one-billionth or 10^{-9} in scientific notation. For example, a nanometre (nm) is one-billionth of a metre or 10^{-9} m. This is much smaller than anything you can see with the naked eye. Table 1.1.1 compares the nanometre to other metric units for length.

TABLE 1.1.1 Some metric units for length

Unit	Symbol	Relative to standard unit of length (m)
picometre	pm	10^{-12}
nanometre	nm	10^{-9}
micrometre	μm	10^{-6}
millimetre	mm	10^{-3}
metre	m	1
kilometre	km	10^{3}

For example, the width of a human hair or a pore on your skin is still thousands of times larger than the nanoscale features in nanomaterials. The **nanoscale** is used to describe objects that are about 1–100 nm wide. Figure 1.1.1 shows the sizes of different objects. You can see that tobacco mosaic virus and DNA belong to the nanoscale.

Worked example 1.1.1

CONVERTING MILLIMETRES TO NANOMETRES

Convert 15 mm into nanometres.

Thinking	Working
Write the length in metres.	15 mm = 0.015 m
Write the length in scientific notation.	0.015 m = 1.5×10^{-2} m
Multiply by 10^9 to convert to nanometres. (Hint: To do this, you just need to add 9 to the index on the number 10.)	$(1.5 \times 10^{-2}) \times 10^9 = 1.5 \times 10^{(-2+9)}$ nm $= 1.5 \times 10^7$ nm

Worked example: Try yourself 1.1.1

CONVERTING KILOMETRES TO NANOMETRES

Convert 2.43 km into nanometres.

NANOMATERIALS

Nanomaterials can have very different properties from those of the same material in bulk form. For example, carbon readily forms nanomaterials such as the carbon nanotubes shown in Figure 1.1.2. These nanostructures are nothing like soft, powdery charcoal, which we normally associate with carbon. Carbon nanotubes are extremely strong like diamond and conduct electricity like graphite. But unlike diamond and graphite, they are flexible and have a high tensile strength (resistance to stretching) and their conductivity can be engineered to make them insulating, conducting or semiconducting. You will look more closely at carbon nanomaterials in Chapter 8.

The term 'nanomaterial' is usually associated with modern, high-tech materials. However, nanomaterials have always been present in nature. For example, milk contains **nanoparticles** of proteins and fats. These particles scatter light and make milk appear white.

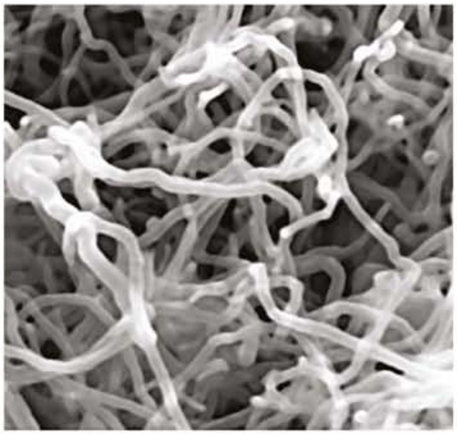


FIGURE 1.1.2 These carbon nanotubes have different properties from other materials made from carbon such as charcoal, graphite and diamond.

CHEMFILE

What do opals and butterflies have in common?

Opal is a nanomaterial made of tiny spheres of silica (Figure 1.1.3, top). These spheres diffract light to produce spectacular flashes of red, green and blue. Butterflies also get their coloured patterns from nanostructures on the surfaces of their wings.

FIGURE 1.1.3 (Top) An opal is made of tiny spherical nanoparticles of silica. (Bottom) The colour of a butterfly's wing is due to nanostructures in the wing.

Forming nanomaterials

Two processes are used to manufacture nanomaterials: the bottom-up method and the top-down method.

- The bottom-up method uses specially designed **molecules** or **atoms** in chemical reactions to gradually build up the new nanoparticle from the smaller atoms or molecular units.
- The top-down method uses the larger bulk material as the starting material. The bulk material is broken down into nanoparticles by mechanical or chemical means.

Even though the two methods start at opposite ends of the scale, the bottom-up and top-down approaches both produce materials that exist on the nanoscale and rely on physical and chemical processes to achieve these nanomaterials.

Manufactured nanomaterials

FIGURE 1.1.4 Silica gel sachets like this one are often placed with tablets and capsules to keep them dry. The silica gel works by adsorbing water from the atmosphere so the humidity does not affect the tablets and capsules. The silica gel is able to adsorb large amounts of water because of its nanostructure, shown in the inset. The nanostructure gives the gel an enormous surface area compared to its volume.

Scientists are learning more about how the structure of nanomaterials influences the properties of materials. This has allowed scientists to create new technologies based on nanomaterials. For example, materials such as silica gel (Figure 1.1.4) and activated charcoal can adsorb large amounts of liquids and gases. The term **adsorption** is used when a molecule attaches to a surface of a solid or liquid. This is different from absorption, where molecules are incorporated into the substance, as shown in Figure 1.1.5.

These products contain billions of nanoscale holes that trap unwanted molecules such as water and other gases. In activated charcoal, the holes are so tiny and so numerous that even a grain of the activated charcoal can have a surface area of several square metres. This means that only a small amount of activated charcoal is needed to adsorb a large number of gas molecules. For this reason, activated charcoal is used to store natural gas. Activated charcoal is also used in gas masks to adsorb dangerous gases from the atmosphere. Activated charcoal gas masks were invented in 1915 and were used in World War I to protect soldiers against poisonous gases.

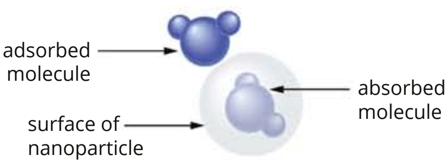


FIGURE 1.1.5 Molecules are adsorbed onto the surface of nanoparticles but are not usually absorbed by the particle. This diagram shows the difference between the two.

Engineered nanomaterials

More recently, scientists have been able to engineer nanoscale features on the surfaces of materials to give the materials new and useful properties. A simple example is the patterning of the surface of a CD-ROM. Information is encoded on the surface of the CD-ROM as a series of nano-sized 'pits' or hollows, as shown in Figure 1.1.6. Improvements in the technology have meant that smaller pits can be made so that more information can be stored on a surface. This has led to the development of DVD and Blu-ray disks.

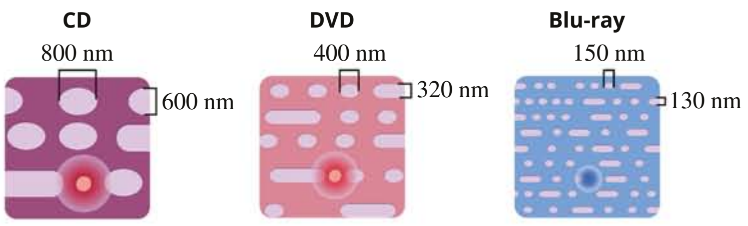


FIGURE 1.1.6 CD-ROMs store information as a series of nano-sized pits that are approximately 800 nm by 600 nm. DVDs are able to store more information because the pits are smaller: 400 nm by 320 nm. Blu-ray disks can store even more information because their pits are only 150 nm by 130 nm.

NANOPARTICLES

Nanoparticles are a specific type of nanomaterial with unique properties and a broad range of applications. Nanoparticles are usually spherical with diameters of 1–100 nm. They are used in chemotherapy and sunscreens and as industrial catalysts.

Nanoparticles range in diameter from 1 to 100 nm.

The importance of surface area

One of the most important properties of nanoparticles is their large surface area compared to their volume. In chemistry, surfaces are extremely important since surfaces are often where chemical reactions take place. Substances made of nanoparticles have very large surface areas because they are so small.

For example, consider a 1 m^3 cube. It has six sides, each exactly 1 m in length, and so has a total surface area of 6 m^2 and a volume of 1 m^3. If the cube is cut into eight 0.5 m cubes, the total volume of all the cubes stays the same (1 m^3), as shown in Figure 1.1.7. However, the surface area has doubled. This is because parts of the cube that were originally on the inside of the cube have now become part of the surface. The same block divided into 100 nm cubes has a surface area of 60 000 000 m^2 but the volume is still 1 m^3.

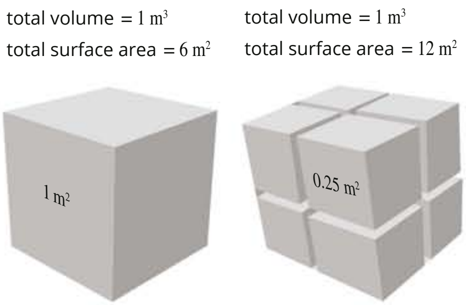


FIGURE 1.1.7 When a 1 m cube is divided into eight equal cubes, the volume stays the same but the surface area doubles.

A large surface area to volume ratio is one of the most important features of nanoparticles.

The large surface area of nanoparticles is important in three ways.

1 Adsorption of molecules: The large surface area of nanoparticles means that even a small volume of nanoparticles can adsorb a large number of molecules. Therefore, nanoparticles can be used to remove unwanted chemicals and gases in the same way that silica gel and activated charcoal are used.

2 Transportation of molecules: Nanoparticles can be used to transport the molecules that are adsorbed onto the nanoparticle. The nanoparticles' small size and large surface area mean that they can transport chemicals through air, skin and even cells. This feature of nanoparticles has a variety of applications in medicine for transporting drugs into the body and is already being used in some chemotherapy treatments for cancer.

3 Catalysts: The surfaces of some nanoparticles can be used to increase the rate of particular chemical reactions. The nanoparticles are acting as catalysts because they speed up the reaction but are not consumed (used up) by the reaction. The reactant molecules adsorb onto the surface of the nanoparticles, which allows reactant molecules to combine to form the product. The large surface area of nanoparticles means that many of these reactions can take place at the same time, which increases the rate of the reaction significantly.

CHEMISTRY IN ACTION

Professor Chengzhong Yu (from the Australian Institute for Biotechnology and Nanotechnology at the University of Queensland) was awarded the 2015 Le Févre Memorial Prize by the Australian Academy of Science. Professor Chengzhong Yu and a team of scientists are investigating using nanoparticles to improve the delivery of oral medications. Oral medications are subjected to changes in pH (high acid levels in the gut) and enzymatic breakdown in the mouth and stomach. This acid and enzyme attack means that many protein-based medications break down before they have a chance to act on the specific target tissue.

Professor Yu and his team are developing new, cost-effective nanomaterials that will improve delivery of vaccines, genes and drugs for human and animal health care.

Applications of nanotechnology in medicine are far-reaching. Figure 1.1.8 shows the targeted destruction of a tumour by nanoparticles. In medicine, nanotechnology could improve the analysis and treatment of cancers, genetic disorders and viral infections once thought untreatable.

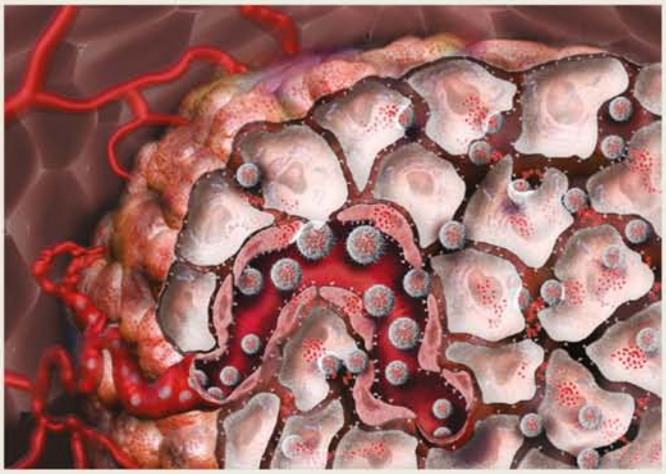


FIGURE 1.1.8 This computer illustration shows nanoparticles (spheres) containing cytotoxic drugs. The nanoparticles target tumour cells, leading to their destruction.

Other properties and applications

Nanoparticles have many other useful properties. Their small size and unique structural properties mean they can be used for developing composite (made up of several parts) nanomaterials. Composite nanomaterials incorporate nanoparticles into other materials.

The stain-resistant cotton shown in Figure 1.1.9 is a composite nanomaterial. In this case, the cotton fibres are covered with water-resistant nanoparticles so that liquids cannot penetrate the material. This makes the fabric water-repellent and stain-resistant.

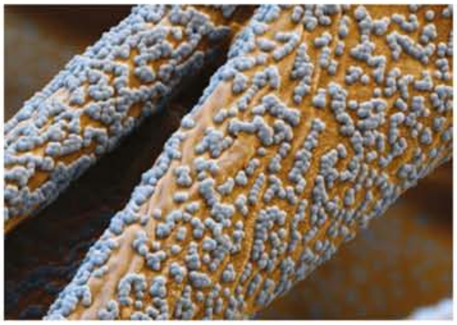


FIGURE 1.1.9 Water-repellent nanoparticles can be incorporated into cotton fibres to create a composite nanomaterial that is a water-resistant fabric.

When a substance is processed into nanoparticles, its physical, chemical and optical properties can change. For example, when gold is in the form of nanoparticles, it loses its metallic lustre. Instead, it can take on a variety of colours depending on the size of the gold particles. For this reason, gold nanoparticles are often used to colour glass. Figure 1.1.10 shows samples containing gold nanoparticles of different sizes. All of the particles absorb white light, but they reflect different-coloured light, depending on the particle size.

FIGURE 1.1.10 These vials contain gold particles of various sizes. The different-sized particles are different colours because they interact with light differently.

The fact that nanoparticles interact differently with light makes them useful in sunscreens. Zinc oxide (ZnO) nanoparticles are commonly used in sunscreens. Zinc oxide absorbs a broad range of the UV spectrum and so provides excellent protection from the sun. Normally, sunscreens that contain metal oxides are milky white when applied to the skin. However, sunscreen that contains zinc oxide nanoparticles is clear, and therefore is preferred by beach-goers.

CHEMFILE

Nanoparticles: risks to health and the environment

Nanoparticles have opened up a range of technological possibilities. However, some people are concerned about the possible dangers to humans and the environment. Other useful materials such as asbestos have been found to have devastating side-effects. Scientists at Australia's CSIRO (Commonwealth Scientific and Industrial Research Organisation) and around the world are studying the potential dangers associated with nanoparticles and their applications.

THE PROBLEM WITH NANOPARTICLES

Nanoparticles are so small that they can travel through the air, through skin and into your bloodstream and even into cells. Inside the body, the particles may interact with biomolecules to cause unwanted chemical reactions. This makes nanoparticles potentially dangerous if breathed in or in contact with the skin (for example, in sunscreen, fabrics or cosmetics).

NANOPARTICLES IN SUNSCREENS

Scientists at CSIRO are looking at the zinc oxide nanoparticles used in sunscreens to determine whether they are safe. This research focuses on whether the nanoparticles can penetrate skin, their long-term health effects and how they might impact on the environment.

Initial studies suggest that small amounts of zinc oxide from sunscreens are absorbed into the body and can be detected in the blood and urine. It is still not clear whether the absorbed zinc oxide has any negative effects on the human body. The most recent research indicates that the cells of the immune system can break down the nanoparticles.

1.1 Review

SUMMARY

- Nanomaterials are materials with nanoscale features that determine important properties of the materials.
- Nanoparticles have diameters of 1–100 nm.
- Nanoparticles can have very different physical, chemical and optical properties from the bulk material.
- Nanoparticles can be made in two ways: the bottom-up and top-down methods.
- Nanoparticles have a large surface area compared to their volume.
- The surfaces of nanoparticles can be used to adsorb molecules, transport molecules and act as catalysts for chemical reactions.
- Nanoparticles can transport particles through the air and into the human body. This has raised concern about their safety for human health and the environment.
- Regulations are being developed to address the potential risks of nanomaterials.

KEY QUESTIONS

1 Convert 8.35 cm into nanometres.

2 Convert the following lengths into nanometres. Use scientific notation in your answers.

a 1.35 cm

b 4.2 mm

3 A human hair is about 0.050 mm wide, whereas a tobacco mosaic virus is 20 nm wide. How many times larger is the width of a human hair than the width of a tobacco mosaic virus?

4 **a** For the shapes in the following table, calculate the surface area, volume and then surface area to volume ratio.

Shape	Surface area	Volume	$\frac{\text{Surface area}}{\text{Volume}}$
Cube 2 cm × 2 cm × 2 cm			
Sphere of radius 1.38 cm			
Tube (cylinder) Radius of 1 cm Height of 2.82 cm			

Hint: The following formulas may be useful:

- Surface area of a sphere = $4\pi r^2$
- Surface area of a cylinder = $2\pi rh + 2\pi r^2$
- Volume of a sphere = $\frac{4}{3}\pi r^3$
- Volume of a cylinder = $\pi r^2 h$

b Which shape has the greatest surface area to volume ratio?

c Which shape would be the most useful to hold the greatest volume?

d Suggest an application where a big surface area to volume ratio is important and another application where small surface area to volume ratio is important.

5 Explain why the size of nanoparticles makes them useful for transporting medicines into the body.

1.2 The atomic world

The development of advanced materials such as nanoparticles is the result of centuries of scientific discovery. Over time, scientists have gained a deep understanding of the structure of atoms, which are the basic building blocks of **matter**. As scientists' understanding has increased, their ability to control matter on the atomic scale has also improved. However, atoms are too small to be seen with even the most powerful optical microscope. The average human can only see objects that are 0.04 mm wide. Therefore, much of what scientists know about atoms has come from theoretical models and indirect observations.

> A scientific **model** is a description that scientists use to represent the important features of what they are trying to describe. They are able to test the consistency of their observations against various predictions of the model.

ATOMIC THEORY

FIGURE 1.2.1 John Dalton (1766–1844) proposed that matter was composed of atoms.

In 1802, an English scientist called John Dalton (Figure 1.2.1) presented the first **atomic theory of matter**. Dalton proposed that all matter is made up of tiny spherical particles, which are indivisible and indestructible.

Dalton also accurately described **elements** as materials containing just one type of atom and **compounds** as materials containing different types of atoms in fixed ratios. Elements cannot be broken down into simpler substances.

Subsequent experiments showed that Dalton's atomic theory of matter was mostly correct. However, scientists now know that atoms are not indivisible or indestructible. Atoms are made up of even smaller **subatomic particles**.

CHEMFILE

Viewing atoms

Dalton's atomic theory of matter assumed that atoms are spherical. However, atoms cannot be seen with conventional microscopes. Therefore, there was no way to confirm the shape of atoms. It wasn't until 1981 that a microscope capable of viewing atoms was developed by IBM researchers Gerd Binnig and Heinrich Rohrer. This type of microscope is known as a **scanning tunnelling microscope (STM)**. Using STMs, scientists confirmed that atoms are indeed spherical.

STMs use an extremely sharp metal tip to detect atoms. The tip is scanned, line-by-line, across the surface of a crystal. As the tip moves, the tip measures minute height differences in the crystal's surface due to the individual atoms. This is similar to the way sight-impaired people use their finger to sense braille on a page. The data from the tip is then sent to a computer that constructs an image of the atoms. An STM image of silicon atoms on the surface of a silicon wafer is shown in Figure 1.2.2.

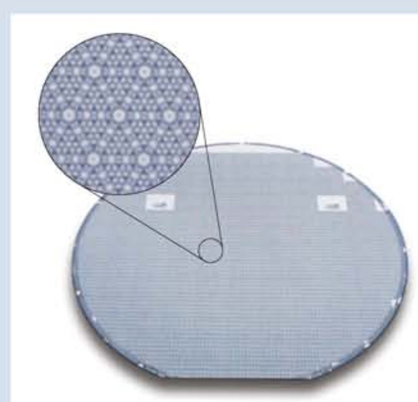
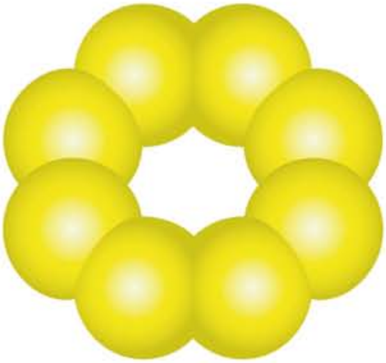


FIGURE 1.2.2 This image of the silicon atoms in a silicon wafer was taken by a scanning tunnelling microscope (STM).

Elements

As Dalton predicted, elements are made of just one type of atom and these atoms are identical. Most non-metallic elements, such as sulfur, form molecules with a definite number of sulfur atoms (8). However, some non-metals form **covalent network lattices** or **giant molecules**. Carbon is an example of such a non-metallic element. Diamond and graphite are both examples of covalent network lattices formed by carbon. Graphene is a giant molecule formed by carbon. (You will learn more about covalent network lattices formed from carbon in Chapter 8.) A comparison of the sizes of two different molecules is shown in Figure 1.2.3.


sulfur molecule

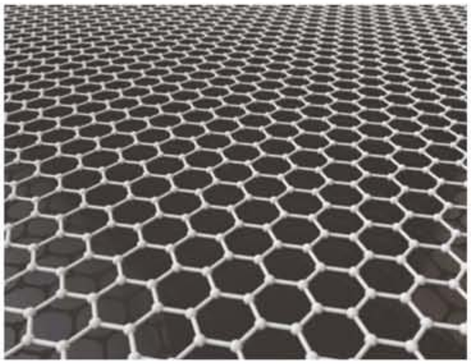

carbon giant molecule

FIGURE 1.2.3 Most non-metal elements, such as sulfur, form molecules. Other elements, such as carbon, form covalent network lattices or giant molecules given by the example here of graphene.

The metallic elements form a different type of network lattice structure, which you will look at in detail in Chapter 3.

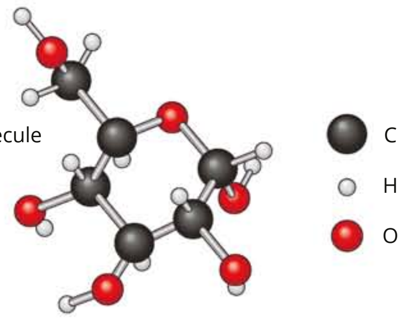
Several non-metallic elements are **monatomic**, which means they exist as individual atoms. Monatomic elements are known as the **noble gases** because they are chemically inert (unreactive). The noble gases include helium, neon, argon, krypton, xenon and radon.

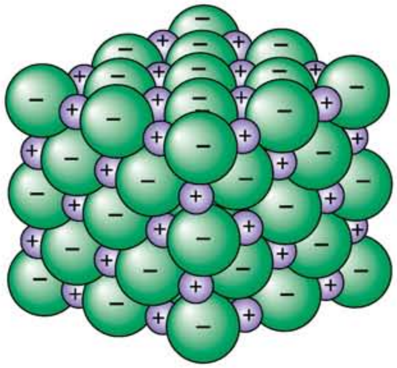
Monatomic elements are those made up of only one atom. The prefix mon- (or mono-) is frequently used in science. It means only one, or single.

Compounds

Dalton also predicted correctly that different types of atoms could combine to form new substances. These substances are known as compounds. The atoms in compounds can also form molecules or large networks of atoms as shown in Figure 1.2.4.

glucose molecule





sodium chloride lattice

FIGURE 1.2.4 Compounds can be made up of molecules, like glucose, which contains carbon, oxygen and hydrogen atoms, or lattices like sodium chloride (table salt).

FIGURE 1.2.5 The red powder in this test-tube is mercury(II) oxide (HgO). If you look closely at the test-tube, you will see beads of liquid mercury forming from the decomposition of the compound.

To determine whether a pure substance is an element or a compound, you must determine if the substance can be broken down into simpler substances. For example, when heated, mercury(II) oxide (HgO) decomposes to liquid mercury (Hg) and oxygen gas (O_2). If it was not a compound, the mercury(II) oxide would not break down. The appearances of the compound mercury(II) oxide and the resulting mercury element can be seen in Figure 1.2.5. As oxygen is a colourless gas, you cannot see it. Oxygen is detected by placing a lit splint at the top of the test-tube. When oxygen is present, the splint ignites with a large flame.

Molecules are formed when two or more atoms join together chemically. Compounds contain different types of atoms in definite proportions.

ELEMENT SYMBOLS

Scientists have discovered 118 different elements. Only about 98 of these occur in nature (the exact number is debatable). The other elements have only been observed in the laboratory.

Each element has a unique name and **chemical symbol**. Table 1.2.1 lists the chemical symbols of some of the most common elements.

TABLE 1.2.1 Chemical symbols and names of some of the most common elements

Element	Symbol	Element	Symbol
Aluminium	Al	Mercury	Hg
Argon	Ar	Nitrogen	N
Carbon	C	Oxygen	O
Chlorine	Cl	Potassium	K
Copper	Cu	Silver	Ag
Hydrogen	H	Sodium	Na
Iron	Fe	Uranium	U

The chemical symbol is usually made up of one or two letters. The first letter is always capitalised and subsequent letters are always lower case.

In many cases, the chemical symbol corresponds to the name of the element. For example, nitrogen has the chemical symbol N, chlorine has the chemical symbol Cl and uranium has the chemical symbol U.

However, some chemical symbols do not correspond to the name of the element. For example, sodium has the chemical symbol Na, potassium has the chemical symbol K and iron has the chemical symbol Fe. This is because the chemical symbols have been derived from the Latin or Greek names of the elements. In Latin, sodium is known as *natrium*, potassium is known as *kalium* and iron is known as *ferrum*.

The atomic symbols are usually displayed in a **periodic table** as shown in Figure 1.2.6. The periodic table helps to group elements that have similar chemical properties. You will learn more about the periodic table in Chapter 2.

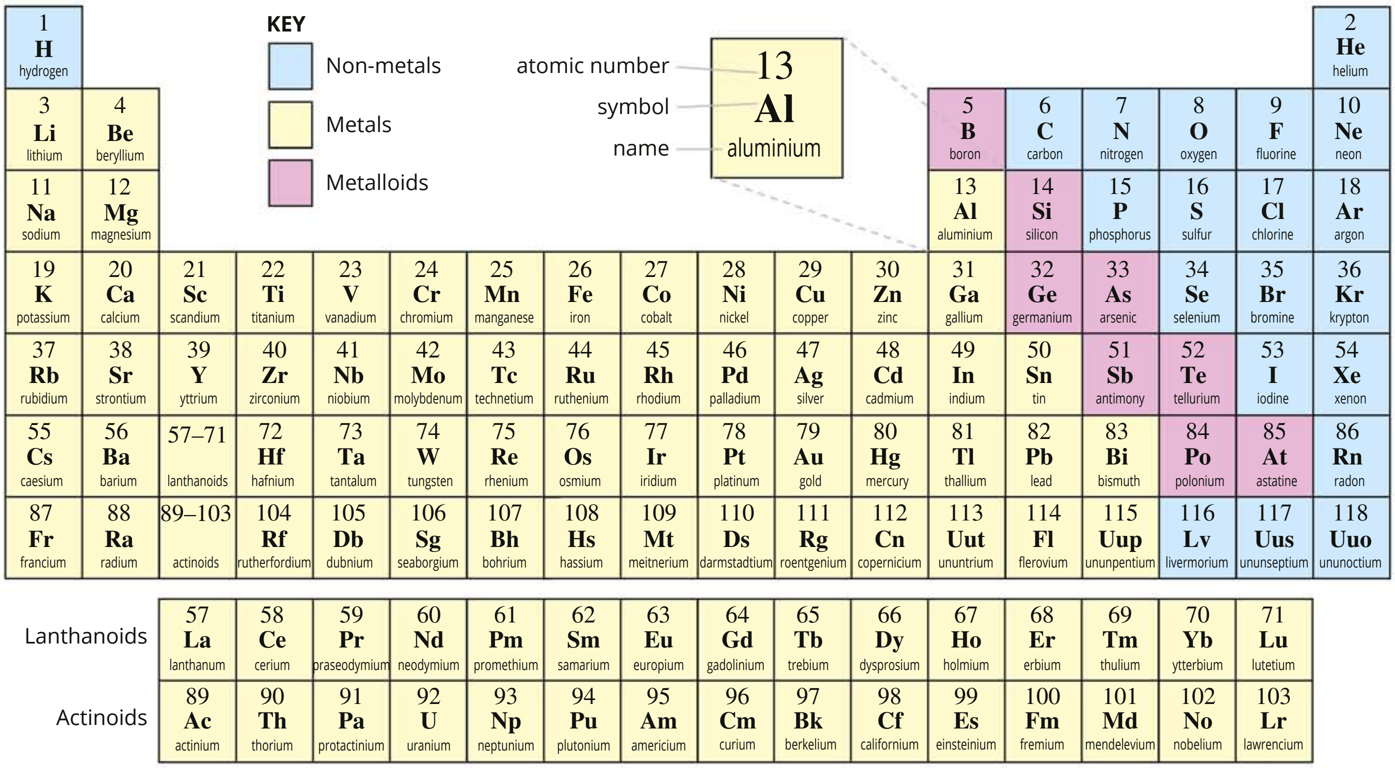


FIGURE 1.2.6 The periodic table groups the chemical elements according to their chemical properties.

1.2 Review

SUMMARY

- All substances are made up of atoms.
- The atoms in elements can exist as individual atoms (monatomic), molecules, giant molecules or lattices.
- The atoms in compounds can exist as molecules or large networks of atoms.
- Every element has a chemical symbol that is usually made up of one or two letters. The first letter is capitalised and the second letter is lower case.
- Elements are organised into the periodic table.

KEY QUESTIONS

1 What special name is given to the group of elements that are monatomic at room temperature?

2 Classify each of the following as elements or compounds.

a Copper
b Sulfur
c Water
d Carbon dioxide
e Diamond
f Sodium chloride
g Gold
h Silicon carbide

3 Explain the difference between an element and a compound.

4 Identify the common name of each of the following elements from its non-English name.

a Ferrum
b Kalium
c Wolfram
d Plumbum

1.3 Inside atoms

FIGURE 1.3.1 A simplified model of the atom. The central glow represents the nucleus where the protons and neutrons are housed. The nucleus is surrounded by a cloud of electrons that orbit the nucleus.

Until the mid-1800s, scientists believed that atoms were hard spheres that couldn't be broken down into smaller parts. By the end of the 1800s, there was increasing evidence to suggest that atoms are made up of smaller particles. This led to a series of atomic models that attempted to explain the structure of atoms.

STRUCTURE OF ATOMS

The current model of the atom is based on the work of many scientists. All atoms are made up of a small, positively charged **nucleus** surrounded by a much larger cloud of negatively charged **electrons** as shown in Figure 1.3.1. The nucleus is in turn made up of two subatomic particles—**protons** and **neutrons**. The protons are positively charged and the neutrons have no charge.

Electrons

Electrons are negatively charged particles. You can imagine them forming a cloud of negative charge around the nucleus. This cloud gives the atom its size and volume.

An electron is approximately 1800 times smaller than a proton or neutron. Therefore, electrons contribute very little to the total mass of an atom. However, the space occupied by the cloud of electrons is 10 000–100 000 times larger than the nucleus.

Negative particles attract positive particles. This is called **electrostatic attraction**. Electrons are bound to the nucleus by the electrostatic attraction to the protons within the nucleus. The charge on an electron is equal but opposite to the charge on a proton. Electrons are said to have a charge of –1 whereas protons have a charge of +1.

In some circumstances, electrons can be easily removed from an atom. For example, when you rub a rubber balloon on a woollen jumper or dry hair, electrons are transferred to the balloon and the balloon develops a negative charge. The negative charge is observed as an electrostatic force that can stick the balloon to a wall or even move an aluminium can. You will look more closely at the removal of electrons from atoms when looking at ionic compounds in Chapter 4.

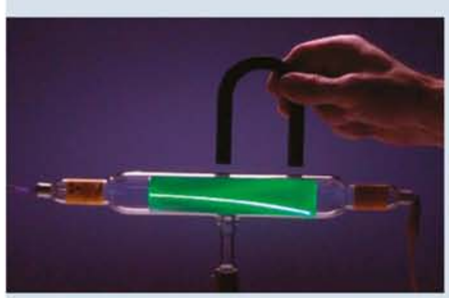
The electricity that powers lights and appliances is the result of electrons moving in a current through wires. Sparks and lightning are also caused by electrons moving through air.

CHEMFILE

Discovering the electron

In the 1850s, a series of experiments was carried out in which an electric current was passed through different gases in sealed tubes at very low pressures. The tubes were called cathode ray tubes.

When a high voltage was applied, the cathode ray tubes glowed with a coloured light and the glass on the wall opposite the negative electrode became fluorescent. This is shown in Figure 1.3.2.



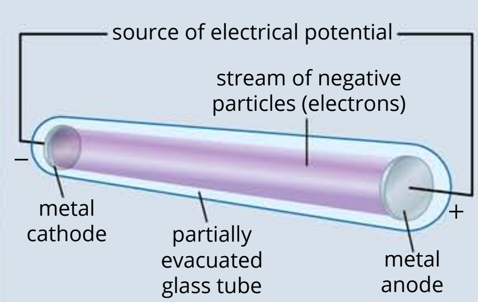


FIGURE 1.3.2 This glass tube contains a gas at low pressure. When an electric potential is applied, a green glow is observed on a phosphorescent screen.

In 1858, German physicist Julius Plucker conducted these experiments and suggested that the fluorescence was caused by invisible rays coming from the negative cathode. He called these cathode rays.

When an electric field was applied at right angles near the cathode, the position of the fluorescence moved away from the negative pole of the electric field. This can be seen in Figure 1.3.3.

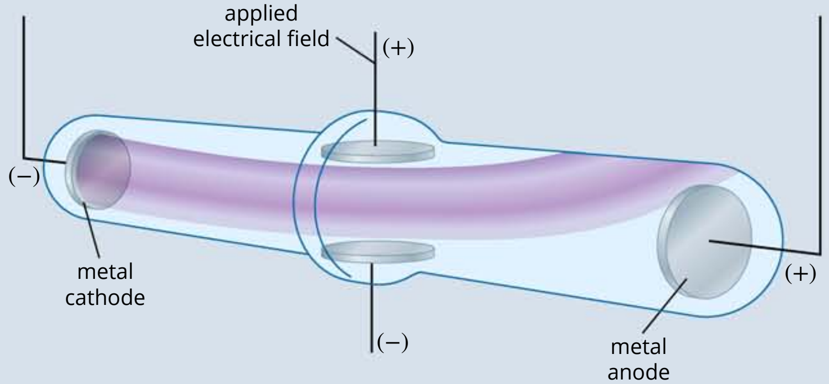


FIGURE 1.3.3 Cathode rays are deflected by an applied electric field.

In the late 1890s, English physicist Joseph John Thomson repeated these experiments, using different metals as electrodes and different gases in the tubes. In every case, the results were the same. The properties of the cathode rays were independent of both the gas and the metal. From his experiments, Thomson deduced that:

- the rays were a stream of particles
- the particles came from the negative electrode (cathode) and were negatively charged
- the particles must be found in all matter and therefore were subatomic particles
- atoms must also contain positive subatomic particles since atoms have no overall charge.

Thomson's research laid the foundation for other scientists to build the modern model of the atom. For his discovery of the electron, Thomson was awarded the 1906 Nobel Prize in Physics.

The nucleus

The nucleus of an atom is approximately 10 000–100 000 times smaller than the size of the atom. To put this in perspective, if an atom were the size of the Melbourne Cricket Ground (Figure 1.3.4), then the nucleus would be about the size of a pea. Nonetheless, the nucleus contributes around 99.97% of the atom's mass. This means that atomic nuclei are extremely dense.

The subatomic particles in the nucleus, the protons and neutrons, are referred to collectively as **nucleons**. Protons are positively charged particles with a mass of approximately 1.673×10^{-27} kg. Neutrons are almost identical in mass.

Table 1.3.1 summaries the properties of protons, neutrons and electrons.

FIGURE 1.3.4 If an atom were the size of the Melbourne Cricket Ground, then the nucleus would be the size of a pea.

TABLE 1.3.1 Properties of the subatomic particles

Particle	Symbol	Charge	Size relative to a proton	Mass (kg)
Proton	p	+1	1	1.673×10^{-27}
Neutron	n	0	1	1.675×10^{-27}
Electron	e	–1	$\frac{1}{1800}$	9.109×10^{-31}

CHEMFILE

Discovering the nucleus

The secrets of the nucleus were unlocked by New Zealand physicist Ernest Rutherford. Between 1899 and 1911, Rutherford conducted experiments in which he fired a beam of **alpha particles** (positively charged particles) at a piece of extremely thin gold foil. The vast majority of the alpha particles passed straight through the gold foil. From this observation, Rutherford deduced that the gold atoms were made up almost entirely of empty space. Figure 1.3.5 shows the apparatus and observations of Rutherford's experiments.

However, Rutherford was surprised to discover that occasionally, an alpha particle would bounce straight back. He stated: 'It was about as incredible as if you had fired a 16-inch shell at a piece of tissue paper and it came back and hit you!'

This remarkable observation suggested that the centre of the atom is very small, positive and extremely dense. This central region was later named the nucleus.

Rutherford proposed that the nucleus contained positive particles (because the positive alpha particles were deflected or rebounded), which he termed 'protons'. James Chadwick confirmed the existence of neutrons in 1932.

Rutherford's model (1911) proposed the following.

- Most of the mass of an atom, and all of the positive charge must be located in a tiny central region called the nucleus.
- Most of the volume of an atom is empty space, occupied only by electrons.
- The electrons move in circular orbits around the nucleus.
- The force of the attraction between the positive nucleus and the negative electrons is electrostatic.

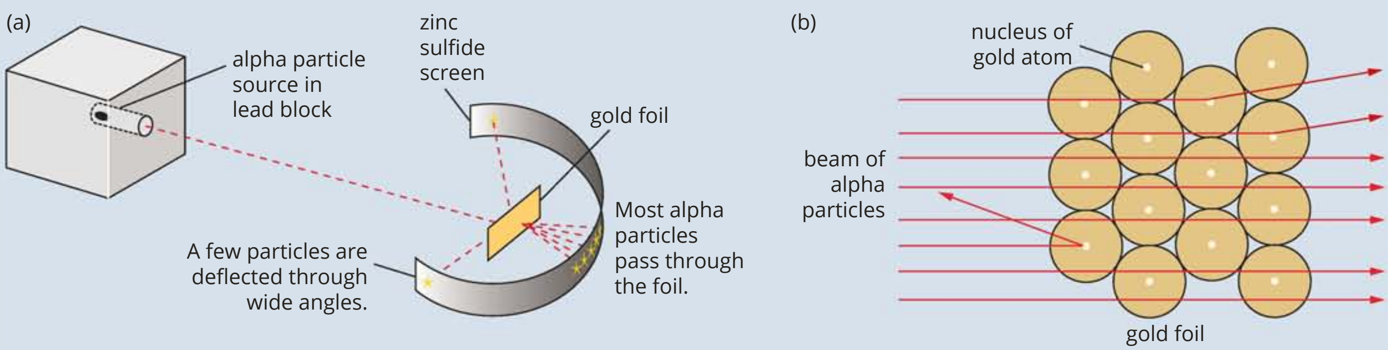


FIGURE 1.3.5 (a) Ernest Rutherford's apparatus that provided evidence for the discovery of nuclei in atoms. (b) Only those alpha particles that closely approach the nuclei in the gold foil are deflected significantly. Most particles pass almost directly through the foil.

1.3 Review

SUMMARY

- All atoms are composed of a small, positively charged nucleus surrounded by a negatively charged cloud of electrons.
- The mass of an atom is mostly determined by the mass of the nucleus, while the size of an atom is determined by the cloud of electrons.
- The nucleus is made up of two subatomic particles—protons and neutrons. These particles are referred to as nucleons.
- Protons have a positive charge, electrons have a negative charge and neutrons have no charge.
- Protons and neutrons are similar in size and mass while electrons are approximately 1800 times smaller.
- The charges on protons and electrons are equal but opposite.

KEY QUESTIONS

1 How many times larger is the atom compared to its nucleus?

2 What subatomic particles make up the most mass of an atom and where are they found?

3 How are electrons held within the cloud surrounding the nucleus?

1.4 Classifying atoms

DIFFERENT TYPES OF ATOMS

Each element is made up of one type of atom. The type of atom that makes up each element is determined by the number of protons in the nucleus.

The number of protons in an atom's nucleus is known as the **atomic number** and is represented by the symbol Z.

All atoms that belong to the same element must have the same number of protons and therefore have the same atomic number, Z. For example, all hydrogen atoms have $Z = 1$, all carbon atoms have $Z = 6$ and all gold atoms have $Z = 79$.

The number of protons and neutrons in the nucleus is known as the **mass number** and is represented by the symbol A. The mass number represents the total mass of the nucleus.

As all atoms are electrically neutral, the number of protons in an atom is equal to the number of electrons in an atom. The atomic number therefore tells you both the number of protons and the number of electrons. For example, carbon atoms, with $Z = 6$, have six protons and six electrons.

STRUCTURE OF ATOMS

The number of protons, neutrons and electrons defines the basic structure of an atom. The standard way of representing an atom is to show its atomic and mass numbers as shown in Figure 1.4.1.

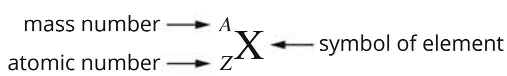


FIGURE 1.4.1 The standard way of representing an atom to show its atomic number and mass number.

For an aluminium atom, this would be written as shown in Figure 1.4.2.

$$^{27}_{13}\mathrm{Al}$$

FIGURE 1.4.2 This representation of an aluminium atom indicates the number of protons, neutrons and electrons in the atom.

From this representation, you can determine that the:

- number of protons is 13 because the number of protons is equal to the atomic number (Z)
- number of neutrons is 14 because the number of neutrons plus the number of protons is equal to the mass number. Therefore you can subtract the atomic number from the mass number to determine the number of neutrons ($A - Z$)
- number of electrons is 13 because atoms have no overall charge. Therefore the number of electrons must equal the number of protons.

Worked example 1.4.1

CALCULATING THE NUMBER OF SUBATOMIC PARTICLES

Calculate the number of protons, neutrons and electrons for the atom with this atomic symbol: $^{40}_{18}Ar$

Thinking	Working
The atomic number is equal to the number of protons.	The number of protons = Z = 18
Find the number of neutrons. Number of neutrons = mass number – atomic number	The number of neutrons = $A - Z$ = 40 – 18 = 22
Find the number of electrons. The number of electrons is equal to the atomic number because the total negative charge is equal to the total positive charge.	Number of electrons = Z = 18

Worked example: Try yourself 1.4.1

CALCULATING THE NUMBER OF SUBATOMIC PARTICLES

Calculate the number of protons, neutrons and electrons for the atom with this atomic symbol: $^{235}_{92}U$

ISOTOPES

All atoms that belong to the same element have the same number of protons in the nucleus and therefore the same atomic number, *Z*. However, not all atoms that belong to the same element have the same mass number, *A*. For example, hydrogen atoms can have mass numbers of 1, 2 or 3. In other words, hydrogen atoms may contain just a single proton, a proton and a neutron, or a proton and two neutrons as shown in Figure 1.4.3. Atoms that have the same number of protons (atomic number) but different numbers of neutrons (and therefore different mass numbers) are known as **isotopes**.

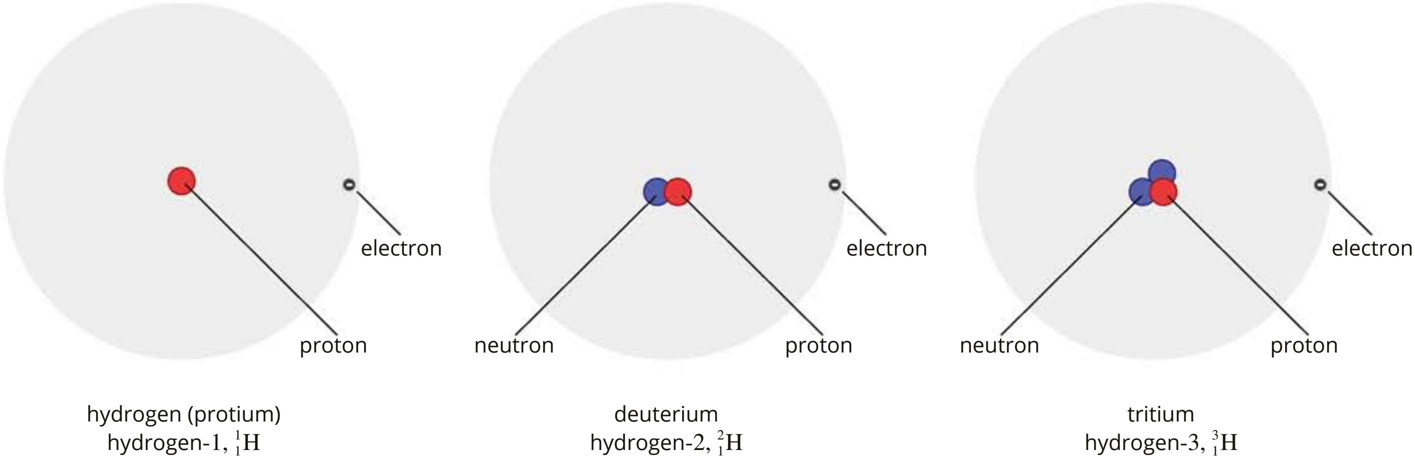


FIGURE 1.4.3 The three isotopes of hydrogen are given special names. A hydrogen atom with just one proton in its nucleus is known as hydrogen or protium. A hydrogen atom with one proton and one neutron is known as deuterium. A hydrogen atom with one proton and two neutrons is known as tritium.

Carbon also has three naturally occurring isotopes. These three isotopes are known as carbon-12, carbon-13 and carbon-14. Carbon-12 atoms have a mass number of 12, carbon-13 atoms have a mass number of 13 and carbon-14 atoms have a mass number of 14. In the 1950s and 1960s, nuclear weapons testing caused a spike in carbon-14 in the atmosphere. This has been declining in the last 50 years. These three carbon isotopes can be represented as:

$$^{12}_{6}C \qquad ^{13}_{6}C \qquad ^{14}_{6}C$$

carbon–12 carbon–13 carbon–14

Isotopes have identical chemical properties but different physical properties such as mass and density. In particular, some isotopes are **radioactive**.

CHEMFILE

Isotopes

In nature, different elements have different numbers of isotopes. Gold has only one isotope, whereas lead has four and mercury seven isotopes.

CHEMISTRY IN ACTION

Carbon-14 and the war against poachers

Isotopes are important in the war against ivory poaching in Africa. Living organisms take up carbon-14 from the environment. Over time, the amount of carbon-14 in tissues of plants and animals decreases as the isotope radioactively decays. By looking at the levels of the carbon-14 isotope in elephant tusks and ivory (Figure 1.4.4), scientists can determine how old they are.

If the authorities know the age of the ivory, then legal action can be taken against the poachers and sellers of the product. Ivory products prior to 1989 are allowed to be traded. Since 1989, the trade on ivory has been made illegal world-wide.

FIGURE 1.4.4 These tusks are from African elephants killed for their ivory.

1.4 Review

SUMMARY

- You can determine the number of subatomic particles in an atom from an element's atomic number and mass number.
- The atomic number indicates how many protons or electrons an atom has.
- The mass number tells you how many protons and neutrons are in the nucleus of the atom.
- Isotopes are atoms with the same atomic number but different mass numbers, i.e. they have the same number of protons but different numbers of neutrons.
- Isotopes have the same chemical properties but different physical properties such as mass, density and radioactivity.

KEY QUESTIONS

1. What term is given to the number of protons and neutrons in the nucleus of an atom?
2. Calculate the numbers of protons, neutrons and electrons in the atom $^{31}_{15}P$.
3. What is the correct name of the element that has an atom with seven protons and eight neutrons?
4. Explain the similarities and differences between isotopes of the same element.
5. How many more neutrons does an atom of carbon-14 have than an atom of the carbon-12 isotope?

1.5 Electronic structure of atoms

When fireworks explode, they create a spectacular show of coloured lights (Figure 1.5.1). The light is produced by metal atoms that have been heated by the explosion. These coloured lights posed a significant problem for early scientists. The models the scientists were using could not explain the source of the light. However, the light was a clue that ultimately led to a better understanding of the arrangement of electrons in atoms.

FIGURE 1.5.1 The spectacular colours in this New Year's Eve fireworks display are emitted by metal atoms that have been heated to very high temperatures.

CHEMFILE

How helium got its name

Helium was discovered on the Sun before being discovered on Earth. The French astronomer Jules Janssen discovered helium in 1868 while studying the light from a solar eclipse in India similar to the solar eclipse shown in Figure 1.5.4. Although the spectrum showed the full range of colours, the bright yellow line in the helium spectrum stood out. The line could not be matched to the line spectra of any of the known elements. It was concluded that the line belonged to an unknown element. This element was named helium after the Greek Sun god, Helios.

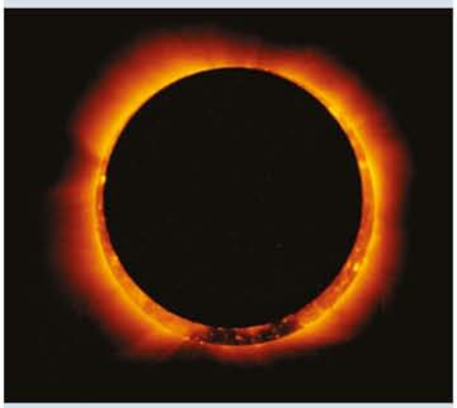


FIGURE 1.5.4 The emission spectrum of helium was first detected in sunlight of a solar eclipse like the one shown here.

EMISSION SPECTRA

When atoms are heated, they give off electromagnetic radiation or light. If the light passes through a prism, it produces a spectrum with a black background and a number of coloured lines. Figure 1.5.2 shows the apparatus used to produce these spectra.

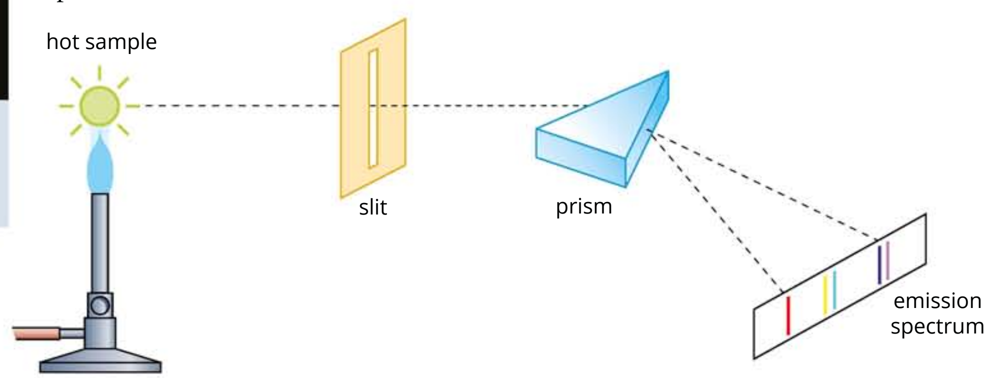


FIGURE 1.5.2 The apparatus used to analyse the light given out when an element is heated. The coloured lines are called an emission spectrum.

These spectra are known as line spectra or **emission spectra** and are related to the electronic structure within the atoms. Each emission spectrum is unique for a particular element and can be used to identify different elements.

The line spectrum produced by helium is shown in Figure 1.5.3.

FIGURE 1.5.3 The emission spectrum of helium is made up of lines ranging from violet to red in colour.