Table of Contents

Preface iii

Topic 1: Materials and their atoms 1

1.1 Properties and uses of materials 1
1.2 Atomic structure 15
1.3 Quantities of atoms 31
1.4 The periodic table 37
Summary Test 1: Materials and their Atoms 45

Topic 2: Combining Atoms 50

2.1: Types of materials 50
2.2: Bonding between atoms 53
2.3: Quantities of molecules and ions 96
Summary Test 2: Combining Atoms 105

Topic 3: Molecules 110

3.1: Molecule polarity 110
3.2: Interactions between molecules 118
3.3: Hydrocarbons 125
3.4: Polymers 148
Summary Test 3: Molecules 155

Topic 4: Mixtures and solutions 161

4.1: Miscibility and solutions 161
4.2: Solutions of ionic substances 173
4.3: Quantities in reactions 182
4.4: Energy in reactions 195
Summary Test 4: Mixtures and solutions 203

Topic 5: Acids and bases 207

5.1 Acid–base concepts 207
5.2: Reactions of acids and bases 217
5.3: The pH scale 231
Summary Test 5: Acids and bases 239

Topic 6: Redox Reactions 243

6.1: Concepts of oxidation and reduction 243
6.2: Metal reactivity 259
6.3: Electrochemistry 267
Summary Test 6: Redox Reactions 276

Topic 7: Science inquiry skills 280

Summary Test 7: Science inquiry skills 312

Solutions 317

Topic 1: Materials and their Atoms 317
Topic 2: Combining Atoms 327
Topic 3: Molecules 343
Topic 4: Mixtures and Solutions 355
Topic 5: Acids and Bases 367
Topic 6: Redox Reactions 377
Topic 7: Science Inquiry Skills 384

Appendicies 392

Appendix 1: Molar Masses of the Elements 392
Appendix 2: The Periodic Table of Elements 393
Appendix 3: SI prefixes, symbols and values 394

Topic 1: Materials and their atoms

1.1 Properties and uses of materials

Science understanding

The uses of materials are related to their properties, including solubility, thermal and electrical conductivities, melting point, and boiling point.

Chemistry is, fundamentally, the study of matter and its properties. **Matter** has mass and takes up space (e.g., a stone, air, your eyeball, the Earth). Matter is distinct from **energy**, which does not have mass or take up space (e.g., light, sound, motion). All matter is composed of particles: small ‘units’ of a material that cannot be broken apart any further without changing the identity of the substance. Most materials on Earth are made up of atoms, ions, molecules, or a mixture of these three.

Materials are classified according to their **properties**, which are characteristics that define the substance. The properties of a material relate directly to the nature and arrangement of the particles comprising the material. Properties of materials can be classified as either physical properties or chemical properties.

Physical Properties

Physical properties are traits of a material that can be observed directly without any chemical reaction occurring, e.g., colour, length, density, melting point. Physical properties can be either extensive or intensive.

Extensive physical properties change in proportion with the amount of the material. For example, mass is an extensive physical property because if the amount of material is doubled, its mass will also double. Other extensive physical properties include volume and number of particles.

Intensive physical properties do not change when the amount of the material changes. Density is one example of an intensive physical property: the density of water is approximately 1 g/mL, and if the amount of water is doubled the density remains 1 g/mL (i.e., it does not become 2 g/mL). Other intensive physical properties include colour, lustre, temperature, malleability, ductility, viscosity, and solubility. Because intensive physical properties do not depend on the amount of substance, they are useful for identifying materials and separating mixtures.

Solubility

When a material dissolves in a liquid to create a homogenous mixture, the dissolved material is called the **solute**, the liquid is called the **solvent**, and the mixture is called a **solution**. Solubility measures the amount of a material that can be dissolved in a given liquid at a given temperature. For example, at 25 °C, about 200 g of sugar can be dissolved in 100 mL of water (equivalent to 1 decilitre), so the solubility of sugar is 200 g/dL at 25 °C.

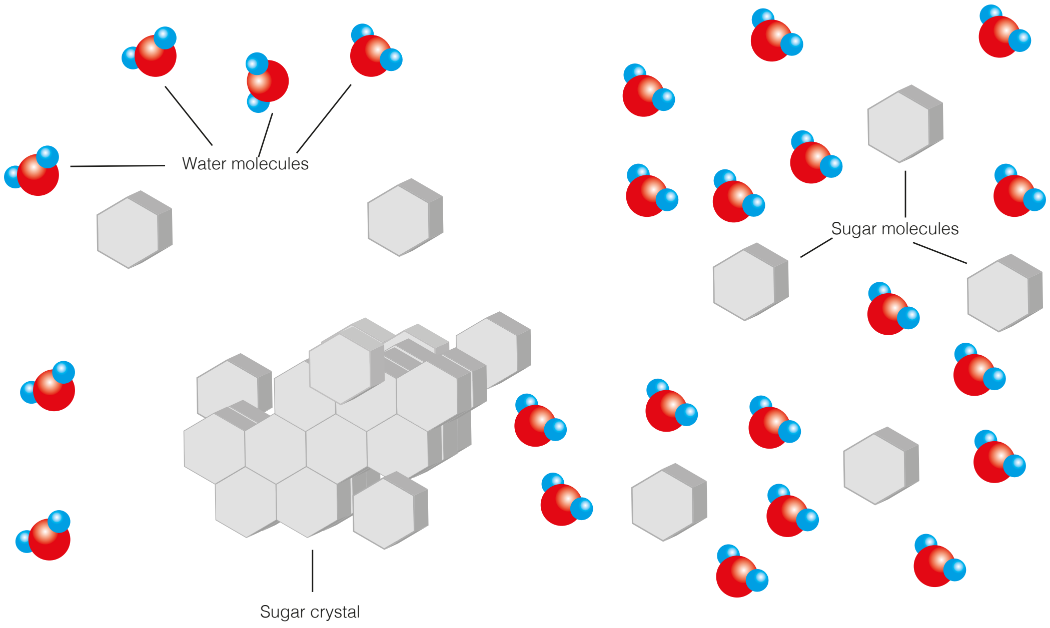

Figure 1.01: Sugar dissolving in water

For building or manufacturing, it is usually undesirable to use solid materials that have any significant solubility in water. Containers or packaging that will come into contact with food or beverages should ideally be totally **insoluble** so that the material does not contaminate the product.

Thermal Conductivity

The particles in substances are constantly in motion, and this motion of particles is experienced as heat. The amount of heat energy a material contains is an extensive physical property corresponding to the total kinetic energy of the particles in the material. Temperature represents the average kinetic energy and is an intensive physical property.

Thermal conductivity is a measure of the ability of a material to transmit heat through conduction. Conduction occurs when particles, in their normal course of motion due to their heat energy, collide with other particles and transfer some of that kinetic energy; this is analogous to a billiard ball striking another billiard ball and transferring some momentum. Materials with high thermal conductivity transfer heat rapidly and are called **thermal conductors**, while materials with low thermal conductivity transfer heat more slowly. Materials with very low thermal conductivity are called **thermal insulators**. Many applications require either maximised or minimised heat transfer, also called **thermal exchange**.

In general, metals are excellent thermal conductors, while other materials are less so.

Example

Hot beverages are generally not served in glasses because glass has a relatively high thermal conductivity. This allows heat to be rapidly transferred from the beverage through the glass to your hand, which might cause a burn. However, a thermos prevents thermal exchange by using materials with low thermal conductivity (e.g., plastic) and by separating the beverage from the exterior of the thermos with a vacuum chamber. A pure vacuum contains no matter, so it does not conduct heat at all.

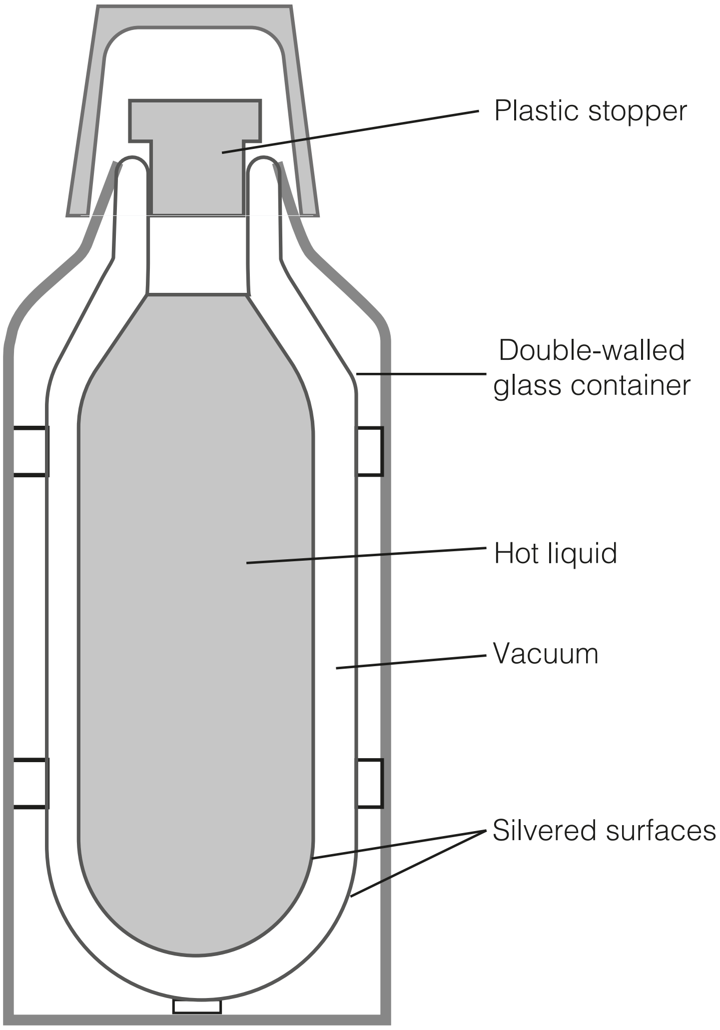

Figure 1.02: Diagram of a thermos

Science as a human endeavour

Window Insulation

Many Australian homes were built during a time when electricity was inexpensive and the danger posed by climate change was underappreciated. Little thought was given to thermal insulation, and many household windows are constructed of a single pane of glass in an aluminium frame.

A rising interest in home energy efficiency led by the environmentally and economically conscious has caused a surge in double-glazed window retrofitting. Double-glazed windows use two panes of glass with an air gap to reduce thermal exchange by 60–80%, keeping the heat in during winter, and out during summer.

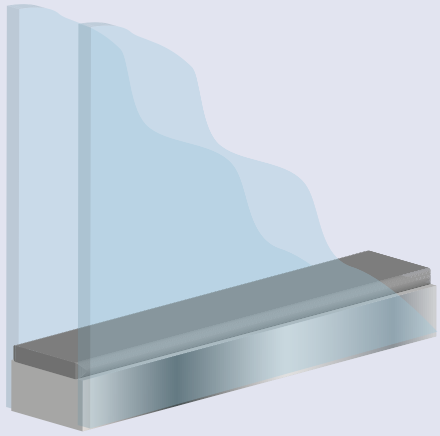

Figure 1.03: Cut-away diagram of double-glazed windowpane

Electrical Conductivity

The particles in a material may be neutral or may carry an electric charge. The motion of electric charge is called **current electricity** (or just ‘electricity’), and the ability of a material to carry electricity through the movement of its charged particles is called **electrical conductivity**.

Some materials contain charged particles that are free to move with little resistance; these are good **electrical conductors**. Metals (e.g., copper) are good conductors because they have delocalised electrons which are free to move. As shown in Figure 1.04, dissolved ions (e.g., sodium chloride dissolved in seawater) will also move toward electrodes with opposite charges. The motion of these ions represents a flow of electricity, making solutions of ionic substances good conductors. Pure water contains no free charges and does not conduct electricity.

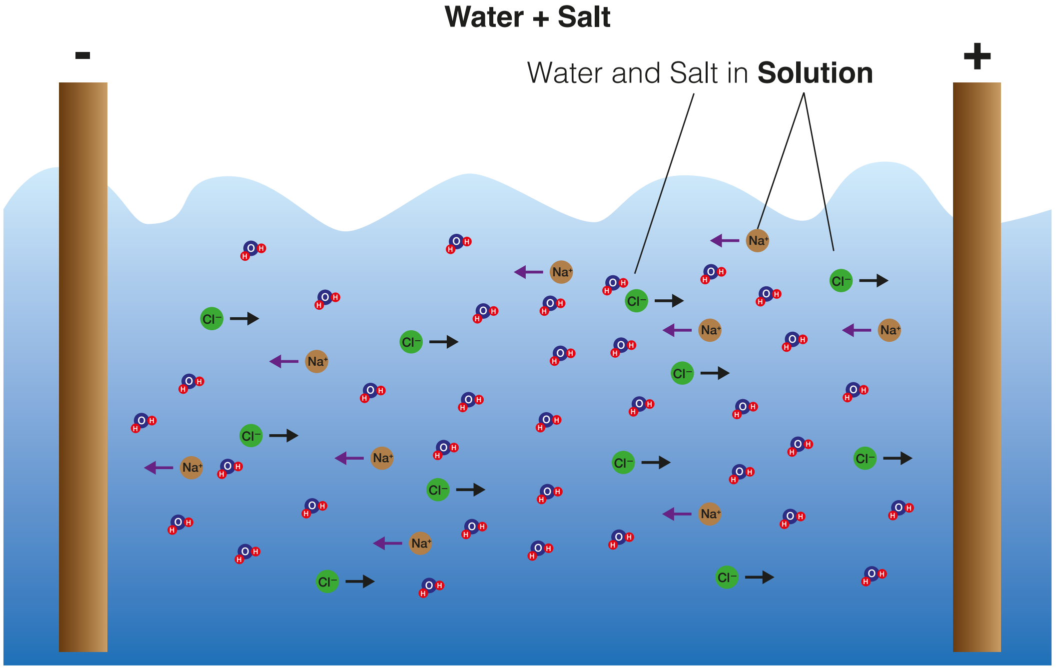

Figure 1.04: Ionic substances dissolved in water can carry electricity

For applications involving transmitting electricity, such as electrical wiring, high conductivity is desirable.

Other substances can carry electricity, but the charged particles encounter more resistance as they do so, and this causes the material to heat up as electricity is transmitted. These are called ‘**high-resistance conductors**’, and usually consist of metal **alloys** that have been specifically designed with high resistance and high melting points in order to reliably produce heat when operated (e.g., the heating element in an electric oven). One common example is nichrome, an alloy of nickel and chrome.

Many materials cannot conduct electricity at all, either because they contain charged particles that are not free to move or no charged particles at all; these are **electrical insulators**. Examples include gases (nitrogen, oxygen, etc) and most non-metallic solids (glass, rubber, plastic, dry wood, etc.). Electrical insulators are used to control and limit electrical current. For example, electrical wiring is coated with plastic to prevent electricity from being conducted into objects the wire is touching.

Changes of State

Changes of state between solid, liquid, and gas phases are physical changes because they do not change the chemical identity of the material. When water freezes into ice, no chemical change has occurred: both ice and water are composed of molecules of water (H_2O). The melting point and boiling point of a substance are therefore intensive physical properties.

Melting Point

Solid materials are composed of particles that are bonded together in a rigid lattice. The position of the particles, relative to other particles in the same material, doesn't change over time. However, the particles do vibrate with heat energy, and this determines the temperature of the solid material. If sufficient thermal energy is transferred to the material, its temperature becomes high enough that the particles can break out of the lattice and begin to move relative to one another. The solid becomes a liquid; this process is called **melting**.

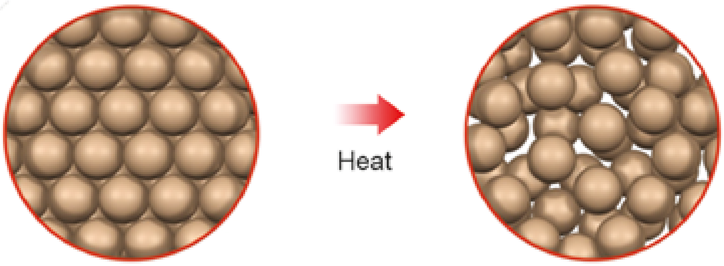

Figure 1.05: The change in behaviour of particles at the melting point

The temperature at which the transition from solid to liquid occurs is called the **melting point** and is characteristic of materials at defined pressures. For example, water has a melting point of 0 °C at atmospheric pressure, while sodium chloride has a melting point of 801 °C. The reverse transition, from liquid to solid, occurs at precisely the same temperature, so the "freezing point" of a material is always identical to the melting point.

Materials with high melting points are used when an object must withstand extremely high temperatures without melting. For example, kilns are usually made from brick rather than metal, as most metals have melting points lower than the temperature necessary for heating clay and other ceramics to set them.

Boiling Point

Liquid materials are composed of particles that are held together less tightly than those in solids. Particles in liquids can move relative to one another, but the particles remain bound together as a whole. If sufficient thermal energy is transferred to the material, its temperature becomes high enough that each particle can overcome the attractive forces and break away from the other particles altogether. The liquid becomes a gas; this process is called **boiling**.

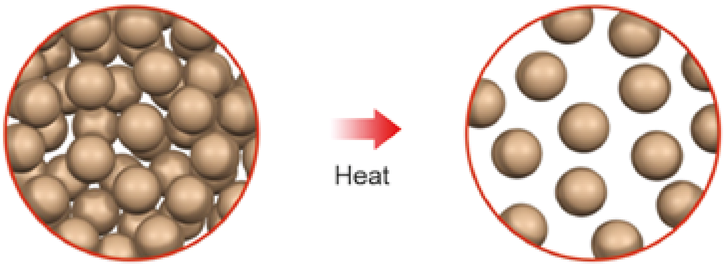

Figure 1.06: The change in behaviour of particles at the boiling point

The temperature at which the transition from liquid to gas occurs is called the **boiling point** and is also characteristic of materials at defined pressures. For example, water has a boiling point of 100 °C, while ethanol (alcohol) has a boiling point of 78 °C. The reverse transition, from gas to liquid, occurs at precisely the same temperature, so the "condensation point" of a material is always identical to the boiling point.

Liquids with high boiling points are used as coolants because this reduces the risk that the liquid will evaporate into a gas, which could cause an explosion. For example, commercially available coolant mixtures for vehicles usually have a boiling point above 120 °C, which is safer than using water.

Chemical Properties

A **chemical property** describes the way a material can undergo chemical changes. Observing a chemical property always requires a chemical reaction to occur, and the original substance must change its identity in that process.

Example

Acidity is a chemical property: it is a measure of the ability of a substance to donate a hydrogen cation (H^+). Sulfuric acid (H_2SO_4) is much more acidic than water (H_2O) because the hydrogen atoms in sulfuric acid can more easily take part in reactions. Sulfuric acid can rapidly dissolve metals because of its high acidity. However, this can only be observed by allowing the sulfuric acid to react with the metal, and this process consumes and transforms the sulfuric acid itself.

Chemical properties are the focus of Topics 5 and 6.

Questions

1. Most substances on Earth exist as either solids, liquids, or gases.

(a) In the three boxes below, draw a representation of the arrangement of particles in each of the three states of matter.

solid	**liquid**	**gas**

(3 marks) **KA1**

(b) With reference to the particles comprising the liquid, explain why a liquid has a defined volume but not a defined shape.

(c) Define the term ‘boiling point’.

2. For each of the following items, identify the property or properties of the material that make it suited to that use.

Material	Use	Property/Properties
aluminium	cookware	high thermal conduction high melting point
plastic	cookware handles	
wool	gloves	
copper	wiring	
nichrome	heating elements	
Kevlar	bulletproof vests	
gelatin	medicated gel capsules	

(6 marks) **KA1**

3. Fibreglass insulation used in walls and roof spaces consists of extremely fine glass fibres with pockets of air trapped between them.

Figure 1.07: Fibreglass insulation

(a) Glass is a moderately good thermal conductor. Describe the process of thermal conduction.

(b) Gases are very poor thermal conductors. Explain how the arrangement of particles in a gas reduces the rate of thermal exchange.

(c) Explain how fibreglass can be an excellent thermal insulator despite being made from glass.

Science understanding

Nanomaterials are substances that contain particles in the size range 1–100 nm.

- Suggest uses of materials, including nanomaterials, given their properties and vice versa.

© Copyright SACE 2022

Solubility, conductivity, and melting and boiling points are examples of **bulk properties**, which are properties caused by many particles acting together (e.g., although copper is an excellent electrical conductor, one copper atom alone cannot conduct electricity).

"Nano" is the SI prefix meaning "one billionth", so a nanometre is one billionth the length of a metre. The full stop at the end of this sentence is approximately 1 000 000 nanometres wide. Many materials display quite different properties when divided into grains or pieces smaller than 100 nanometres.

A sugar molecule is approximately one nanometre in width, and even some atoms have a radius of more than one quarter of a nanometre. At the scale of nanomaterials, atoms and molecules are large enough that materials cannot be treated as continuous substances. The number and arrangement of the individual atoms or molecules becomes relevant.

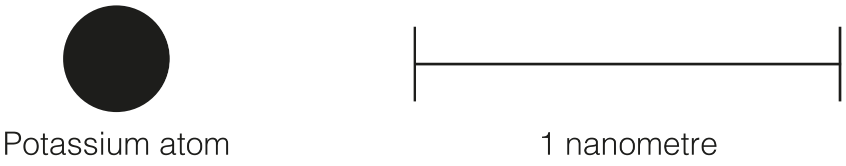

Figure 1.08: Scale of a single potassium atom

A defining feature of nanomaterials is their enormous surface area to volume ratio; greater surface area allows for more efficient catalysis of chemical reactions.

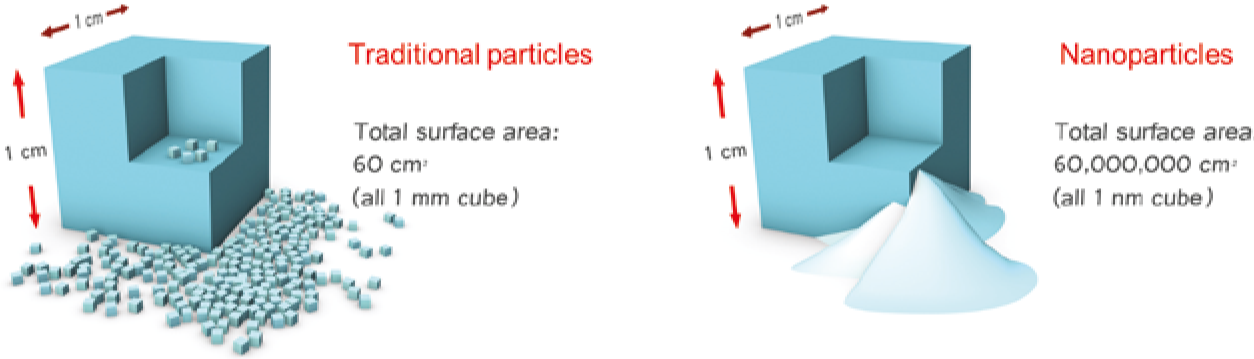

Figure 1.09: Comparison of the surface area to volume ratio of traditional materials and nanoparticles

Science as a human endeavour

Contemporary Nanotechnology Applications

Applications of nanoscale materials are many and varied.

In consumer electronics, many modern screens use Organic Light-Emitting Diode (OLED) technology, which is made from nanostructured polymer films. Unlike earlier technologies, which used colour pixels in front of a backlight, each pixel in an OLED screen emits red, green, or blue light independently. This allows for much deeper blacks: when a pixel is off, it emits no light.

In the environmental sphere, nanoscale filters are being developed which can absorb and remove large amounts of pollutants from drinking water. This reduces the amount of money and material required at large-scale water treatment plants. Large 'sponges' which can absorb many times their own weight in oil can also be used to aid clean-up efforts after major oil spills.

Some nanoparticles have useful medical properties. Silver nanoparticles can kill bacteria without harming larger organisms and have been included in some bandages. Iron oxide nanoparticles have been found to bind very well to cancer cells, which allows tiny cancerous tumours to be seen on MRI scans much more easily.

Nanomaterial science is still in its infancy, and it is usually difficult or impossible to predict the properties of a nanomaterial based on its structure. Scientists in many fields are working on measuring the properties of different nanomaterials to find useful applications.

Example

In its bulk state, gold is a yellow, non-reactive metal. However, nanoparticles of gold can be wildly different colours depending on their specific size, including red, green, and purple. Gold nanoparticles can also be used as a catalyst, and this too depends on specific size: a nanocluster made of 28 gold atoms might catalyse one reaction, while a nanocluster made of 38 gold atoms might catalyse a different reaction.

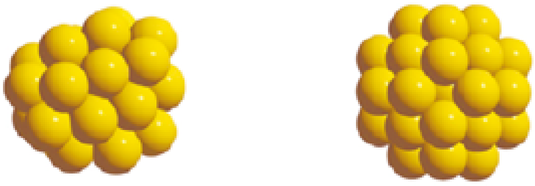

Figure 1.10: Au_{28} cluster and Au_{38} cluster

Science as a human endeavour

Virus Nanoparticles

A single virus particle is usually between 20–200 nanometres in size. Viruses straddle the border between living and non-living: although they are able to reproduce very effectively in the right conditions, they fulfill very few of the other characteristics of life. Some scientists argue that viruses should be definitively classified as non-living, which would make them natural nanomaterials—the most dangerous group of nanomaterials ever discovered!

Synthetic lipid nanoparticles were critical in the development of the mRNA vaccines which received widespread attention during the COVID-19 pandemic. The nanoparticles are used as an 'envelope' for the delivery of mRNA molecules into cells. In the absence of these envelopes, the highly unstable mRNA would break down too quickly for it to be effective at initiating an immune response.

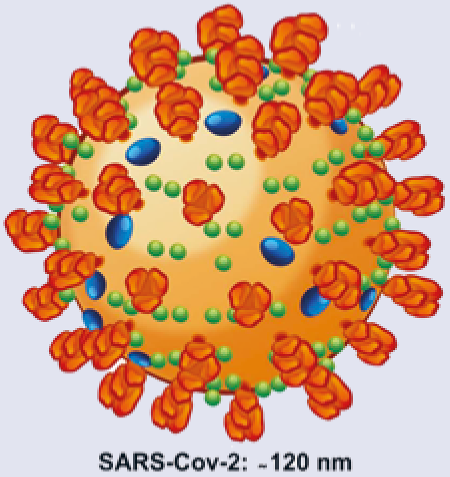

Figure 1.11: The virus that causes COVID-19 has a diameter of approximately 120 nm

Questions

4. Most commercially available sunscreens include tiny grains of titanium dioxide with diameters in the range 6–108 nm. Titanium dioxide is called a “physical blocker” because it prevents UV radiation from reaching the skin by reflecting and scattering it.
   (a) Explain why the titanium dioxide is considered to be a nanomaterial.

   (b) Identify the property of titanium dioxide nanoparticles that makes them useful in sunscreens.

5. The airline industry would like to consume less jet fuel to save on costs and reduce its emissions of carbon dioxide. It has been discovered that incorporating cobalt nanoparticles into the aluminium used to make aeroplanes can increase its strength by up to 100 times.
   (a) Describe the range of possible size of a cobalt nanoparticle.

   (b) Explain how increasing the strength of the aluminium used to make the aeroplane fuselage could lead to lower jet fuel consumption in the long-term.

6. Carbon nanotubes have excellent electrical conductivity and are extremely thin and long. They have been incorporated into some solar panels to increase the efficiency of electricity generation.
   (a) Provide a definition of the term ‘nanotechnology’.

   (b) Identify and explain one benefit of nanotechnology to consumers.

Science understanding

Differences in the properties of substances in a mixture can be used to separate them.

- Identify how the components of a mixture can be separated by methods including filtration, distillation, and evaporation.

All materials are classified as either pure substances or mixtures.

Pure substances are composed of one type of particle. **Elements** are pure substances that contain only one type of atom (e.g., helium, iron, nitrogen), while **compounds** are pure substances containing different types of atoms that are chemically bonded in fixed ratios (e.g., water, methane, sodium chloride).

Substances that are not pure are called mixtures. **Mixtures** contain more than one element or compound that have been physically combined, but which have *not* reacted chemically with one another. Mixtures are classified as either homogenous or heterogeneous.

Homogenous mixtures are thoroughly mixed. From the Greek, *homo* means ‘same’, and each part of a homogenous mixture is similar in composition and properties to every other part of the mixture, even at the scale of atoms and molecules. Examples of homogenous mixtures include saltwater, alloys, and air.

Heterogeneous mixtures are incompletely mixed. Also from the Greek, *hetero* means 'different', and different parts of a heterogeneous mixture are distinguishable from each other in composition and character. Examples of heterogeneous mixtures include soil, salad dressing, and crude oil. Some biological mixtures can appear to be homogenous at the macro scale but are actually heterogeneous at the scale of atoms and molecules.

Example

Blood seems uniform to the naked eye, but the presence of different cells means that not all parts of the mixture are identical: red blood cells contain different elements to white blood cells. Because the components are not thoroughly mixed at the molecular level, the mixture is heterogeneous.

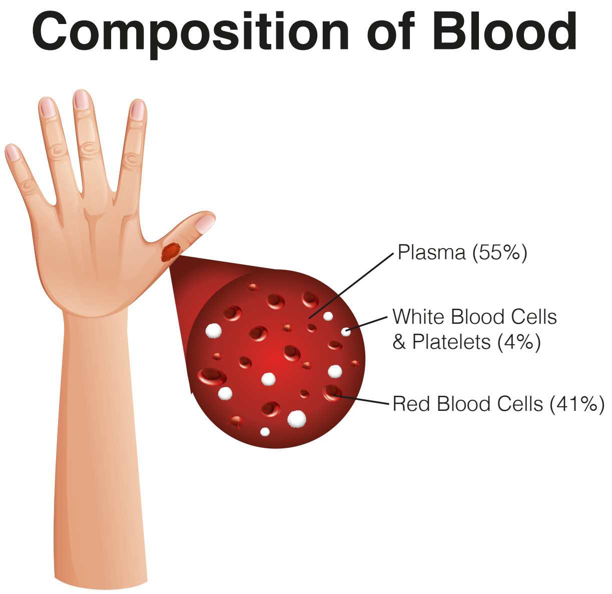

Figure 1.12: Cellular composition of blood

Mixtures, both homogenous and heterogeneous, can be separated by exploiting differences in their component substances.

Filtration

Filtration is used to separate heterogeneous mixtures that contain solid particles in a liquid medium. The mixture is passed through a **filter**, which has tiny openings that are large enough to allow liquid molecules to pass through while preventing the passage of the larger solid grains. Both the solid and the liquid components can be **isolated** and retained.

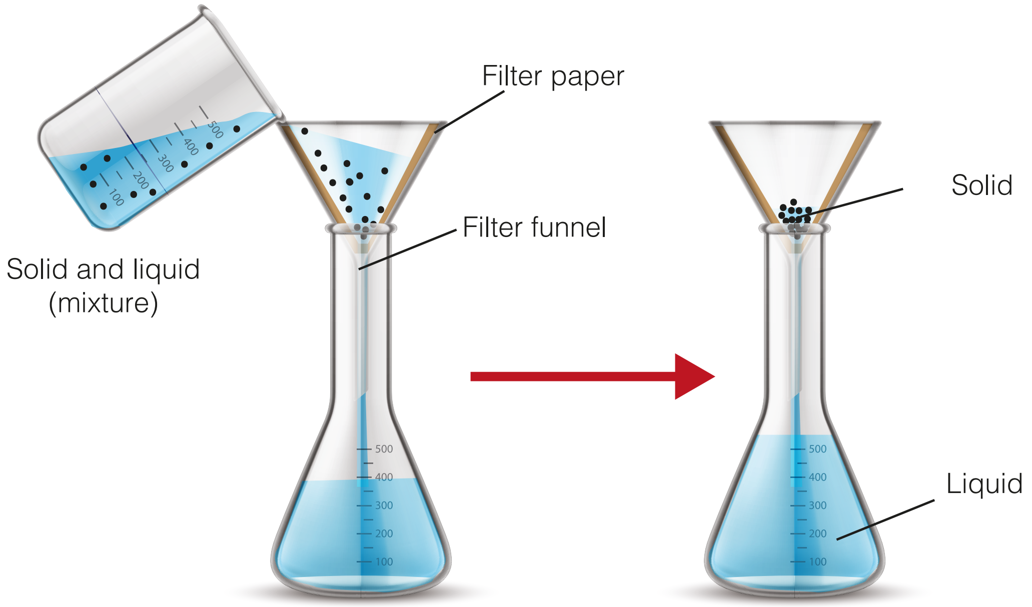

Figure 1.13: Laboratory setup for simple filtration

Evaporation

Evaporation exploits differences in boiling points to separate a liquid solvent from one or more solutes. The mixture is heated near to or above the boiling point of the solvent and the solvent evaporates. The solute, which has a much higher boiling point, remains in the evaporating dish. The solute(s) are retained but the solvent is lost.

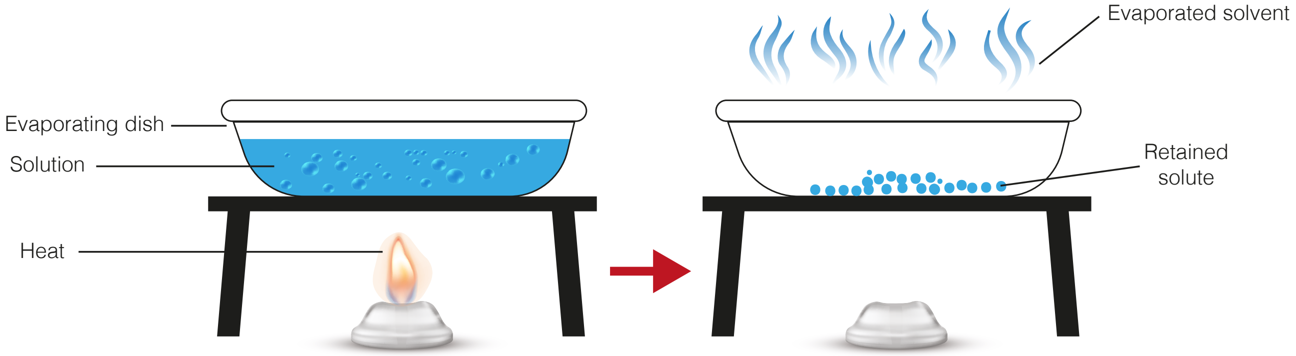

Figure 1.14: Laboratory setup for simple evaporation

Simple Distillation

Simple distillation is used to separate a liquid with a low-boiling point from other substances. Heat is transferred to the mixture and the component with the lowest boiling point vaporises. The vapour enters a condenser where it cools into a liquid and is collected; this is called the **distillate**. The low-boiling point liquid is isolated, and the other components of the mixture are retained.

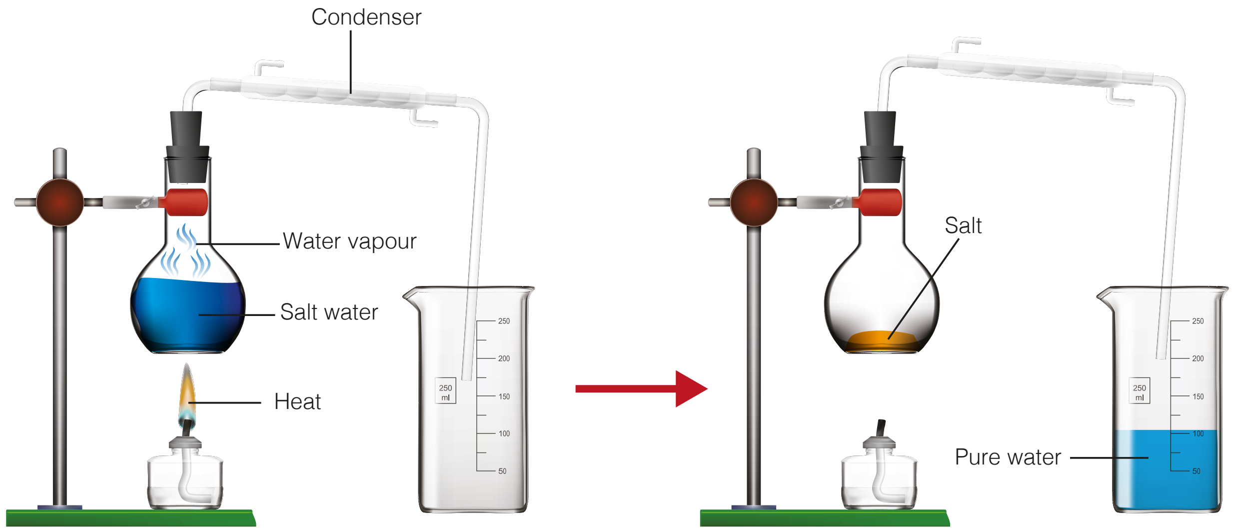

Figure 1.15: Laboratory setup for simple distillation

Science as a human endeavour

Cannabidiol Oil

Cannabidiol (CBD), a compound found in the hemp plant, is used to treat epilepsy. It can be extracted from the plant using **steam distillation**. Water is heated to generate steam, which is passed through the plant matter to vaporise cannabidiol (and some other cannabinoids). The extracts are carried with the steam into a condenser where they reform into liquids and are collected in a flask.

A similar process can be used to extract essential oils from many plants.

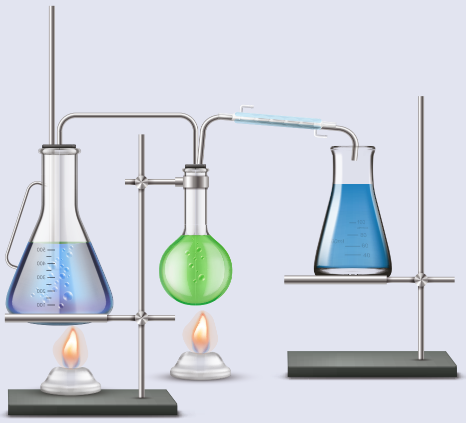

Figure 1.16: Steam distillation apparatus

Fractional Distillation

Fractional distillation allows liquids with similar boiling points to be separated. The technique is similar to simple distillation, but the apparatus includes a **fractionating column** with increased internal surface area for the condensation of vapours.

Figure 1.17: Fractionating columns contain beads, rings, or warped surfaces for greater surface area

The use of a fractionating column allows for much greater control over the process as the distillate flows into the condenser. The receiving flask can be swapped so as to collect different substances in different flasks. This technique is used to separate the components of crude oil.

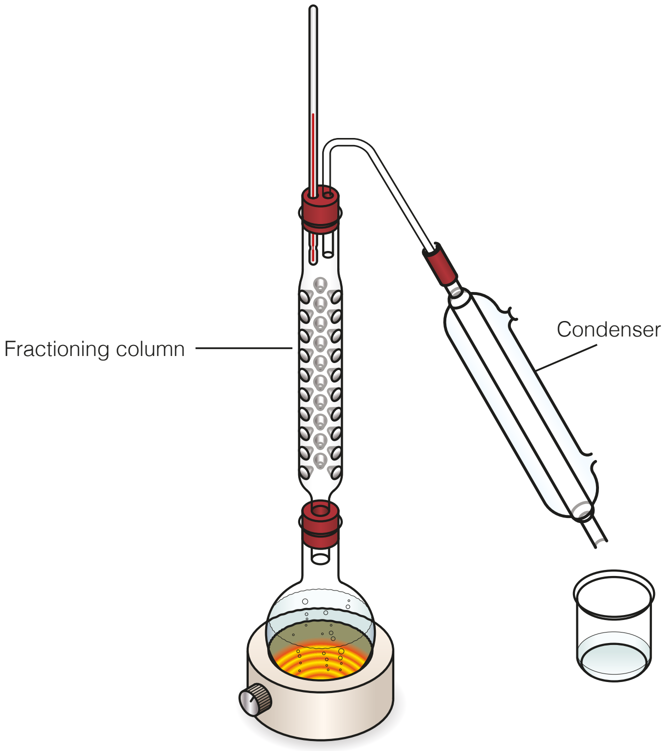

Figure 1.18: Laboratory setup for fractional distillation

Questions

7. Classify each of the following as a pure substance or mixture. For each substance, classify it as either an element or compound. For each mixture, classify it as either homogeneous or heterogeneous.

	Substances		**Mixtures**	
	Element	**Compound**	**Homogenous**	**Heterogeneous**
a lead weight	✓			
clear apple juice				
baking soda ($NaHCO_3$)				
air				
helium				
beach sand				
concrete				
carbon dioxide				
milk				
sugar ($C_{12}H_{22}O_{11}$)				
ice cream sundae				

(10 marks) **KA1**

8. Figure 1.19 shows a mixture containing potassium nitrate dissolved in water and a suspension of lead iodide, the yellow solid.

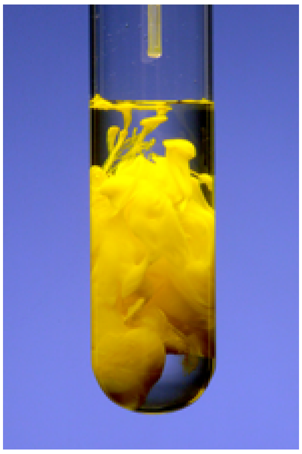

Figure 1.19: A mixture of aqueous potassium nitrate, liquid water, and solid lead iodide

(a) State and explain whether the mixture is homogenous or heterogeneous.

(b) Identify and describe a method of separating lead iodide from the mixture.

(c) The boiling points of water and potassium iodide are 100 °C and 1330 °C respectively. Describe and explain how evaporation can be used to separate the two materials.

(d) Name one other method that could be used to separate the water from the potassium iodide.

9. Methanol (wood alcohol) is a poisonous by-product of the fermentation process that produces ethanol (drinking alcohol). When spirits such as vodka are distilled, the first part of the distillate can contain a significant proportion of methanol and is therefore discarded. Some properties of methanol and ethanol are shown below.

Property	Methanol	Ethanol
Flammability	Very flammable	Very flammable
Density	0.792 g/cm^3	0.789 g/cm^3
Electrical Conductivity	Not conductive	Not conductive
Boiling Point	65 °C	78 °C
Appearance	Clear colourless liquid	Clear colourless liquid

(a) Identify the property that is used to separate methanol and ethanol during distillation.

(b) Describe the process of distillation.

(c) After discarding methanol, the ethanol distillate that is obtained is a pure substance. Provide a definition of a pure substance.