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SCIENCE DOUBLE AWARD

Student Book

Brian Arnold, Phil Bradfield, Jim Clark, Penny Johnson, Steve Owen, Steve Potter, Steve Woolley, Rachel Yu

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BIOLOGY

UNIT 1: ORGANISMS AND LIFE PROCESSES

UNIT 2: ANIMAL PHYSIOLOGY

UNIT 3: PLANT PHYSIOLOGY

UNIT 4: ECOLOGY AND THE ENVIRONMENT

UNIT 5: VARIATION AND SELECTION

UNIT 6: MICROORGANISMS AND GENETIC MODIFICATION

CHEMISTRY

UNIT 1: PRINCIPLES OF CHEMISTRY

UNIT 2: INORGANIC CHEMISTRY

UNIT 3: PHYSICAL CHEMISTRY

UNIT 4: ORGANIC CHEMISTRY

PHYSICS

UNIT 1: FORCES AND MOTION

UNIT 2: ELECTRICITY

UNIT 3: WAVES

UNIT 4: ENERGY RESOURCES AND ENERGY TRANSFER

UNIT 5: SOLIDS, LIQUIDS AND GASES

UNIT 6: MAGNETISM AND ELECTROMAGNETISM

UNIT 7: RADIOACTIVITY AND PARTICLES

UNIT 8: ASTROPHYSICS

ABOUT THIS BOOK

This book is written for students following the Edexcel International GCSE (9–1) Science Double Award specification. You will need to study all of the content in this book for your examinations, except anything in Extension boxes.

In each unit of this book, there are concise explanations and worked examples, plus numerous exercises that will help you build up confidence. The book also describes the methods for carrying out all of the required practicals.

The language throughout this textbook is graded for speakers of English as an additional language (EAL), with advanced Science-specific terminology highlighted and defined in the glossaries on the eBook. A list of command words at the back of the book will help you to learn the language you will need in your examinations.

You will also find that questions in this book have Progression icons and Skills tags. The Progression icons refer to Pearson's Progression scale. This scale – from 1 to 12 – tells you what level you have reached in your learning and will help you to see what you need to do to progress to the next level. Furthermore, Edexcel have developed a Skills grid showing the skills you will practise throughout your time on the course. The skills in the grid have been matched to questions in this book to help you see which skills you are developing. You can find Pearson's Progression scale at www.pearsonglobalschools.com/igscienceprogression along with guidelines on how to use it. Edexcel's skills grid can be found on their website.

Learning Objectives show what you will learn in each chapter.

Looking Ahead tells you what you would learn if you continued your study of Science to a higher level, such as International A Level.


WAVES PROPERTIES OF WAVES 559

7 PROPERTIES OF WAVES

Talking to someone using a mobile phone is something most of us do several times a day. The technology that had to be developed for this to happen was based on a thorough understanding of the properties of waves.

In this chapter you will learn about different types of waves and their properties (characteristics).

▲ Figure 7.1 Using microwaves to communicate

LEARNING OBJECTIVES

- Explain the difference between longitudinal and transverse waves
- Know the definitions of amplitude, wavefront, frequency, wavelength and period of a wave
- Know that waves transfer energy and information without transferring matter
- Know and use the relationship between the speed, frequency and wavelength of a wave:
  wave speed = frequency × wavelength
  $v = f \times \lambda$
- Use the relationship between frequency and time period:
  $\text{frequency} = \frac{1}{\text{time period}}$
  $f = \frac{1}{T}$
- Use the above relationships in different contexts including sound waves and electromagnetic waves
- Explain that all waves can be reflected and refracted
- Explain why there is a change in the observed frequency and wavelength of a wave when its source is moving relative to an observer, and that this is known as the Doppler effect

UNITS

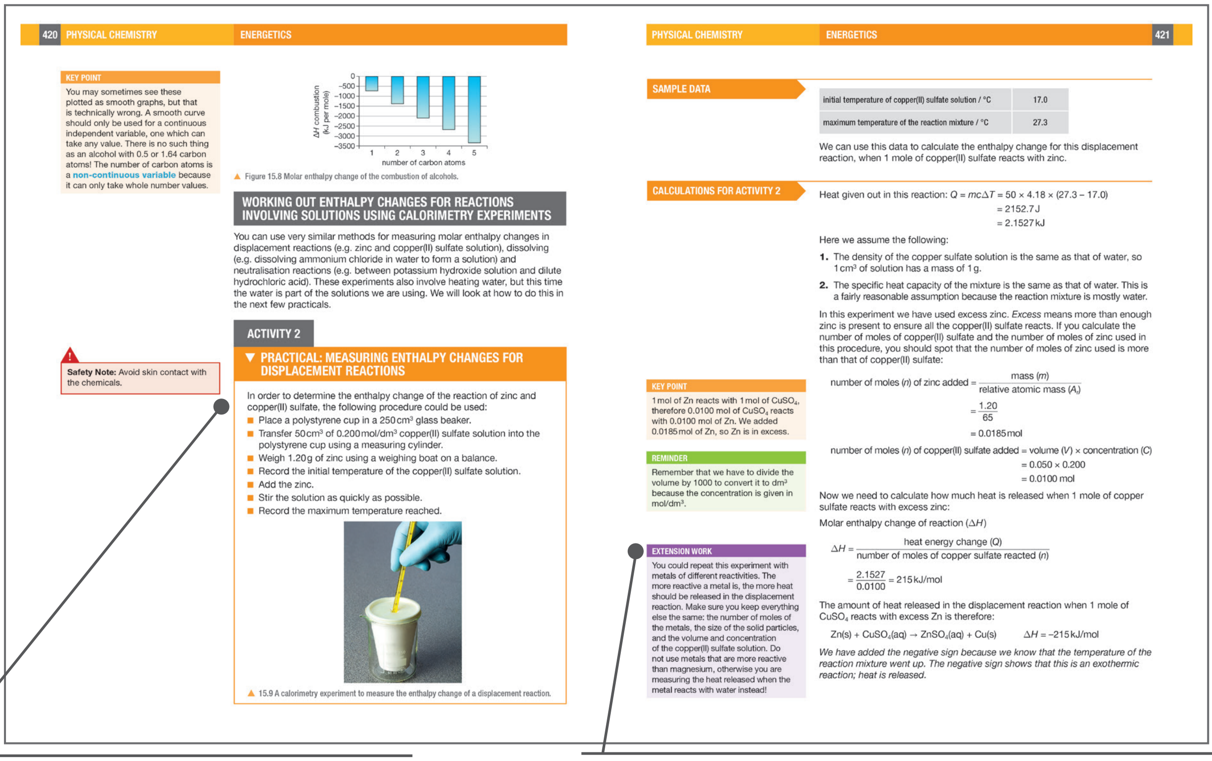
In this unit, you will need to use degrees (°) as the unit of angle, hertz (Hz) as the unit of frequency, metre (m) as the unit of length, metre per second (m/s) as the unit of speed and second (s) as the unit of time.

WHAT ARE WAVES?

Waves are a way of transferring energy from place to place. As we can see in Figure 7.1 we often use them to transfer information. All these transfers take place with no matter being transferred.

▲ Figure 7.2 Waves are produced if we drop a stone into a pond. The circular wavefronts spread out from the point of impact, carrying energy in all directions, but the water in the pond does not move from the centre to the edges.

Unit boxes tell you which units – for example, metres, grams and seconds – you will need to know and use for the study of a topic.


420 PHYSICAL CHEMISTRY ENERGETICS

KEY POINT

You may sometimes see these plotted as smooth graphs, but that is technically wrong. A smooth curve should only be used for a continuous independent variable, one which can take any value. There is no such thing as an alcohol with 0.5 or 1.64 carbon atoms! The number of carbon atoms is a **non-continuous variable** because it can only take whole number values.

Figure 15.8 Molar enthalpy change of the combustion of alcohols.

WORKING OUT ENTHALPY CHANGES FOR REACTIONS INVOLVING SOLUTIONS USING CALORIMETRY EXPERIMENTS

You can use very similar methods for measuring molar enthalpy changes in displacement reactions (e.g. zinc and copper(II) sulfate solution), dissolving (e.g. dissolving ammonium chloride in water to form a solution) and neutralisation reactions (e.g. between potassium hydroxide solution and dilute hydrochloric acid). These experiments also involve heating water, but this time the water is part of the solutions we are using. We will look at how to do this in the next few practicals.

Safety Note: Avoid skin contact with the chemicals.

ACTIVITY 2

PRACTICAL: MEASURING ENTHALPY CHANGES FOR DISPLACEMENT REACTIONS

In order to determine the enthalpy change of the reaction of zinc and copper(II) sulfate, the following procedure could be used:

- Place a polystyrene cup in a 250 cm^3 glass beaker.
- Transfer 50 cm^3 of 0.200 mol/dm^3 copper(II) sulfate solution into the polystyrene cup using a measuring cylinder.
- Weigh 1.20 g of zinc using a weighing boat on a balance.
- Record the initial temperature of the copper(II) sulfate solution.
- Add the zinc.
- Stir the solution as quickly as possible.
- Record the maximum temperature reached.

15.9 A calorimetry experiment to measure the enthalpy change of a displacement reaction.

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SAMPLE DATA

initial temperature of copper(II) sulfate solution / °C	17.0
maximum temperature of the reaction mixture / °C	27.3

We can use this data to calculate the enthalpy change for this displacement reaction, when 1 mole of copper(II) sulfate reacts with zinc.

CALCULATIONS FOR ACTIVITY 2

Heat given out in this reaction: $Q = mc\Delta T = 50 \times 4.18 \times (27.3 - 17.0)$
$= 2152.7\,J$
$= 2.1527\,kJ$

Here we assume the following:

1. The density of the copper sulfate solution is the same as that of water, so 1 cm^3 of solution has a mass of 1 g.
2. The specific heat capacity of the mixture is the same as that of water. This is a fairly reasonable assumption because the reaction mixture is mostly water.

In this experiment we have used excess zinc. *Excess* means more than enough zinc is present to ensure all the copper(II) sulfate reacts. If you calculate the number of moles of copper(II) sulfate and the number of moles of zinc used in this procedure, you should spot that the number of moles of zinc used is more than that of copper(II) sulfate:

$$\text{number of moles } (n) \text{ of zinc added} = \frac{\text{mass } (m)}{\text{relative atomic mass } (A_r)} = \frac{1.20}{65} = 0.0185\,\text{mol}$$

$$\text{number of moles } (n) \text{ of copper(II) sulfate added} = \text{volume } (V) \times \text{concentration } (C) = 0.050 \times 0.200 = 0.0100\,\text{mol}$$

KEY POINT

1 mol of Zn reacts with 1 mol of $CuSO_4$, therefore 0.0100 mol of $CuSO_4$ reacts with 0.0100 mol of Zn. We added 0.0185 mol of Zn, so Zn is in excess.

REMINDER

Remember that we have to divide the volume by 1000 to convert it to dm^3 because the concentration is given in mol/dm^3.

Now we need to calculate how much heat is released when 1 mole of copper sulfate reacts with excess zinc:

Molar enthalpy change of reaction (ΔH)

$$\Delta H = \frac{\text{heat energy change } (Q)}{\text{number of moles of copper sulfate reacted } (n)} = \frac{2.1527}{0.0100} = 215\,\text{kJ/mol}$$

The amount of heat released in the displacement reaction when 1 mole of $CuSO_4$ reacts with excess Zn is therefore:

$Zn(s) + CuSO_4(aq) \rightarrow ZnSO_4(aq) + Cu(s) \qquad \Delta H = -215\,kJ/mol$

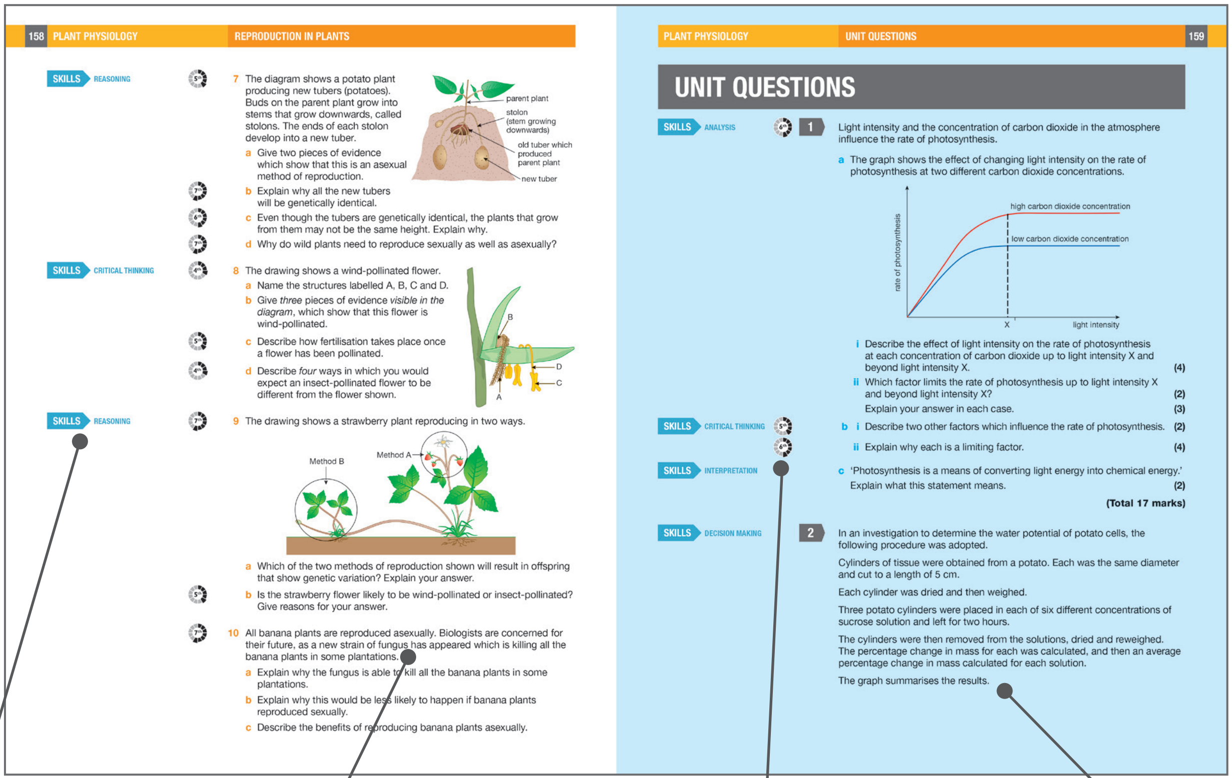
We have added the negative sign because we know that the temperature of the reaction mixture went up. The negative sign shows that this is an exothermic reaction; heat is released.

EXTENSION WORK

You could repeat this experiment with metals of different reactivities. The more reactive a metal is, the more heat should be released in the displacement reaction. Make sure you keep everything else the same: the number of moles of the metals, the size of the solid particles, and the volume and concentration of the copper(II) sulfate solution. Do not use metals that are more reactive than magnesium, otherwise you are measuring the heat released when the metal reacts with water instead!

Practicals describe the methods for carrying out all of the practicals you will need to know for your examination.

Extension work boxes include content that is not on the specification and which you do not have to learn for your examination. However, it will help to extend your understanding of the topic.


158 PLANT PHYSIOLOGY REPRODUCTION IN PLANTS

SKILLS REASONING

7 The diagram shows a potato plant producing new tubers (potatoes). Buds on the parent plant grow into stems that grow downwards, called stolons. The ends of each stolon develop into a new tuber.

a Give two pieces of evidence which show that this is an asexual method of reproduction.
b Explain why all the new tubers will be genetically identical.
c Even though the tubers are genetically identical, the plants that grow from them may not be the same height. Explain why.
d Why do wild plants need to reproduce sexually as well as asexually?

SKILLS CRITICAL THINKING

8 The drawing shows a wind-pollinated flower.

a Name the structures labelled A, B, C and D.
b Give *three* pieces of evidence *visible in the diagram*, which show that this flower is wind-pollinated.
c Describe how fertilisation takes place once a flower has been pollinated.
d Describe *four* ways in which you would expect an insect-pollinated flower to be different from the flower shown.

SKILLS REASONING

9 The drawing shows a strawberry plant reproducing in two ways.

a Which of the two methods of reproduction shown will result in offspring that show genetic variation? Explain your answer.
b Is the strawberry flower likely to be wind-pollinated or insect-pollinated? Give reasons for your answer.

10 All banana plants are reproduced asexually. Biologists are concerned for their future, as a new strain of fungus has appeared which is killing all the banana plants in some plantations.
a Explain why the fungus is able to kill all the banana plants in some plantations.
b Explain why this would be less likely to happen if banana plants reproduced sexually.
c Describe the benefits of reproducing banana plants asexually.

PLANT PHYSIOLOGY UNIT QUESTIONS 159

UNIT QUESTIONS

SKILLS ANALYSIS

1 Light intensity and the concentration of carbon dioxide in the atmosphere influence the rate of photosynthesis.

a The graph shows the effect of changing light intensity on the rate of photosynthesis at two different carbon dioxide concentrations.

i Describe the effect of light intensity on the rate of photosynthesis at each concentration of carbon dioxide up to light intensity X and beyond light intensity X. (4)
ii Which factor limits the rate of photosynthesis up to light intensity X and beyond light intensity X? (2)
Explain your answer in each case. (3)

SKILLS CRITICAL THINKING

b i Describe two other factors which influence the rate of photosynthesis. (2)
ii Explain why each is a limiting factor. (4)

SKILLS INTERPRETATION

c 'Photosynthesis is a means of converting light energy into chemical energy.'
Explain what this statement means. (2)

(Total 17 marks)

SKILLS DECISION MAKING

2 In an investigation to determine the water potential of potato cells, the following procedure was adopted.

Cylinders of tissue were obtained from a potato. Each was the same diameter and cut to a length of 5 cm.

Each cylinder was dried and then weighed.

Three potato cylinders were placed in each of six different concentrations of sucrose solution and left for two hours.

The cylinders were then removed from the solutions, dried and reweighed. The percentage change in mass for each was calculated, and then an average percentage change in mass calculated for each solution.

The graph summarises the results.

Skills tags tell you which skills you are practising in each question.

Chapter Questions test your knowledge of the topic in that chapter.

Progression icons show the level of difficulty according to the Pearson International GCSE Science Progression Scale.

Unit Questions test your knowledge of the whole unit and provide quick, effective feedback on your progress.

ASSESSMENT OVERVIEW

The following tables give an overview of the assessment for this course.

We recommend that you study this information closely to help ensure that you are fully prepared for this course and know exactly what to expect in the assessment.

BIOLOGY PAPER 1	SPECIFICATION	PERCENTAGE	MARK	TIME	AVAILABILITY
Written examination paper Paper code 4SD0/1B Externally set and assessed by Edexcel	Science Double Award	33.3%	110	2 hours	January and June examination series First assessment June 2019
CHEMISTRY PAPER 1	**SPECIFICATION**	**PERCENTAGE**	**MARK**	**TIME**	**AVAILABILITY**
Written examination paper Paper code 4SD0/1C Externally set and assessed by Edexcel	Science Double Award	33.3%	110	2 hours	January and June examination series First assessment June 2019
PHYSICS PAPER 1	**SPECIFICATION**	**PERCENTAGE**	**MARK**	**TIME**	**AVAILABILITY**
Written examination paper Paper code 4SD0/1P Externally set and assessed by Edexcel	Science Double Award	33.3%	110	2 hours	January and June examination series First assessment June 2019

ASSESSMENT OBJECTIVES AND WEIGHTINGS

ASSESSMENT OBJECTIVE	DESCRIPTION	% IN INTERNATIONAL GCSE
AO1	Knowledge and understanding of science	38%–42%
AO2	Application of knowledge and understanding, analysis and evaluation of science	38%–42%
AO3	Experimental skills, analysis and evaluation of data and methods in science	19%–21%

EXPERIMENTAL SKILLS

In the assessment of experimental skills, students may be tested on their ability to:

- solve problems set in a practical context
- apply scientific knowledge and understanding in questions with a practical context
- devise and plan investigations, using scientific knowledge and understanding when selecting appropriate techniques
- demonstrate or describe appropriate experimental and investigative methods, including safe and skilful practical techniques
- make observations and measurements with appropriate precision, record these methodically and present them in appropriate ways
- identify independent, dependent and control variables
- use scientific knowledge and understanding to analyse and interpret data to draw conclusions from experimental activities that are consistent with the evidence
- communicate the findings from experimental activities, using appropriate technical language, relevant calculations and graphs
- assess the reliability of an experimental activity
- evaluate data and methods taking into account factors that affect accuracy and validity.

CALCULATORS

Students are permitted to take a suitable calculator into the examinations. Calculators with QWERTY keyboards or that can retrieve text or formulae will not be permitted.

BIOLOGY UNIT 1 ORGANISMS AND LIFE PROCESSES

All living organisms are composed of microscopic units known as cells. These building blocks of life have a number of features in common, which allow them to grow, reproduce, and generate more organisms. In Chapter 1 we start by looking at the structure and function of cells, and the essential life processes that go on within them. Despite the fact that cells are similar in structure, there are many millions of different species of organisms. Chapter 2 looks at the diversity of living things and how we can classify them into groups on the basis of the features that they show.

1 LIFE PROCESSES

There are structural features that are common to the cells of all living organisms. In this chapter you will find out about these features and look at some of the processes that keep cells alive.

LEARNING OBJECTIVES

- Understand the characteristics shared by living organisms
- Describe cell structures and their functions, including the nucleus, cytoplasm, cell membrane, cell wall, mitochondria, chloroplasts, ribosomes and vacuole
- Know the similarities and differences in the structures of plant and animal cells
- Understand the role of enzymes as biological catalysts in metabolic reactions
- Understand how temperature changes can affect enzyme function, including changes to the shape of the active site
- Understand how enzyme function can be affected by changes in pH altering the active site
- Investigate how enzyme activity can be affected by changes in temperature
- Describe the differences between aerobic and anaerobic respiration
- Understand how the process of respiration produces ATP in living organisms
- Know that ATP provides energy for cells
- Know the word equation and balanced chemical symbol equation for aerobic respiration
- Know the word equations for anaerobic respiration
- Investigate the evolution of carbon dioxide and heat from respiring seeds or other suitable living organisms
- Understand the processes of diffusion, osmosis and active transport by which substances move into and out of cells
- Understand how factors affect the rate of movement of substances into and out of cells
- Investigate diffusion in a non-living system (agar jelly)
- Describe the levels of organisation within organisms – organelles, cells, tissues, organ systems

All living organisms are composed of units called **cells**. The simplest organisms are made from single cells (Figure 1.1) but more complex plants and animals are composed of millions of cells. In many-celled (**multicellular)** organisms, there may be hundreds of different types of cells with different structures. They are specialised so that they can carry out particular functions in the animal or plant. Despite all the differences, there are basic features that are the same in all cells.

▲ Figure 1.1 Many simple organisms have 'bodies' made from single cells. Here are four examples.

There are eight life processes which take place in most living things. Organisms:

- require nutrition – plants make their own food, animals eat other organisms
- respire – release energy from their food
- excrete – get rid of waste products
- respond to stimuli – are sensitive to changes in their surroundings
- move – by the action of muscles in animals, and slow growth movements in plants
- control their internal conditions – maintain a steady state inside the body
- reproduce – produce offspring
- grow and develop – increase in size and complexity, using materials from their food.

CELL STRUCTURE

This part of the book describes the cell structure of 'higher' organisms such as animals, plants and fungi. The cells of bacteria are simpler in structure and will be described in Chapter 2.

Most cells contain certain parts such as the nucleus, cytoplasm and cell membrane. Some cells have structures missing, for instance red blood cells are unusual in that they have no nucleus. The first chapter in a biology textbook will usually present diagrams of 'typical' plant and animal cells. In fact, there is really no such thing as a 'typical' cell. Humans, for example, are composed of hundreds of different kinds of cells – from nerve cells to blood cells, skin cells to liver cells. What we really mean by a 'typical' cell is a general diagram that shows all the features that you will find in most cells (Figure 1.2). However, not all these are present in *all* cells – for example the cells in the parts of a plant that are not green do not contain chloroplasts.

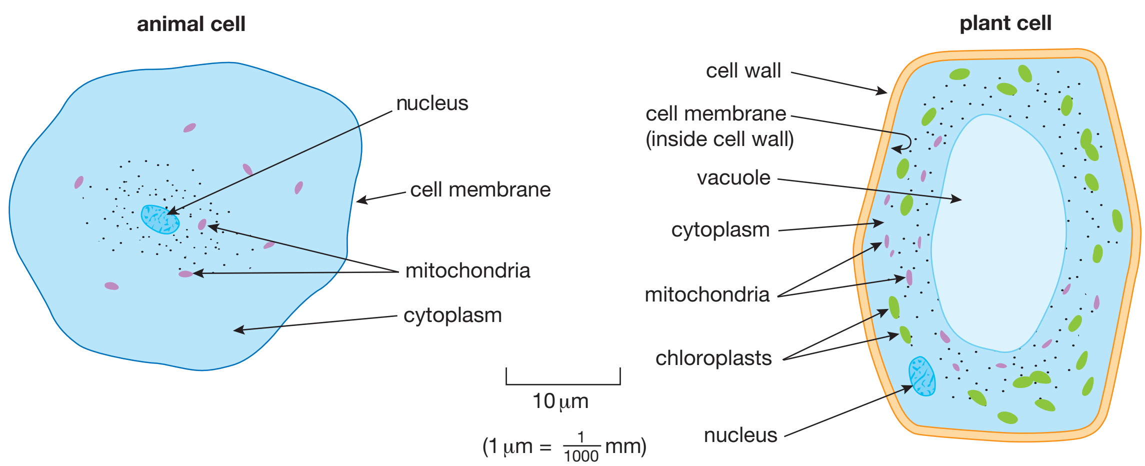
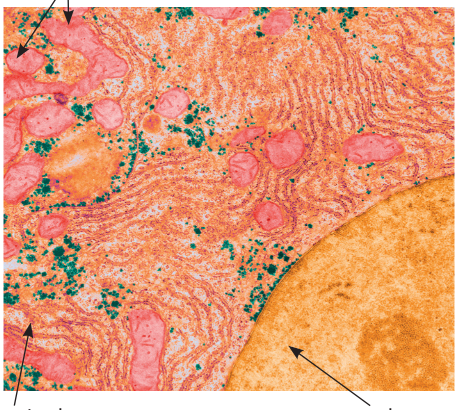


Figure 1.2 The structure of a 'typical' animal and plant cell.

The living material that makes up a cell is called **cytoplasm**. It has a texture rather like sloppy jelly, in other words somewhere between a solid and a liquid. Unlike a jelly, it is not made of one substance but is a complex material made of many different structures. You can't see many of these structures under an ordinary light microscope. An electron microscope has a much higher magnification and can show the details of these structures, which are called **organelles** (Figure 1.3).



▲ Figure 1.3 The organelles in a cell can be seen using an electron micropscope.

The largest organelle in the cell is the **nucleus**. Nearly all cells have a nucleus. The few types that don't are usually dead (e.g. the xylem vessels in a stem, Chapter 11) or don't live for very long (e.g. red blood cells, Chapter 5). The nucleus controls the activities of the cell. It contains **chromosomes** (46 in human cells) which carry the genetic material, or **genes**. Genes control the activities in the cell by determining which proteins the cell can make. The DNA remains in the nucleus, but the instructions for making proteins are carried out of the nucleus to the cytoplasm, where the proteins are assembled on tiny structures called **ribosomes**. A cell contains thousands of ribosomes, but they are too small to be seen through a light microscope.

One very important group of proteins found in cells are **enzymes.** Enzymes control the chemical reactions that take place in the cytoplasm.

All cells are surrounded by a **cell membrane**, sometimes called the cell *surface* membrane to distinguish it from other membranes inside the cell. This is a thin layer like a 'skin' on the surface of the cell. It forms a boundary between the cytoplasm of the cell and the outside. However, it is not a complete barrier. Some chemicals can pass into the cell and others can pass out. We say that the membrane is **partially permeable**. The membrane can go further than this and actually *control* the movement of some substances – it is **selectively permeable**.

One organelle that is found in the cytoplasm of all living cells is the **mitochondrion** (plural mitochondria). In cells that need a lot of energy such as muscle or nerve cells, there are many mitochondria. This gives us a clue to their function. They carry out some of the reactions of **respiration** (see page 11) releasing energy that the cell can use. Most of the energy from respiration is released in the mitochondria.

PLANT CELLS

All of the structures you have seen so far are found in both animal and plant cells. However, some structures are only ever found in plant cells. There are three in particular – the cell wall, a permanent vacuole and chloroplasts.

The **cell wall** is a layer of non-living material that is found outside the cell membrane of plant cells. It is made mainly of a carbohydrate called **cellulose**, although other chemicals may be added to the wall in some cells. Cellulose is a tough material that helps the cell keep its shape and is one reason why the 'body' of a plant has a fixed shape. Animal cells do not have a cell wall and tend to be more variable in shape. Plant cells absorb water, producing an internal pressure that pushes against adjacent cells, giving the plant support (see Chapter 11). Without a cell wall strong enough to resist these pressures, this method of support would be impossible. The cell wall is porous, so it is not a barrier to water or dissolved substances. We call it *freely permeable*.

Mature (fully grown) plant cells often have a large central space surrounded by a membrane, called a **vacuole**. This vacuole is a permanent feature of the cell. It is filled with a watery liquid called cell sap, which is a store of dissolved sugars, mineral ions and other solutes. Animal cells do contain vacuoles, but they are only small, temporary structures.

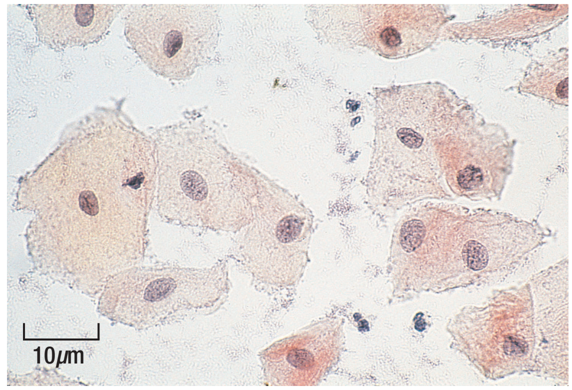
Cells of the green parts of plants, especially the leaves, contain another very important organelle, the **chloroplast**. Chloroplasts absorb light energy to make food in the process of photosynthesis (see Chapter 10). They contain a green pigment called **chlorophyll**. Cells from the parts of a plant that are not green, such as the flowers, roots and woody stems, have no chloroplasts.

KEY POINT

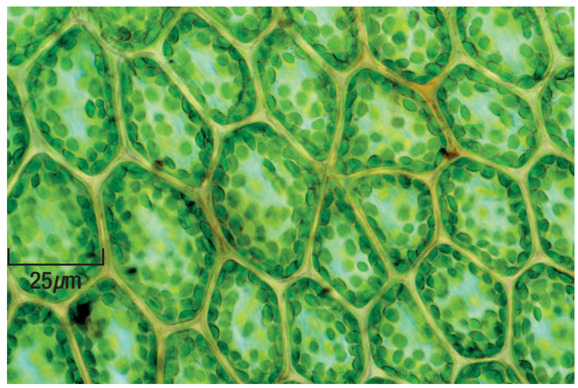
Nearly all cells contain cytoplasm, a nucleus, a cell membrane and mitochondria. As well as these structures, plant cells have a cell wall and a permanent vacuole, and plant cells that photosynthesise contain chloroplasts.

Figure 1.4 shows some animal and plant cells seen through the light microscope.

(a)



(b)



▲ Figure 1.4 (a) Cells from the lining of a human cheek. (b) Cells from the photosynthetic tissue of a leaf.

ENZYMES: CONTROLLING REACTIONS IN THE CELL

The chemical reactions that take place in a cell are controlled by a group of proteins called enzymes. Enzymes are biological **catalysts**. A catalyst is a chemical which speeds up a reaction without being used up itself. It takes part in the reaction, but afterwards is unchanged and free to catalyse more reactions. Cells contain hundreds of different enzymes, each catalysing a different reaction. This is how the activities of a cell are controlled – the nucleus contains the genes, which control the production of enzymes, which then catalyse reactions in the cytoplasm:

genes → proteins (enzymes) → catalyse reactions

Everything a cell does depends on which enzymes it can make, which in turn depends on which genes in its nucleus are working.

What hasn't been mentioned is why enzymes are needed at all. They are necessary because the temperatures inside organisms are low (e.g. the human body temperature is about 37 °C) and without catalysts, most of the reactions that happen in cells would be far too slow to allow life to go on. The reactions can only take place quickly enough when enzymes are present to speed them up.

It is possible for there to be thousands of different sorts of enzymes because they are proteins, and protein molecules have an enormous range of structures and shapes (see Chapter 4).

KEY POINT

The chemical reactions taking place in a cell are known as metabolic reactions. The sum of all the metabolic reactions is known as the **metabolism** of the cell. The function of enzymes is to catalyse metabolic reactions.

KEY POINT

You have probably heard of enzymes being involved in digestion of food. In the intestine enzymes are secreted onto the food to break it down. These are called *extracellular* enzymes, which means they function 'outside cells'. However, most enzymes stay inside cells and carry out their function there; they are *intracellular*. You will find out about digestive enzymes in Chapter 4.

KEY POINT

Secretion is the release of a fluid or substances from a cell or tissue.

The molecule that an enzyme acts on is called its **substrate**. Each enzyme has a small area on its surface called the **active site**. The substrate attaches to the active site of the enzyme. The reaction then takes place and products are formed. When the substrate joins up with the active site it lowers the energy needed for the reaction to start, allowing the products to be formed more easily.

Enzymes also catalyse reactions where large molecules are built up from smaller ones. In this case, several substrate molecules attach to the active site, the reaction takes place and the larger product molecule is formed. The product then leaves the active site.

The substrate fits into the active site of the enzyme like a key fitting into a lock. Just as a key will only fit one lock, a substrate will only fit into the active site of a particular enzyme. This is known as the **lock and key model** of enzyme action. It is the reason why enzymes are *specific*, i.e. an enzyme will only catalyse one reaction.

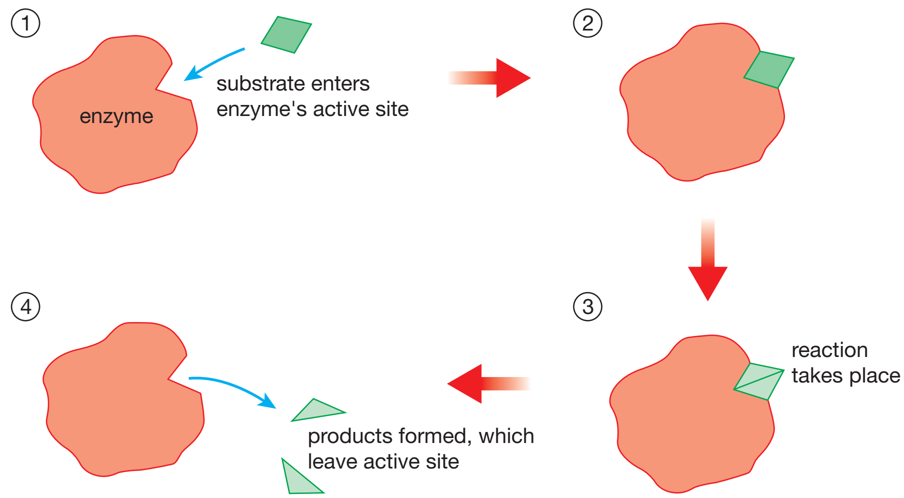


Figure 1.5 Enzymes catalyse reactions at their active site. This acts like a 'lock' to the substrate 'key'. The substrate fits into the active site, and products are formed. This happens more easily than without the enzyme – so enzymes act as catalysts.

After an enzyme molecule has catalysed a reaction, the product is released from the active site, and the enzyme is free to act on more substrate molecules.

FACTORS AFFECTING ENZYMES

KEY POINT

'Optimum' temperature means the 'best' temperature, in other words the temperature at which the reaction takes place most rapidly.

DID YOU KNOW?

Kinetic energy is the energy an object has because of its movement. The molecules of enzyme and substrate are moving faster, so they have more kinetic energy.

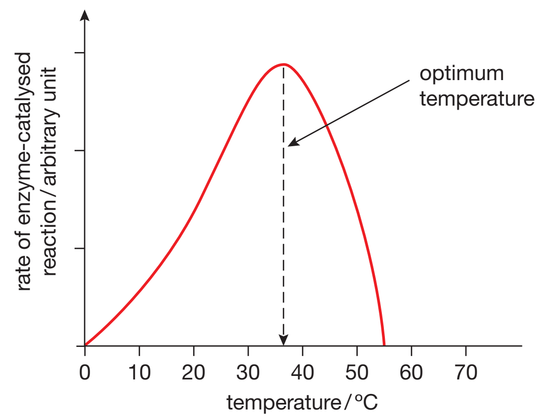
A number of factors affect the activity of enzymes. The rate of reaction may be increased by raising the concentration of the enzyme or the substrate. Two other factors that affect enzymes are temperature and pH.

TEMPERATURE

The effect of temperature on the action of an enzyme is easiest to see as a graph, where we plot the rate of the reaction against temperature (Figure 1.6).

Enzymes in the human body have evolved to work best at body temperature (37 °C). The graph in Figure 1.6 shows a peak on the curve at this temperature, which is called the *optimum temperature* for the enzyme.

As the enzyme is heated up to the optimum temperature, the rise in temperature increases the rate of reaction. This is because higher temperatures give the molecules of the enzyme and the substrate more kinetic energy, so they collide more often. More collisions means that the reaction will take place more frequently.



▲ Figure 1.6 Effect of temperature on the action of an enzyme.

However, above the optimum, temperature starts to have another effect. Enzymes are made of protein, and proteins are broken down by heat. From 40 °C upwards, the heat destroys the enzyme. We say that it is denatured. You can see the effect of **denaturing** when you boil an egg. The egg white is made of protein, and turns from a clear runny liquid into a white solid as the heat denatures the protein. Denaturing changes the shape of the active site so that the substrate will no longer fit into it. Denaturing is permanent – the enzyme molecules will no longer catalyse the reaction.

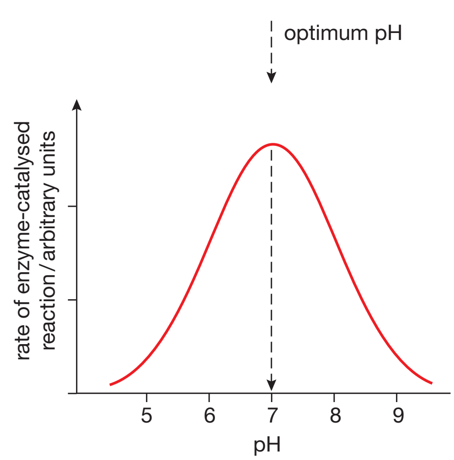
Not all enzymes have an optimum temperature near 37 °C, only those of animals such as mammals and birds, which all have body temperatures close to this value. Enzymes have evolved to work best at the normal body temperature of the organism. Bacteria that always live at an average temperature of 10 °C will probably have enzymes with an optimum temperature near 10 °C.

pH

The pH around the enzyme is also important. The pH inside cells is neutral (pH 7) and most enzymes have evolved to work best at this pH. At extremes of pH either side of neutral, the enzyme activity decreases, as shown in Figure 1.7. The pH at which the enzyme works best is called its *optimum pH*. Either side of the optimum, the pH affects the structure of the enzyme molecule and changes the shape of its active site, so that the substrate will not fit into it so well.

KEY POINT

Although most enzymes work best at a neutral pH, a few have an optimum below or above pH 7. The stomach produces hydrochloric acid, which makes its contents very acidic (see Chapter 4). Most enzymes stop working at a low pH, but the stomach makes an enzyme called pepsin which has an optimum pH of about 2, so that it is adapted to work well in these unusually acidic surroundings.



▲ Figure 1.7 Most enzymes work best at a neutral pH.

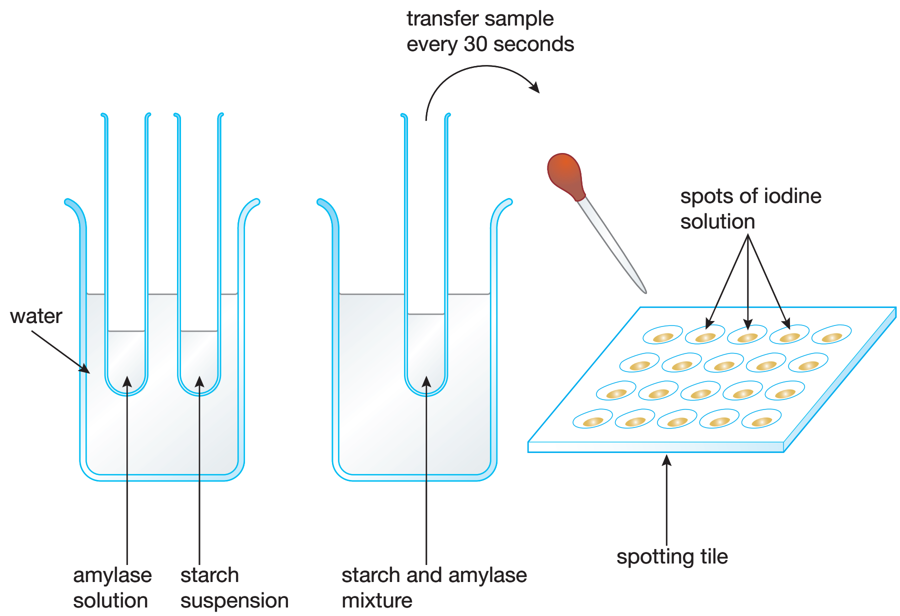
Safety note: Wear eye protection and avoid skin contact with the liquids. Amylase is hazardous to the eyes.

ACTIVITY 1

▼ PRACTICAL: AN INVESTIGATION INTO THE EFFECT OF TEMPERATURE ON THE ACTIVITY OF AMYLASE

The digestive enzyme amylase breaks down starch into the sugar maltose. If the speed at which the starch disappears is recorded, this is a measure of the activity of the amylase.

Figure 1.8 shows apparatus which can be used to record how quickly the starch is used up.



▲ Figure 1.8 Investigating the breakdown of starch by amylase at different temperatures.

Spots of iodine solution are placed into the dips on the spotting tile. Using a syringe, 5 cm^3 of starch suspension is placed in one boiling tube, and 5 cm^3 of amylase solution in another tube, using a different syringe. The beaker is filled with water at 20 °C. Both boiling tubes are placed in the beaker of water for 5 minutes, and the temperature recorded.

The amylase solution is then poured into the starch suspension, leaving the tube containing the mixture in the water bath. Immediately, a small sample of the mixture is removed from the tube with a pipette and added to the first drop of iodine solution on the spotting tile. The colour of the iodine solution is recorded.

A sample of the mixture is taken every 30 seconds for 10 minutes and tested for starch as above, until the iodine solution remains yellow, showing that all the starch is used up.

The experiment is repeated, maintaining the water bath at different temperatures between 20 °C and 60 °C. A set of results is shown in the table below.

	Colour of mixture at different temperatures / (°C)				
Time / min	20	30	40	50	60
0.0	Blue-black	Blue-black	Blue-black	Blue-black	Blue-black
0.5	Blue-black	Blue-black	Brown	Blue-black	Blue-black
1.0	Blue-black	Blue-black	Yellow	Blue-black	Blue-black
1.5	Blue-black	Blue-black	Yellow	Blue-black	Blue-black
2.0	Blue-black	Blue-black	Yellow	Brown	Blue-black
2.5	Blue-black	Blue-black	Yellow	Brown	Blue-black
3.0	Blue-black	Blue-black	Yellow	Brown	Blue-black
3.5	Blue-black	Blue-black	Yellow	Yellow	Blue-black
4.0	Blue-black	Blue-black	Yellow	Yellow	Blue-black
5.5	Blue-black	Blue-black	Yellow	Yellow	Blue-black
6.0	Blue-black	Brown	Yellow	Yellow	Blue-black
6.5	Blue-black	Brown	Yellow	Yellow	Blue-black
7.0	Blue-black	Yellow	Yellow	Yellow	Blue-black
7.5	Blue-black	Yellow	Yellow	Yellow	Brown
8.0	Blue-black	Yellow	Yellow	Yellow	Brown
8.5	Brown	Yellow	Yellow	Yellow	Yellow
9.0	Brown	Yellow	Yellow	Yellow	Yellow
9.5	Yellow	Yellow	Yellow	Yellow	Yellow
10.0	Yellow	Yellow	Yellow	Yellow	Yellow

The rate of reaction can be calculated from the time taken for the starch to be fully broken down, as shown by the colour change from blue-black to yellow. For example, at 50 °C the starch had all been digested after 3.5 minutes. The rate is found by dividing the volume of the starch (5 cm^3) by the time:

$$\text{Rate} = \frac{5.0\,\text{cm}^3}{3.5\,\text{min}} = 1.4\ \text{cm}^3\ \text{per min}$$

Plotting a graph of rate against temperature should produce a curve similar to the one shown in Figure 1.6. Try this, using the results in the table. Better still, you may be able to do this experiment and provide your own results.

If the curve doesn't turn out quite like the one in Figure 1.6, can you suggest why this is? How could you improve the experiment to get more reliable results?

HOW THE CELL GETS ITS ENERGY

A cell needs a source of energy in order to be able to carry out all the processes needed for life. It gets this energy by breaking down food molecules to release the stored chemical energy that they contain. This process is called respiration. Many people think that respiration means the same as 'breathing', but although there are links between the two processes, the biological meaning of respiration is very different.

KEY POINT

Respiration is called an *oxidation* reaction, because oxygen is used to break down food molecules.

Respiration happens in all the cells of our body. Oxygen is used to oxidise food, and carbon dioxide (and water) are released as waste products. The main food oxidised is a sugar called **glucose**. Glucose contains stored chemical energy that can be converted into other forms of energy that the cell can use. It is rather like burning a fuel to get the energy out of it, except that burning releases most of the energy as heat. Respiration releases some heat energy, but most is used to make a substance called ATP (see below). The energy stored in the ATP molecules can then be used for a variety of purposes, such as:

- contraction of muscle cells, producing movement
- active transport of molecules and ions (see page 17)
- building large molecules, such as proteins
- cell division.

The energy released as heat is also used to maintain a constant body temperature in mammals and birds (see Chapter 8).

The overall reaction for respiration is:

glucose	+	oxygen	→	carbon dioxide	+	water	(+ energy)
$C_6H_{12}O_6$	+	$6O_2$	→	$6CO_2$	+	$6H_2O$	(+ energy)

DID YOU KNOW?

Carbon from the respired glucose passes out into the atmosphere as carbon dioxide. The carbon can be traced through this pathway using a radioactive form of carbon called carbon-14.

This is called **aerobic respiration**, because it uses oxygen. Aerobic respiration happens in the cells of humans and those of animals, plants and many other organisms. It is important to realise that the equation above is only a *summary* of the process. It actually takes place gradually, as a sequence of small steps, which release the energy of the glucose in small amounts. Each step in the process is catalysed by a different enzyme. The later steps in the process are the aerobic ones, and these release the most energy. They happen in the mitochondria of the cell.

ATP – THE ENERGEY 'CURRENCY' OF THE CELL

Respiration releases energy while other cell processes use it up. Cells have a way of passing the energy from respiration to the other processes that need it. They do this using a chemical called **adenosine triphosphate** or **ATP**. ATP is present in all living cells.

ATP is composed of an organic molecule called adenosine attached to three phosphate groups. In a cell, ATP can be broken down losing one phosphate group and forming adenosine diphosphate or ADP (Figure 1.9 (a)).

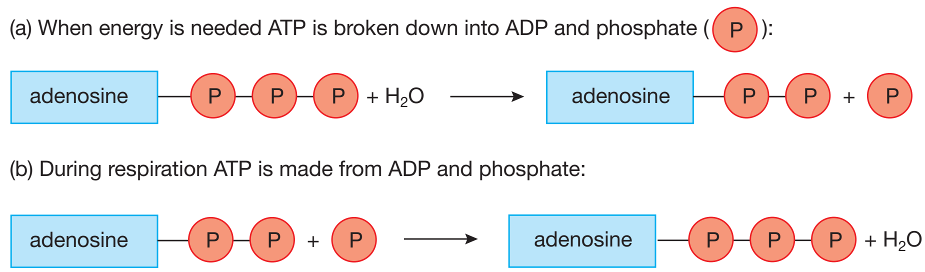


Figure 1.9 ATP is the energy ‘currency’ of the cell.

When this reaction takes place, chemical energy is released and can be used to drive metabolic processes that need it.

During respiration the opposite happens – energy from the oxidation of glucose is used to drive the reverse reaction and a phosphate is added onto ADP (Figure 1.9 (b)).

ATP is often described as the energy ‘currency’ of the cell. It transfers energy between the process that releases it (respiration) and the processes in a cell that use it up.

ANAEROBIC RESPIRATION

There are some situations where cells can respire *without* using oxygen. This is called **anaerobic respiration**. In anaerobic respiration, glucose is not completely broken down, so less energy is released. The advantage of anaerobic respiration is that it can occur in situations where oxygen is in short supply. Two important examples of this are in yeast cells and muscle cells.

Yeasts are single-celled fungi. They are used in commercial processes such as making wine and beer, and baking bread. When yeast cells are prevented from getting enough oxygen, they stop respiring aerobically and start to respire anaerobically instead. The glucose is partly broken down into ethanol (alcohol) and carbon dioxide:

glucose → ethanol + carbon dioxide (+ some energy)

This process is described in more detail in Chapter 21. The ethanol from this type of respiration is the alcohol formed in wine- and beer-making. The carbon dioxide is the gas that makes bread dough rise.

Think about the properties of ethanol – it makes a good fuel and will burn to produce a lot of heat, so it still has a lot of chemical energy ‘stored’ in it.

Muscle cells can also respire anaerobically when they are short of oxygen. If muscles are overworked, the blood cannot reach them fast enough to deliver enough oxygen for aerobic respiration. This happens when a person does a ‘burst’ of activity, such as a sprint, or quickly lifting a heavy weight. This time the glucose is broken down into a substance called **lactate**:

glucose → lactate (+ some energy)

Anaerobic respiration provides enough energy to keep the overworked muscles going for a short period. During the exercise, the level of lactate rises in the muscle cells and bloodstream.

DID YOU KNOW?
It was once thought that lactate was toxic and caused muscle fatigue. We now know that this is *not* true. In fact physiologists have shown that lactate actually *delays* muscle fatigue. Fatigue is caused by other changes that happen in the muscles during exercise.

DID YOU KNOW?
Lactate is sometims called lactic acid.

After the exercise the lactate is respired aerobically in the mitochondria. The volume of oxygen needed to completely oxidise the lactate that builds up in the body during anaerobic respiration is called the **oxygen debt**.

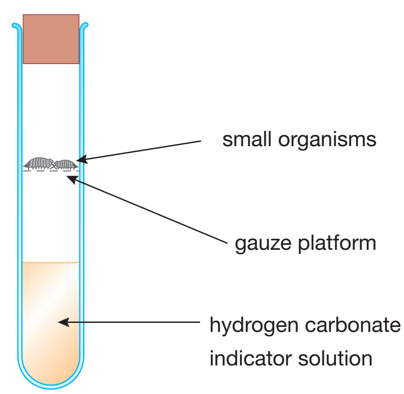
Safety note: Wear eye protection, treat all living organisms with care and avoid skin contact.

ACTIVITY 2

▼ PRACTICAL: DEMONSTRATION OF THE PRODUCTION OF CARBON DIOXIDE BY SMALL LIVING ORGANISMS

Hydrogen carbonate indicator solution is normally orange, but turns yellow if carbon dioxide is added to it. The indicator is sensitive to small changes in carbon dioxide concentration, and can be used to show production of carbon dioxide by small organisms such as woodlice, maggots (fly larvae) or germinating seeds.

The organisms are placed in a stoppered boiling tube with the indicator, as shown in Figure 1.10. The gauze platform supports the organisms above the hydrogen carbonate indicator solution and stops them from coming into contact with the chemical.



▲ Figure 1.10 Testing for carbon dioxide production by small organisms.

Of the three species of organisms mentioned above, which do you think would change the colour of the indicator most quickly? If you are able to observe each of the organisms, this might help with your prediction.

When you have made your prediction (called a ‘hypothesis’), plan an investigation to test it. Take care to consider the variables that need to be **controlled variable**, and don’t forget to include a description of a fourth tube that you would need to set up as the experimental Control (see Appendix A for an explanation of these terms).

It may be possible for you to carry out the investigation using similar apparatus and organisms.

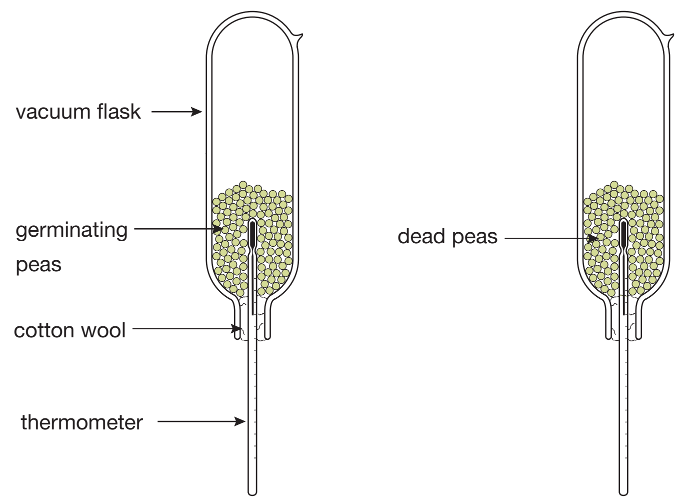
Safety note: Eye protection should be worn when using bleach to wash the peas and skin contact avoided.

ACTIVITY 3

▼ PRACTICAL: DEMONSTRATION THAT HEAT IS PRODUCED BY RESPIRATION

Some peas are soaked in water for 24 hours, so that they start to germinate. A second batch of peas is boiled, to kill them. Each set of peas is washed in a 1% bleach solution, which acts as a disinfectant, killing any bacteria present on the surface of the peas. The peas are then rinsed twice in distilled water to remove any traces of bleach.

Each batch of peas is placed in an inverted vacuum flask as shown in Figure 1.11, leaving some air in each flask. A vacuum flask insulates its contents, so that any small temperature change inside the flask can be measured.



▲ Figure 1.11 Experiment to show that heat is produced during respiration in germinating peas.

The seeds produce carbon dioxide gas, which is denser than air. The inverted flasks and cotton wool allow this to escape. It might otherwise kill the peas.

The apparatus is left set up for a couple of days, and the temperature inside each flask measured at the start and end of the experiment.

The following results were obtained from this experiment:

Temperature in both flasks at the start = 21 °C

Temperature in flask with dead peas at the end = 21 °C

Temperature in flask with living peas at the end = 24 °C

Can you explain these results? Why is it necessary to kill any microorganisms on the surface of the peas? Explain the importance of the flask containing dead peas.

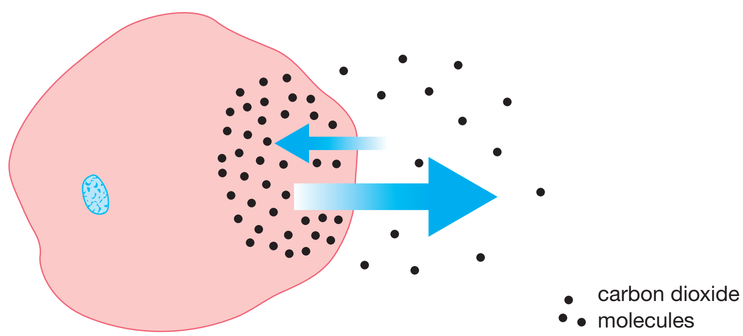
MOVEMENT OF MATERIALS IN AND OUT OF CELLS

Cell respiration shows the need for cells to be able to take in certain substances from their surroundings, such as glucose and oxygen, and get rid of others, such as carbon dioxide and water. As you have seen, the cell surface membrane can control which chemicals can pass in and out – it is described as selectively permeable.

There are three main ways that molecules and ions can move through the membrane. They are diffusion, active transport and osmosis.

DIFFUSION

Many substances can pass through the membrane by **diffusion**. Diffusion happens when a substance is more concentrated in one place than another. For example, if the cell is making carbon dioxide by respiration, the concentration of carbon dioxide inside the cell will be higher than outside. This difference in concentration is called a concentration gradient. The molecules of carbon dioxide are constantly moving about because of their kinetic energy. The cell membrane is permeable to carbon dioxide, so the molecules can move in either direction through it. Since there is a higher concentration of carbon dioxide molecules inside the cell than outside, over time, more molecules will move from inside to outside than move in the other direction. We say that there is a *net* movement of the molecules out of the cell (Figure 1.12).



▲ Figure 1.12 Carbon dioxide is produced by respiration, so its concentration builds up inside the cell. Although the carbon dioxide molecules diffuse in both directions across the cell membrane, the overall (net) movement is out of the cell, down the concentration gradient.

KEY POINT

Diffusion is the net movement of particles (molecules or ions) from a region of high concentration to a region of low concentration, i.e. down a concentration gradient.

The opposite happens with oxygen. Respiration uses up oxygen, so there is a concentration gradient of oxygen from outside to inside the cell. There is therefore a net movement of oxygen *into* the cell by diffusion.

The rate of diffusion is affected by various factors.

- The concentration gradient. Diffusion happens more quickly when there is a steep concentration gradient (i.e. a big difference in concentrations between two areas).
- The surface area to volume ratio. A larger surface area in proportion to the volume will increase the rate.
- The distance. The rate is decreased if the distance over which diffusion has to take place is greater.
- The temperature. The rate is greater at higher temperatures. This is because a high temperature provides the particles with more kinetic energy.

Safety note: Wear eye protection and avoid all skin contact with the acid and the dyed agar blocks.

ACTIVITY 4

▼ PRACTICAL: DEMONSTRATION OF DIFFUSION IN A JELLY

Agar is a jelly that is used for growing cultures of bacteria. It has a consistency similar to the cytoplasm of a cell. Like cytoplasm, it has a high water content. Agar can be used to show how substances diffuse through a cell.

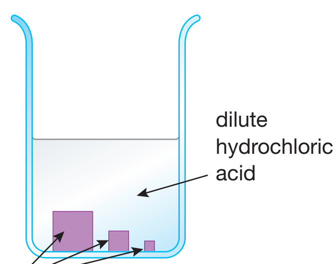
This demonstration uses the reaction between hydrochloric acid and potassium permanganate solution. When hydrochloric acid comes into contact with potassium permanganate, the purple colour of the permanganate disappears.

A Petri dish is prepared which contains a 2 cm deep layer of agar jelly, dyed purple with potassium permanganate. Three cubes of different sizes are cut out of the jelly, with side lengths 2 cm, 1 cm and 0.5 cm. The cubes have different volumes and total surface areas. They also have a different surface area to volume ratio, as shown in the table below.

Length of side of cube / cm	Volume of cube / cm^3 (length × width × height)	Surface area of cube / cm^2 (length × width of one side) × 6	Ratio of surface area to volume of cube (surface area divided by volume)
2	(2 × 2 × 2) = 8	(2 × 2) × 6 = 24	24/8 = 3
1	(1 × 1 × 1) = 1	(1 × 1) × 6 = 6	6/1 = 6
0.5	(0.5 × 0.5 × 0.5) = 0.125	(0.5 × 0.5) × 6 = 1.5	1.5/0.125 = 12

Notice that the smallest cube has the largest surface area to volume ratio. The same is true of cells – a small cell has a larger surface area to volume ratio than a large cell.

The cubes are carefully dropped, at the same time, into a beaker of dilute hydrochloric acid (Figure 1.13).



▶ Figure 1.13 Investigating diffusion in a jelly.

The time taken for each cube to turn colourless is noted.

Which cube would be the first to turn colourless and which the last? Explain the reasoning behind your prediction.

If the three cubes represented cells of different sizes, which cell would have the most difficulty in obtaining substances by diffusion?

It may be possible for you to try this experiment, using similar apparatus.

ACTIVE TRANSPORT

Diffusion happens because of the kinetic energy of the particles. It does not need an 'extra' source of energy from respiration. However, sometimes a cell needs to take in a substance when there is very little of that substance outside the cell, in other words *against* a concentration gradient. It can do this by another process, called **active transport**.

During active transport a cell uses energy from respiration to take up substances, rather like a pump uses energy to move a liquid from one place to another. In fact, biologists speak of the cell 'pumping' ions or molecules in or out. The pumps are large protein molecules located in the cell membrane, and they are driven by the breakdown of ATP. An example of a place where this happens is in the human small intestine, where some glucose in the gut is absorbed into the cells lining the intestine by active transport. The roots of plants also take up certain mineral ions in this way. Cells use active transport to control the uptake of many substances.

KEY POINT

Active transport is the movement of substances against a concentration gradient, using energy from respiration.

OSMOSIS

Water moves across cell membranes by a special sort of diffusion, called **osmosis**. Osmosis happens when the total concentrations of all dissolved substances inside and outside the cell are different. Water will move across the membrane from the more dilute solution to the more concentrated one. Notice that this is still obeying the rules of diffusion – the water moves from where there is a higher concentration of *water* molecules to a lower concentration of *water* molecules. Osmosis can only happen if the membrane is permeable to water but not to some other solutes. We say that it is partially permeable.

Osmosis is important for moving water from cell to cell, for example in plant roots. You will find out more about osmosis in Chapter 11.

KEY POINT

Osmosis in cells is the net movement of water from a dilute solution to a more concentrated solution across the partially permeable cell membrane.

SPECIALISED EXCHANGE SURFACES

All cells exchange substances with their surroundings, but some parts of animals or plants are specially adapted for the exchange of materials because they have a very large surface area in proportion to their volume. In animals, two examples are the alveoli (air sacs) of the lungs (Chapter 3) and the villi of the small intestine (Chapter 4). Diffusion is a slow process, and organs that rely on diffusion need a large surface over which it can take place. The alveoli allow the exchange of oxygen and carbon dioxide to take place between the air and the blood during breathing. The villi of the small intestine provide a large surface area for the absorption of digested food. In plants, exchange surfaces are also adapted by having a large surface area, such as the spongy mesophyll of the leaf (Chapter 10) and the **root hairs**.

KEY POINT

'Adapted' or 'an **adaptation**' means that the structure of a cell or an organism is suited to its function. It is a word that is very commonly used in biology, and will appear again in many of the chapters of this book. We also use it when we say that organisms are adapted to their environment.

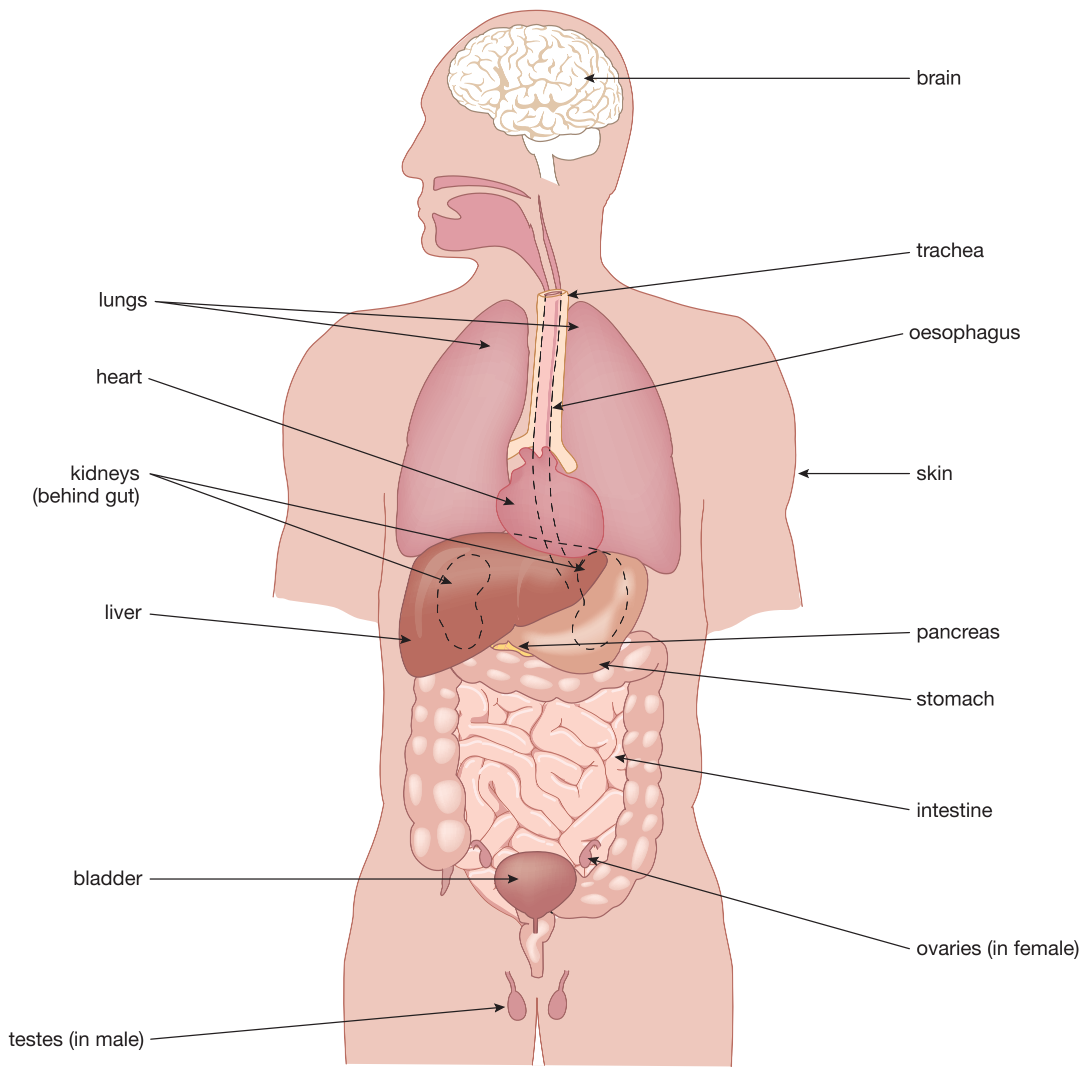
CELLS, TISSUES AND ORGANS

Cells with a similar function are grouped together as **tissues**. For example, the muscle of your arm contains millions of similar muscle cells, all specialised for one function – contraction to move the arm bones. This is muscle tissue. However, a muscle also contains other tissues, such as blood, nervous tissue and epithelium (lining tissue). A collection of several tissues carrying out a particular function is called an **organ**. The main organs of the human body are shown in Figure 1.14. Plants also have tissues and organs. Leaves, roots, stems and flowers are all plant organs.

In animals, jobs are usually carried out by several different organs working together. This is called an **organ system**. For example, the digestive system consists of the gut, along with glands such as the pancreas and gall bladder.

The function of the whole system is to digest food and absorb the digested products into the blood. There are seven main systems in the human body. These are the:

- digestive system
- gas exchange system – including the lungs, which exchange oxygen and carbon dioxide
- circulatory system – including the heart and blood vessels, which transport materials around the body
- excretory system – including the kidneys, which filter toxic waste materials from the blood
- nervous system – consisting of the brain, spinal cord and nerves, which coordinate the body's actions
- endocrine system – glands secreting hormones, which act as chemical messengers
- reproductive system – producing sperm in males and eggs in females, and allowing the development of the embryo.



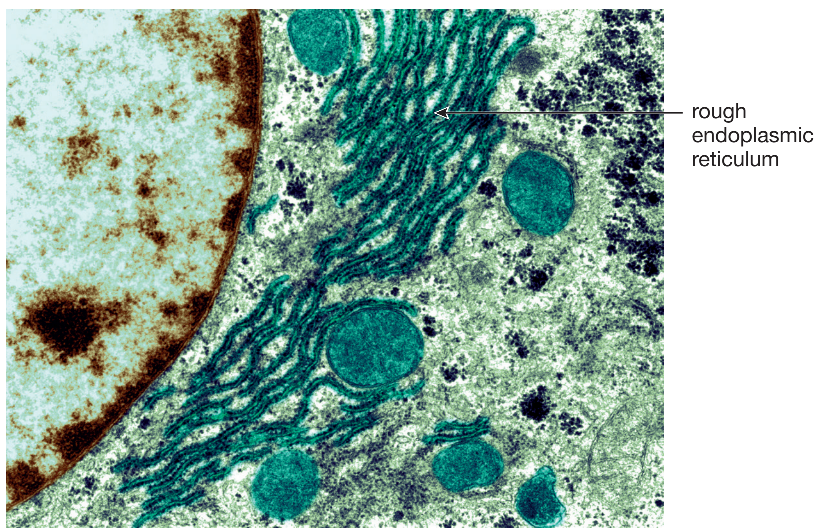
▲ Figure 1.14 Some of the main organs of the human body.

LOOKING AHEAD – MEMBRANES IN CELLS

If you continue to study biology beyond International GCSE, you will learn more about the structure and function of cells. You might like to look on the Internet for some electron micrographs and carry out some further research into cells.

Electron micrographs allow us to see cells at a much greater magnification than by using a light microscope. They also reveal more detail. The image produced by a light microscope can only distinguish features about the size of a mitochondrion. The electron microscope has a much greater *resolution*. Resolution is the ability to distinguish two points in an image as being separate. The maximum resolution of a light microscope is about 200 nanometres (nm), while with an electron microscope we can distinguish structures less than 1 nm in size. That is why ribosomes are only visible using an electron microscope – they are about 25 nm in diameter. A nanometre (nm) is 10^{-9} m, or one millionth of a milimetre.

Electron microscopy reveals that much of the cytoplasm is made up of membranes. As well as the cell surface membrane, there are membranes around organelles such as the nucleus, mitochondria and chloroplasts. In addition, there is an extensive system of membranes running throughout the cytoplasm, called the endoplasmic reticulum (ER). Some ER is covered in ribosomes, and is called rough ER (Figure 1.15).



▲ Figure 1.15 Rough endoplasmic reticulum is a system of membranes extending throughout the cytoplasm of a cell. It is covered with ribosomes the (tiny dots). Ribosomes are the site of protein synthesis.

There are thousands of different chemical reactions that take place inside cells. A key function of a cell membrane is to separate cell functions into different compartments so they don't take place together. For example, the reactions and enzymes of aerobic respiration are kept inside the mitochondria, separate from the rest of the cytoplasm.

CHAPTER QUESTIONS

More questions on life processes can be found at the end of Unit 1 on page 29.

SKILLS CRITICAL THINKING 5th

1 Which of the following comparisons of animal and plant cells is *not* true?

	Animal cells	Plant cells
A	do not have chloroplasts	have chloroplasts
B	have mitochondria	do not have mitochondria
C	have temporary vacuoles	have permanent vacuoles
D	do not have cellulose cell walls	have cellulose cell walls

2 Which of the following descriptions is correct?

A The cell wall is freely permeable and the cell membrane is partially permeable

B The cell wall is partially permeable and the cell membrane is freely permeable

C Both the cell wall and the cell membrane are freely permeable

D Both the cell wall and the cell membrane are partially permeable

6th

3 What are the products of anaerobic respiration in yeast?

A ethanol and carbon dioxide **B** lactate and carbon dioxide

C carbon dioxide and water **D** ethanol and water

SKILLS INTERPRETATION

4 **a** Draw a diagram of a plant cell. Label all of the parts. Alongside each label write the function of that part.

SKILLS CRITICAL THINKING 5th

b Write down three differences between the cell you have drawn and a ‘typical’ animal cell.

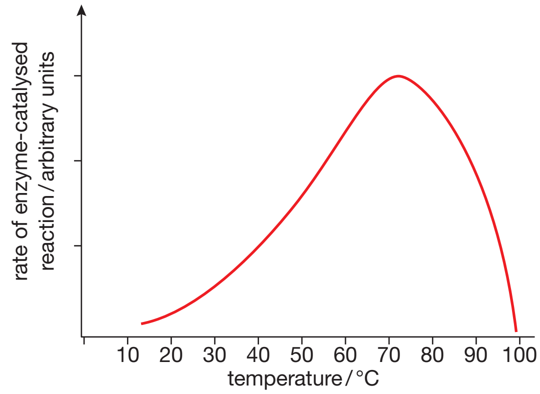
5 Write a short description of the nature and function of enzymes. Include in your description:

- a definition of an enzyme
- a description of the ‘lock and key’ model of enzyme action
- an explanation of the difference between intracellular and extracellular enzymes.

Your description should be about a page in length, including a labelled diagram.

SKILLS ANALYSIS 6th

6 The graph shows the effect of temperature on an enzyme. The enzyme was extracted from microorganism that lives in hot mineral springs near a volcano.



a What is the optimum temperature of this enzyme?

8th b Explain why the activity of the enzyme is greater at 60 °C than at 30 °C.

9th c The optimum temperature of enzymes in the human body is about 37 °C. Explain why this enzyme is different.

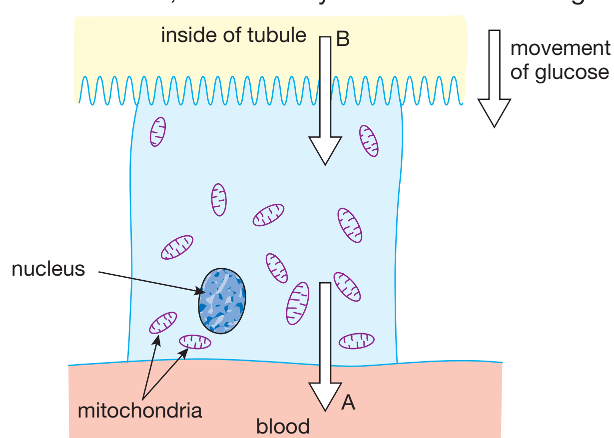
8th d What happens to the enzyme at 90 °C?

SKILLS INTERPRETATION 7th

7 Explain the differences between diffusion and active transport.

SKILLS CRITICAL THINKING, INTERPRETATION 6th

8 The diagram shows a cell from the lining of a human kidney tubule. A major role of the cell is to absorb glucose from the fluid passing along the tubule and pass it into the blood, as shown by the arrow on the diagram.



SKILLS ANALYSIS, INTERPRETATION

5th a What is the function of the mitochondria?

7th b The tubule cell contains a large number of mitochondria. They are needed for the cell to transport glucose across the cell membrane into the blood at ‘A’. Suggest the method that the cell uses to do this and explain your answer.

6th c The mitochondria are *not* needed to transport the glucose into the cell from the tubule at ‘B’. Name the process by which the ions move across the membrane at ‘B’ and explain your answer.

7th d The surface membrane of the tubule cell at ‘B’ is greatly folded. Suggest how this adaptation helps the cell to carry out its function.

2 THE VARIETY OF LIVING ORGANISMS

There is an enormous variety of living organisms. Biologists put them into groups according to their structure and function. The members of each group have certain features in common.

LEARNING OBJECTIVES

- Understand the difference between eukaryotic and prokaryotic organisms
- Describe the features common to plants and recognise examples of flowering plants such as maize, peas and beans
- Describe the features common to animals and recognise examples such as mammals and insects
- Describe the features common to fungi and recognise examples such as *Mucor* and yeast
- Describe the features common to protoctists and recognise examples such as *Amoeba*, *Chlorella* and *Plasmodium*
- Describe the features common to bacteria and recognise examples such as *Lactobacillus bulgaricus* and *Pneumococcus*
- Describe the features common to viruses and recognise examples such as the influenza virus, the HIV virus and the tobacco mosaic virus
- Understand the term 'pathogen' and know that pathogens may include fungi, bacteria, protoctists or viruses.

There are more than ten million species of organisms alive on Earth today, and many more that once lived on Earth but are now extinct. In order to make sense of this enormous variety biologists classify organisms, putting them into groups. Members of each group are related – they are descended from a common ancestor by the process of evolution (see Chapter 19). This common ancestry is reflected in the similarities of structure and function of the members of a group.

The five major groups of living organisms are plants, animals, fungi, protoctists and bacteria.

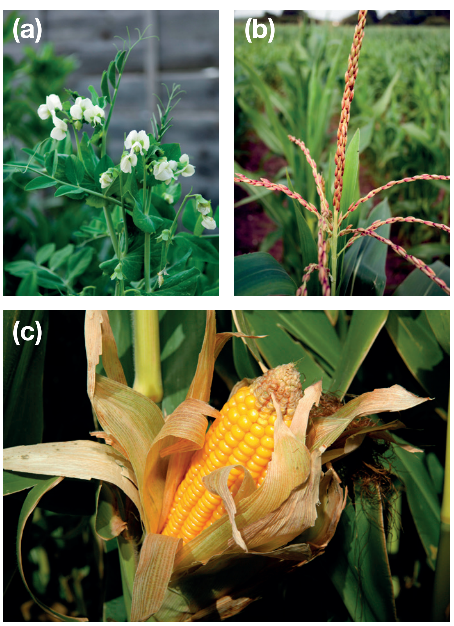


Figure 2.1 (a) A pea plant. Its leaves and **stem cells** contain chloroplasts, giving them their green colour. The white flowers are pollinated by insects. (b) Maize plants are pollinated by wind. These are the male flowers, which make the pollen. (c) The female maize flowers produce seeds after pollination.

PLANTS

You will be familiar with flowering plants, such as those shown in Figure 2.1. This group, or **kingdom**, also contains simpler plants, such as mosses and ferns. All plants are multicellular, which means that their 'bodies' are made up of many cells. Their main distinguishing feature is that their cells contain chloroplasts and they carry out photosynthesis – the process that uses light energy to convert simple inorganic molecules such as water and carbon dioxide into complex organic compounds (see Chapter 10). One of these organic compounds is the carbohydrate cellulose, and all plants have cell walls made of this material.

Plants can make many other organic compounds as a result of photosynthesis. One of the first to be made is the storage carbohydrate **starch**, which is often found inside plant cells. Another is the sugar **sucrose**, which is transported around the plant and is sometimes stored in fruits and other plant organs. The structure and function of flowering plants is dealt with in Unit 3 of this book.

ANIMALS

You will be even more familiar with this kingdom, since it contains the species *Homo sapiens*, i.e. humans! The variety of the animal kingdom is also enormous, including organisms such as sponges, molluscs, worms, starfish, insects and crustaceans, through to larger animals such as fish, amphibians, reptiles, birds and mammals (Figure 2.2). The last five groups are all **vertebrates**, which means that they have a vertebral column, or backbone. All other animals lack this feature, and are called **invertebrates**.

(a)

(b)

(c)

Figure 2.2 (a) A housefly. (b) A mosquito, feeding on human blood. Houseflies and mosquitoes are both insects, which make up the largest sub-group of all the animals. About 60% of all animal species are insects. (c) This high jumper's movement is coordinated by a complex nervous system.

Animals are also multicellular organisms. Their cells never contain chloroplasts, so they are unable to carry out photosynthesis. Instead, they gain their nutrition by feeding on other animals or plants. Animal cells also lack cell walls, which allows their cells to change shape, an important feature for organisms that need to move from place to place. Movement in animals is achieved in various ways, but often involves coordination by a nervous system (see Chapter 6). Another feature common to most animals is that they store carbohydrate in their cells as a compound called **glycogen** (see Chapter 4). The structure and function of animals is dealt with in Unit 2 of this book.

FUNGI

Fungi include mushrooms and toadstools, as well as moulds. These groups of fungi are multicellular. Another group of fungi is the yeasts, which are **unicellular** (made of single cells). Different species of yeasts live everywhere – on the surface of fruits, in soil, water, and even on dust in the air. The yeast powder used for baking contains millions of yeast cells (Figure 2.3). The cells of fungi never contain chloroplasts, so they cannot photosynthesise. Their cells have cell walls, but they are not composed of cellulose (Figure 2.4).

EXTENSION WORK

Because fungi have cell walls, they were once thought to be plants that had lost their chlorophyll. We now know that their cell wall is not made of cellulose as in plants, but of a different chemical called **chitin** (the same material that makes up the outside skeleton of insects). There are many ways that fungi are very different from plants (the most obvious is that fungi do not photosynthesise) and they are not closely related to plants at all.

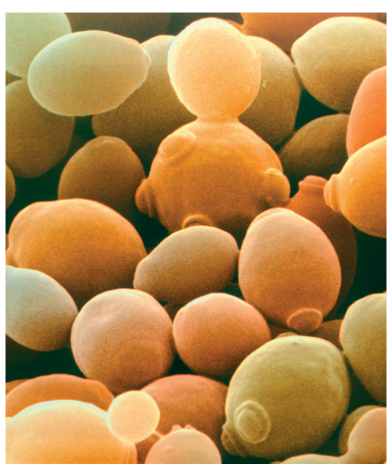


Figure 2.3 Yeast cells, highly magnified

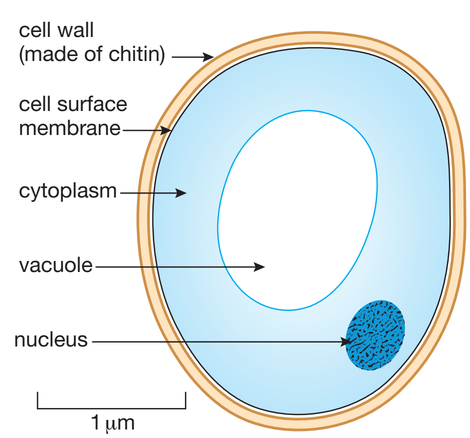


Figure 2.4 Structure of a yeast cell

KEY POINT

The singular of hyphae is hypha.

Figure 2.5 Toadstools growing on a rotting tree trunk

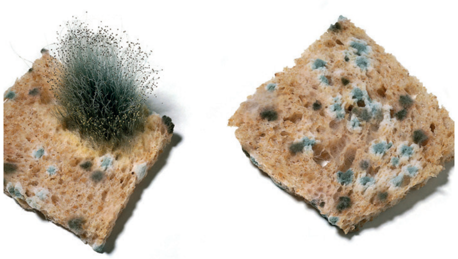


Figure 2.6 The 'pin mould' *Mucor* growing on a piece of bread. The dark spots are structures that produce spores for reproduction.

A mushroom or toadstool is the reproductive structure of the organism, called a fruiting body (Figure 2.5). Under the soil, the mushroom has many fine thread-like filaments called **hyphae** (pronounced high-fee). A mould is rather like a mushroom without the fruiting body. It just consists of the network of hyphae (Figure 2.6). The whole network is called a **mycelium** (pronounced my-sea-lee-um). Moulds feed by absorbing nutrients from dead (or sometimes living) material, so they are found wherever this is present, for example, in soil, rotting leaves or decaying fruit.

If you leave a piece of bread or fruit exposed to the air for a few days, it will soon become mouldy. Mould spores carried in the air have landed on the food and grown into a mycelium of hyphae (Figure 2.7).

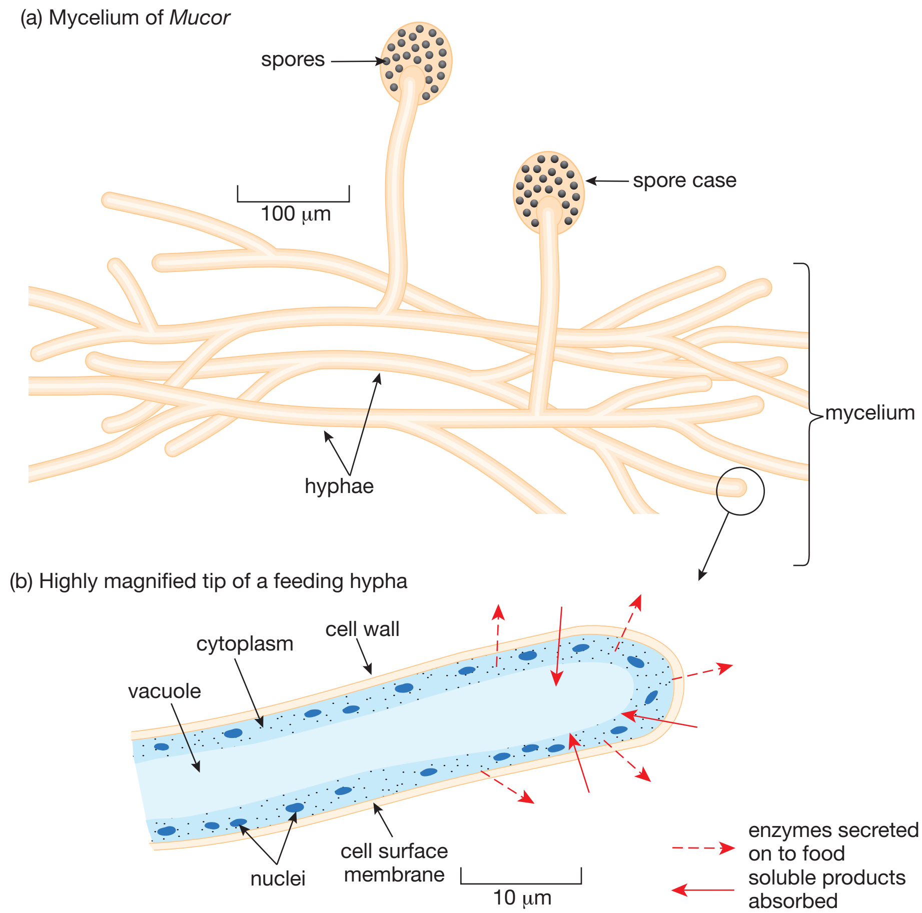


Figure 2.7 The structure of a typical mould fungus, the 'pin mould' *Mucor*.

The thread-like hyphae of *Mucor* have cell walls surrounding their cytoplasm. The cytoplasm contains many nuclei. In other words the hyphae are not divided up into separate cells.

When a spore from *Mucor* lands on the food, a hypha grows out from it. The hypha grows and branches again and again, until the mycelium covers the surface of the food. The hyphae secrete digestive enzymes on to the food, breaking it down into soluble substances such as sugars, which are then absorbed by the mould. Eventually, the food is used up and the mould must infect another source of food by producing more spores.

When an organism feeds on dead organic material in this way, and digestion takes place outside of the organism, this is called **saprotrophic** nutrition. Enzymes that are secreted out of cells for this purpose are called *extracellular* enzymes (see Chapter 1).

PROTOCTISTS

Protoctists are sometimes called the 'dustbin kingdom', because they are a mixed group of organisms that don't fit into the plants, animals or fungi. Most protoctists are microscopic single-celled organisms (Figure 2.8). Some look like animal cells, such as *Amoeba*, which lives in pond water. These are known as **protozoa**. Other protoctists have chloroplasts and carry out photosynthesis, so are more like plants. These are called **algae**. Most algae are unicellular, but some species such as seaweeds are multicellular and can grow to a great size. Some protoctists are the agents of disease, such as *Plasmodium*, the organism that causes malaria.

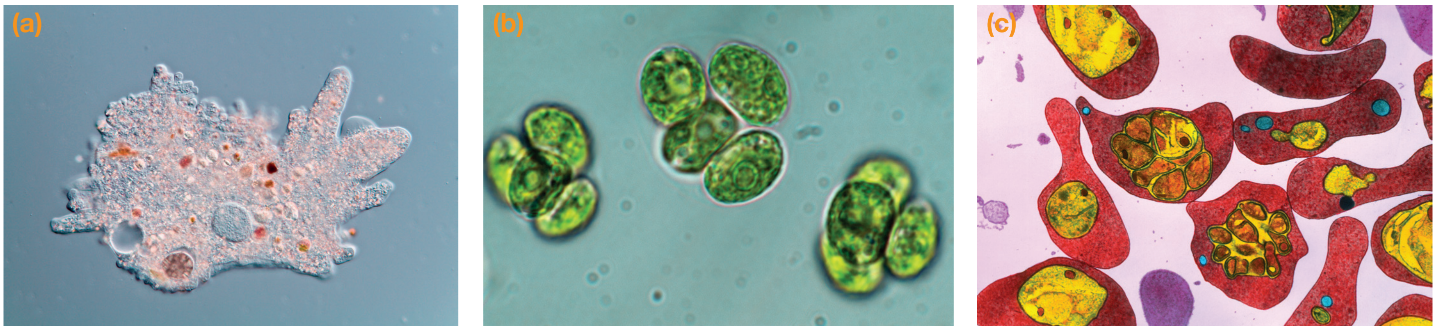


Figure 2.8 (a) *Amoeba*, a protozoan that lives in ponds (b) *Chlorella*, a unicellular freshwater alga (c) Blood cells containing the protoctist parasite *Plasmodium*, the organism responsible for causing malaria

EUKARYOTIC AND PROKARYOTIC ORGANISMS

All the organisms described so far are composed of **eukaryotic** cells and are known as eukaryotic organisms. 'Eukaryotic' means 'having a nucleus' – their cells contain a nucleus surrounded by a membrane, along with other membrane bound organelles, such as mitochondria and chloroplasts.

There are also organisms made of simpler cells, which have no nucleus, mitochondria or chloroplasts. These are called **prokaryotic** cells. 'Prokaryotic' means 'before nucleus'. The main forms of prokaryotic organisms are the bacteria.

BACTERIA

Bacteria are small single-celled organisms. Their cells are much smaller than those of eukaryotic organisms and have a much simpler structure. To give you some idea of their size, a typical animal cell might be 10 to 50 μm in diameter (1 μm, or one micrometre, is a millionth of a metre). Compared with this, a typical bacterium is only 1 to 5 μm in length (Figure 2.9) and its volume is thousands of times smaller than that of the animal cell.

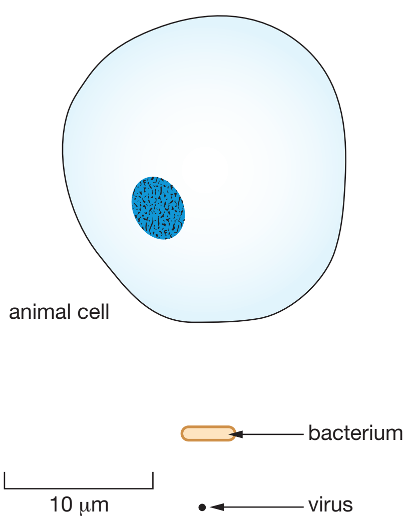
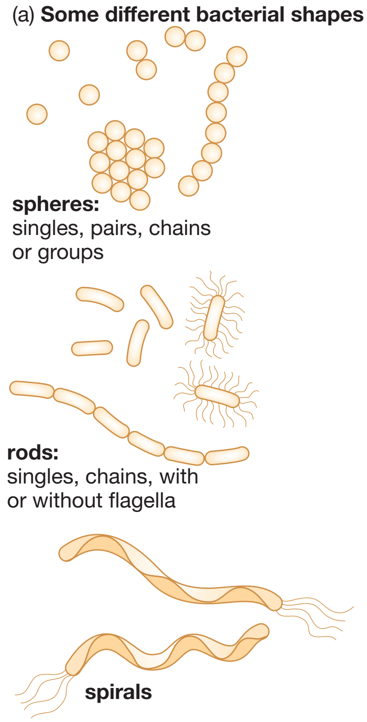


Figure 2.9 A bacterium is much smaller than an animal cell. The relative size of a virus is also shown.

There are three basic shapes of bacteria: spheres, rods and spirals, but they all have a similar internal structure (Figure 2.10).

All bacteria are surrounded by a cell wall, which protects the bacterium and keeps the shape of the cell. Bacterial cell walls are not made of cellulose but a complex compound of sugars and proteins called peptidoglycan. Some species have another layer outside this wall, called a **capsule** or slime layer. Both give the bacterium extra protection. Underneath the cell wall is the cell membrane, as in other cells. The middle of the cell is made of cytoplasm. Since it is a prokaryotic cell, the bacterium has no nucleus. Instead, its genetic material (DNA) is in a single chromosome, loose in the cytoplasm, forming a circular loop.



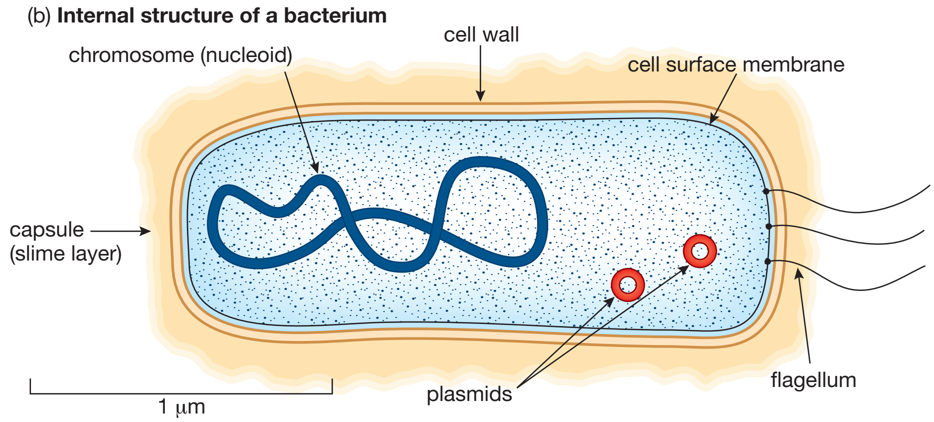


Figure 2.10 Structure of bacteria

Some bacteria can swim, and are propelled through water by corkscrew-like movements of structures called flagella (a single one of these is called a **flagellum**). However, many bacteria do not have flagella and cannot move by themselves. Other structures present in the cytoplasm include the **plasmids**. These are small circular rings of DNA, carrying some of the bacterium's genes. Not all bacteria contain plasmids, although about three-quarters of all known species do. Plasmids have very important uses in genetic engineering (see Chapter 21).

Some bacteria contain a form of chlorophyll in their cytoplasm, and can carry out photosynthesis. However, most bacteria feed off other living or dead organisms. Along with the fungi, many bacteria are important **decomposers** (see Chapter 14), recycling dead organisms and waste products in the soil and elsewhere. Some bacteria are used by humans to make food, such as *Lactobacillus bulgaricus*, a rod-shaped species used in the production of yoghurt from milk (Figure 2.11). Other species are **pathogens**, which means that they cause disease (Figure 2.12).

Despite the relatively simple structure of the bacterial cell, it is still a living cell that carries out the normal processes of life, such as respiration, feeding, excretion, growth and reproduction. As you have seen, some bacteria can move, and they can also respond to a range of stimuli. For example, they may move towards a source of food, or away from a poisonous chemical. You should think about these features when you compare bacteria with the next group, the much simpler viruses.

KEY POINT

'Pathogens are organisms that cause disease. Many common animal and plant diseases are caused by bacteria or viruses. Most protoctists are free-living, but a few species are pathogens, such as *Plasmodium* (Figure 2.8). Even some species of fungi can cause disease, e.g. the skin infection called 'athlete's foot' is caused by a mould.

Figure 2.11 The bacterium *Lactobacillus bulgaricus*, used in the production of yoghurt.

Figure 2.12 Rounded cells of the bacterium *Pneumococcus*, one cause of pneumonia.

VIRUSES

All **viruses** are **parasites**, and can only reproduce inside living cells. The cell in which the virus lives is called the host. There are many different types of viruses. Some live in the cells of animals or plants, and there are even viruses which infect bacteria. Viruses are much smaller than bacterial cells: most are between 0.01 and 0.1 μm in diameter (Figure 2.9).

Viruses are not made of cells. A virus particle is very simple. It has no nucleus or cytoplasm, and is composed of a core of genetic material surrounded by a protein coat (Figure 2.13). The genetic material can be either **DNA**, or a similar chemical called **ribonucleic acid (RNA)**. In either case, the genetic material makes up just a few genes – all that is needed for the virus to reproduce inside its host cell.

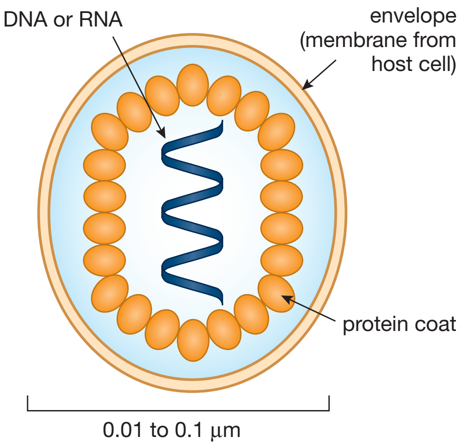


Figure 2.13 The structure of a typical virus, such as the type causing influenza (flu).

EXTENSION WORK

AIDS is not actually a disease but a 'syndrome'. A syndrome is a set of symptoms caused by a medical condition. In the case of HIV, the virus severely damages the person's immune system, so they are more likely to get other diseases, such as tuberculosis. They may also develop some unusual types of cancer. This collection of different symptoms is referred to as AIDS.

Sometimes a membrane called an envelope may surround a virus particle, but the virus does not make this. Instead it is 'stolen' from the surface membrane of the host cell.

Viruses do not feed, respire, excrete, move, grow or respond to their surroundings. They do not carry out any of the normal 'characteristics' of living things except reproduction, and they can only do this parasitically. This is why biologists do not consider viruses to be living organisms. You can think of them as being on the border between an organism and a non-living chemical.

A virus reproduces by entering the host cell and taking over the host's genetic machinery to make more virus particles. After many virus particles have been made, the host cell dies and the particles are released to infect more cells. Many human diseases are caused in this way, such as influenza ('flu'). Other examples include colds, measles, mumps, polio and rubella ('German measles'). Of course, the reproduction process does not continue forever. Usually, the body's immune system destroys the virus and the person recovers. Sometimes, however, a virus cannot be destroyed by the immune system quickly enough, and it may cause permanent damage or death. With other infections, the virus may attack cells of the immune system itself. This is the case with HIV (the Human Immunodeficiency Virus), which causes the illness called AIDS (Acquired Immune Deficiency Syndrome).

Viruses don't just parasitise animal cells. Some infect plant cells, such as the tobacco mosaic virus (Figure 2.14), which interferes with the ability of the tobacco plant to make chloroplasts, causing mottled patches to develop on the leaves (Figure 2.15).

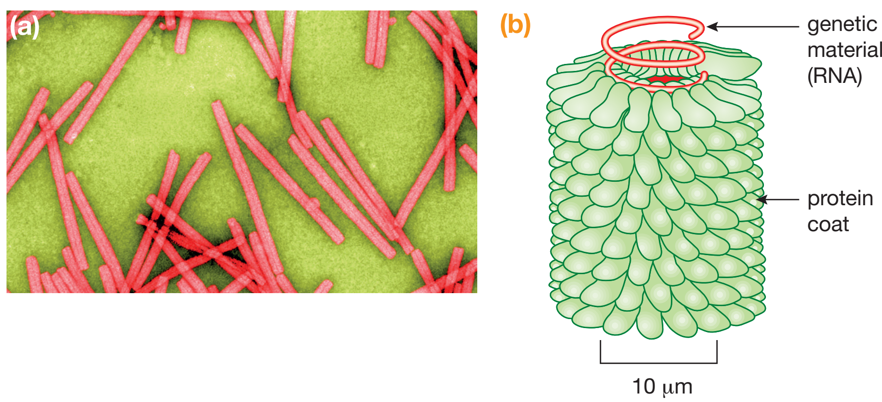


Figure 2.14 (a) Tobacco mosaic virus (TMV), seen through an electron microscope. (b) Structure of part of a TMV particle, magnified 1.25 million times.

Figure 2.15 Discolouration of the leaves of a tobacco plant, caused by infection with tobacco mosaic virus.

CHAPTER QUESTIONS

More questions on the variety of living organisms can be found at the end of Unit 1 on page 29.

SKILLS CRITICAL THINKING 4th

1 Which of the following is *not* a characteristic of plants?

A cells contain chloroplasts

B cell wall made of cellulose

C bodies are multicellular

D store carbohydrate as glycogen

SKILLS CRITICAL THINKING

4th

2 Fungi carry out *saprotrophic nutrition*. What is the meaning of this term?

A extracellular digestion of dead organic matter
B feeding on other living organisms
C making organic molecules by photosynthesis
D secreting digestive enzymes

5th

3 Below are three groups of organisms.

1. viruses
2. bacteria
3. yeasts

Which of these organisms are prokaryotic?

A 1 only
B 2 only
C 1 and 2
D 1, 2 and 3

4 Which of the following diseases is *not* caused by a virus?

A influenza
B measles
C malaria
D AIDS

5 a Name the kingdom to which each of the following organisms belongs:

i mushroom

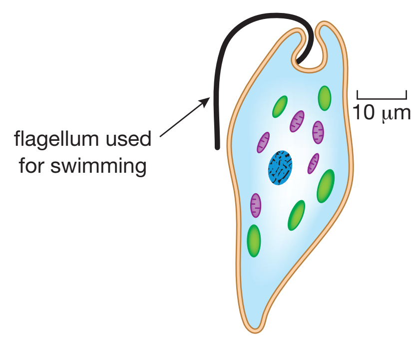
ii *Chlorella*

iii moss

iv *Lactobacillus*

SKILLS ANALYSIS, REASONING

b The diagram shows a species of protoctist called *Euglena*.
Use the diagram to explain why *Euglena* is classified as a protoctist and not as an animal or plant.



SKILLS INTERPRETATION

SKILLS CRITICAL THINKING

6th

6 a Draw a diagram to show the structure of a typical virus particle.

b Is a virus a living organism? Explain your answer.

8th

c Explain the statement ‘viruses are all parasites’.

4th

7 Explain the meanings of the following terms:

a invertebrate

5th

b hyphae

c saprotrophic

UNIT QUESTIONS

SKILLS CRITICAL THINKING 5th

1 These three organelles are found in cells: nucleus, chloroplast and mitochondrion.

a Which of the above organelles would be found in:

i a cell from a human muscle? **(1)**

ii a palisade cell from a leaf? **(1)**

iii a cell from the root of a plant? **(1)**

SKILLS REASONING

b Explain fully why the answers to ii) and iii) above are different. **(1)**

SKILLS INTERPRETATION

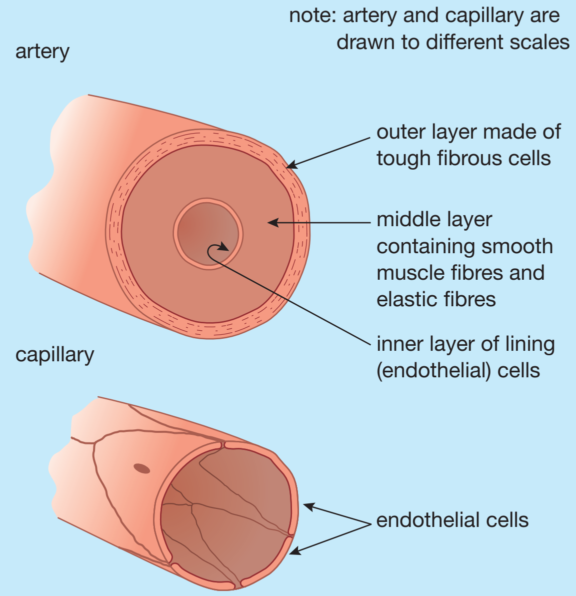
c What is the function of each organelle? **(3)**

(Total 7 marks)

SKILLS INTERPRETATION, REASONING

2 In multicellular organisms, cells are organised into tissues, organs and organ systems.

a The diagram shows a section through an artery and a capillary.



Explain why an artery can be considered to be an organ whereas a capillary cannot. **(2)**

b Organ systems contain two or more organs whose functions are linked. The digestive system is one human organ system. (See Chapter 4.)

SKILLS CRITICAL THINKING 4th

i What does the digestive system do? **(2)**

5th

ii Name three organs in the human digestive system. Explain what each organ does as part of the digestive system. **(6)**

4th

iii Name two other human organ systems and, for each system, name two organs that are part of the system. **(6)**

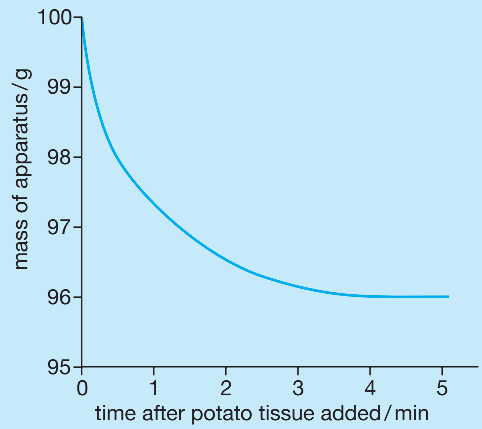
(Total 16 marks)

SKILLS ANALYSIS 4th

3 Catalase is an enzyme found in many plant and animal cells. It catalyses the breakdown of hydrogen peroxide into water and oxygen.

$$\text{hydrogen peroxide} \xrightarrow{\textit{catalase}} \text{water + oxygen}$$

a In an investigation into the action of catalase in potato, 20 g of potato tissue was put into a small beaker containing hydrogen peroxide weighing 80 g in total. The temperature was maintained at 20 °C throughout the investigation. As soon as the potato was added, the mass of the beaker and its contents was recorded until there was no further change in mass. The results are shown in the graph.



5th **i** How much oxygen was formed in this investigation? Explain your answer. **(2)**

6th **ii** Estimate the time by which half this mass of oxygen had been formed. **(2)**

SKILLS REASONING 8th **iii** Explain, in terms of collisions between enzyme and substrate molecules, why the rate of reaction changes during the course of the investigation. **(2)**

b The students repeated the investigation at 30 °C. What difference, if any, would you expect in:

SKILLS DECISION MAKING 9th **i** the mass of oxygen formed?

ii the time taken to form this mass of oxygen?

Explain your answers. **(4)**

(Total 10 marks)

CRITICAL THINKING 7th

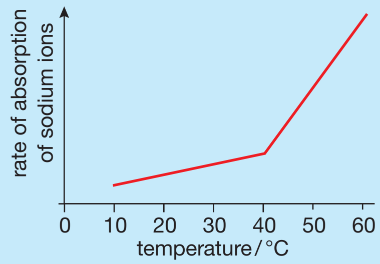
4 Different particles move across cell membranes using different processes.

a The table below shows some ways in which active transport, osmosis and diffusion are similar and some ways in which they are different.
Copy and complete the table with ticks and crosses. **(3)**

Feature	Active transport	Osmosis	Diffusion
particles must have kinetic energy			
requires energy from respiration			
particles move down a concentration gradient			

SKILLS CRITICAL THINKING 7th

b The graph shows the results of an investigation into the rate of diffusion of sodium ions across the membranes of potato cells.



SKILLS ANALYSIS, REASONING 6th

i Explain the increase in the rate of diffusion up to 40 °C. **(2)**

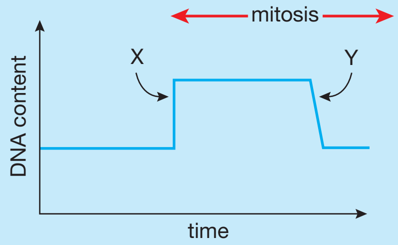
ii Suggest why the rate of increase is much steeper at temperatures above 40 °C. **(2)**

(Total 7 marks)

SKILLS REASONING 8th

5 Cells in the wall of the small intestine divide by mitosis to replace cells lost as food passes through.

a Chromosomes contain DNA. The graph shows the changes in the DNA content of a cell in the wall of the small intestine as it divides by mitosis.

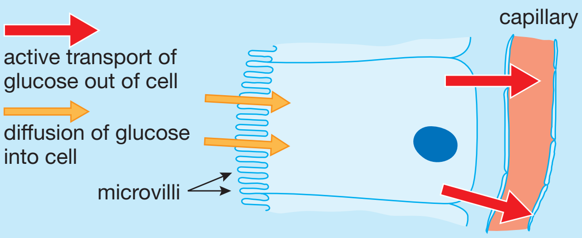


i Why is it essential that the DNA content is doubled (X) before mitosis begins? **(2)**

SKILLS ANALYSIS

ii What do you think happens to the cell at point Y? **(1)**

b The diagram shows a cell in the wall of a villus in the small intestine. Some of the processes involved in the absorption of glucose are also shown.



SKILLS INTERPRETATION 6th

i What is the importance of the small intestine having villi? **(1)**

7th

ii Suggest how the microvilli adapt this cell to its function of absorbing glucose. **(1)**

8th

iii Suggest how the active transport of glucose out of the cell and into the blood stream helps with the absorption of glucose from the small intestine. **(2)**

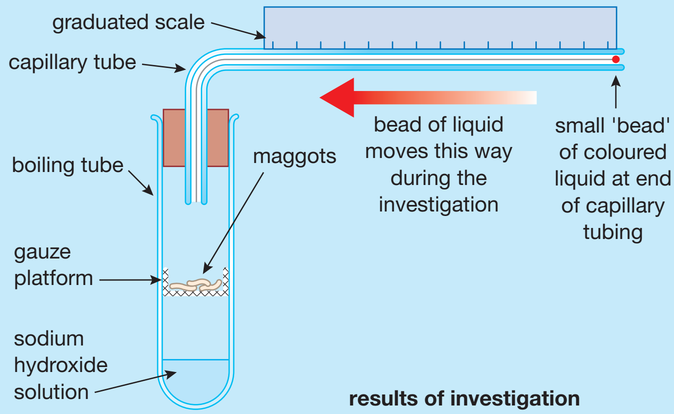
(Total 7 marks)

SKILLS REASONING

8th

6 A respirometer is used to measure the rate of respiration. The diagram shows a simple respirometer. The sodium hydroxide solution in the apparatus absorbs carbon dioxide. Some results from the investigation are also shown.

Safety note: Eye protection should be worn when setting up the apparatus as sodium hydroxide is very hazardous to the eyes.



results of investigation

Experiment	Distance moved by bead / mm
1	20
2	3
3	18

Assume that the maggots in the apparatus respire aerobically.

a Write the symbol equation for aerobic respiration. (4)

b From the equation, what can you assume about the amount of oxygen taken in and carbon dioxide given off by the maggots? Explain your answer. (3)

c Result 2 is significantly different from the other two results. Suggest a reason for this. (2)

9th

d How would the results be different if the organisms under investigation respired anaerobically? **(2)**

(Total 11 marks)

SKILLS INTERPRETATION

5th

7 The table below shows some features of different groups of organisms. Copy and complete the table by putting a tick in the box if the organism has that feature, or a cross if it lacks the feature.

Feature	Type of organism		
	Plant	Fungus	Virus
they are all parasites			
they are made up of a mycelium of hyphae			
they can only reproduce inside living cells			
they feed by extracellular digestion by enzymes			
they store carbohydrate as starch			

(Total 5 marks)

SKILLS CRITICAL THINKING 6th

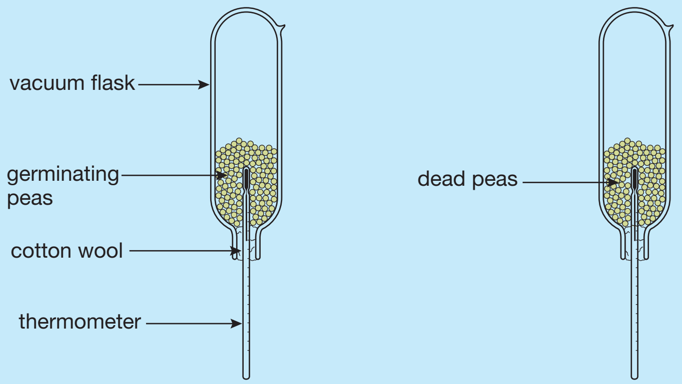
8 Copy and complete the following account.

Plants have cell walls made of ____________________ . They store carbohydrate as the insoluble compound called ____________________ or sometimes as the sugar ____________________ . Plants make these substances as a result of the process called ____________________ . Animals, on the other hand, store carbohydrate as the compound ____________________ . Both animals' and plants' cells have nuclei, but the cells of bacteria lack a true nucleus, having their DNA in a circular chromosome. They sometimes also contain small rings of DNA called ____________________ , which are used in genetic engineering. Bacteria and fungi break down organic matter in the soil. They are known as ____________________ . Some bacteria are pathogens, which means that they ____________________ .

(Total 8 marks)

SKILLS DECISION MAKING

9 The diagram shows the apparatus used to investigate germination of pea seeds. At the start of the experiment the temperature in both flasks was 19 °C



The apparatus was left for 24 hours. At the end of this time the temperature in the flask with germinating peas was 22 °C, while the temperature in the flask with dead peas was 19 °C.

a Explain the biological reason for this difference in temperature. **(2)**

b The seeds in both flasks were washed in disinfectant before the experiment. Explain why this was done. **(1)**

c Cotton wool was used to hold the seeds in the flasks. Suggest why cotton wool was used instead of a rubber bung. **(1)**

SKILLS EXECUTIVE FUNCTION 5th

d Pea seeds were used in both flasks. State another variable that should have been controlled in the experiment. **(1)**

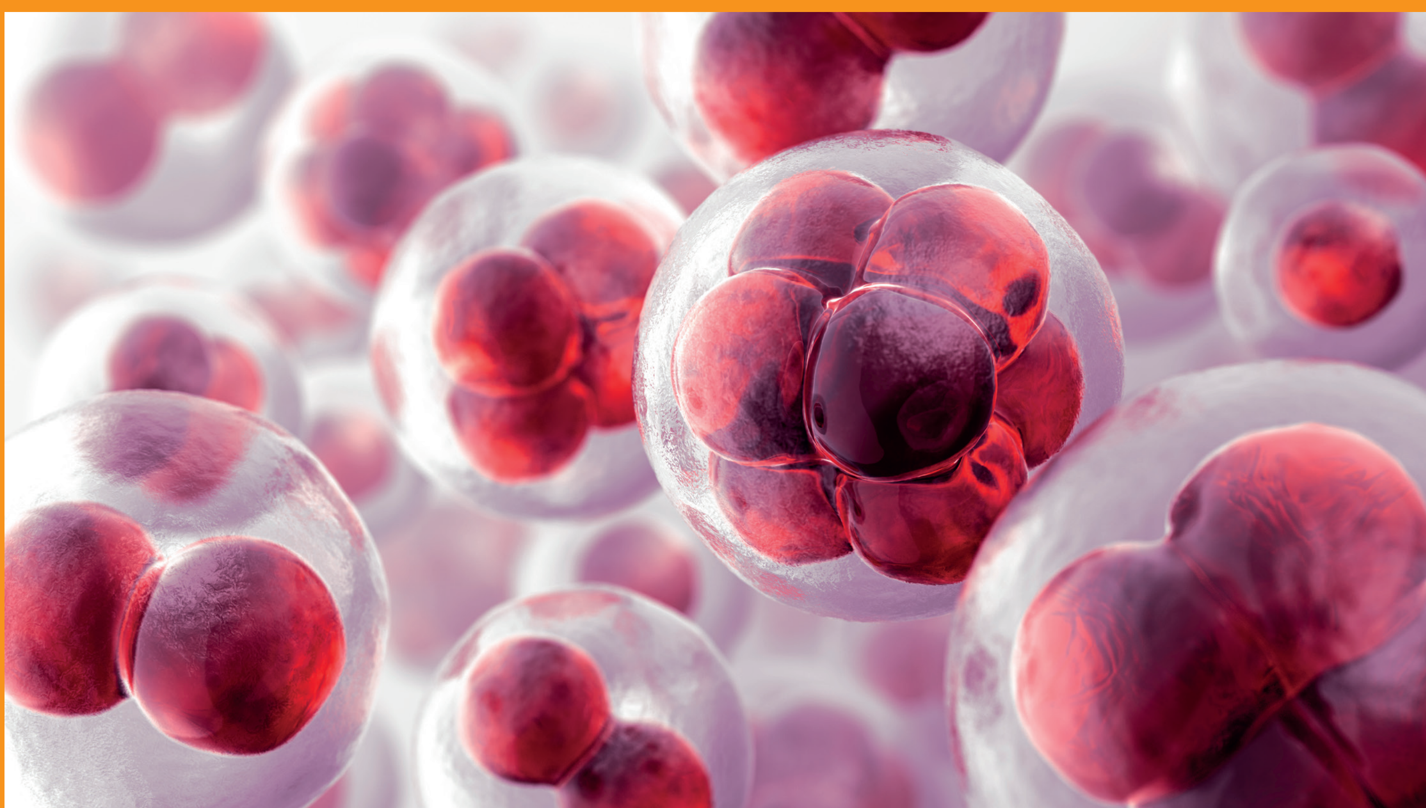
(Total 5 marks)

7th

10 A piece of meat is a tissue composed of muscle fibres. Muscle fibres use ATP when they contract. Describe an investigation to find out if a solution of ATP will cause the contraction of muscle fibres. **(Total 6 marks)**

BIOLOGY UNIT 2 ANIMAL PHYSIOLOGY

Physiology is the branch of biology that looks at how living things function. It studies the workings of an organism at different levels from cells, tissues and organs through to the whole organism. In this unit we look at animal physiology and in particular how the human body works. It is important to study physiology, not least because knowledge of the body is essential in understanding how to treat it when it goes wrong. This is reflected in the fact that one of the six categories of Nobel Prize is awarded for ‘physiology or medicine’.



3 BREATHING AND GAS EXCHANGE

When we breathe, air is moved in and out of the lungs so that gas exchange can take place between the air and the blood. This chapter looks at these processes, and also deals with some ways that smoking can damage the lungs and stop these vital organs from working properly.

LEARNING OBJECTIVES

- Describe the structure of the thorax, including the ribs, intercostal muscles, diaphragm, trachea, bronchi, bronchioles, alveoli and pleural membranes
- Understand the role of the intercostal muscles and the diaphragm in ventilation
- Explain how alveoli are adapted for gas exchange by diffusion between air in the lungs and blood in capillaries
- Investigate breathing in humans, including the release of carbon dioxide and the effect of exercise
- Understand the biological consequences of smoking in relation to the lungs and circulatory system, including coronary heart disease.

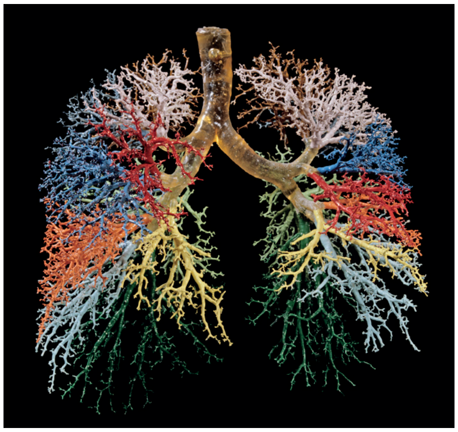
Cells get their energy by oxidising foods such as glucose, during the process called **respiration**. If cells are to respire aerobically, they need a continuous supply of oxygen from the blood. In addition, carbon dioxide from respiration needs to be removed from the body. In humans, these gases are exchanged between the blood and the air in the lungs.

RESPIRATION AND BREATHING

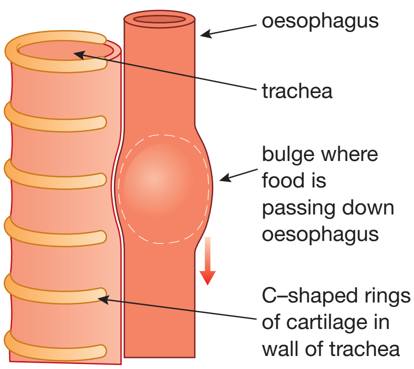
You need to understand the difference between respiration and breathing. Respiration is the oxidation reaction that releases energy from foods such as glucose (Chapter 1). Breathing is the mechanism that moves air into and out of the lungs, allowing gas exchange to take place. The lungs and associated structures are often called the ‘respiratory system’ but this can be confusing. It is better to call them the gas exchange system and this is the term we use in this book.

THE STRUCTURE OF THE GAS EXCHANGE SYSTEM

The lungs are enclosed in the chest or **thorax** by the ribcage and a muscular sheet of tissue called the **diaphragm** (Figure 3.1). As you will see, the actions of these two structures bring about the movements of air into and out of the lungs. Joining each rib to the next are two sets of muscles called **intercostal muscles** (‘costals’ are rib bones). The diaphragm separates the contents of the thorax from the abdomen. It is not flat, but a shallow dome shape, with a fibrous middle part forming the ‘roof’ of the dome, and muscular edges forming the walls.



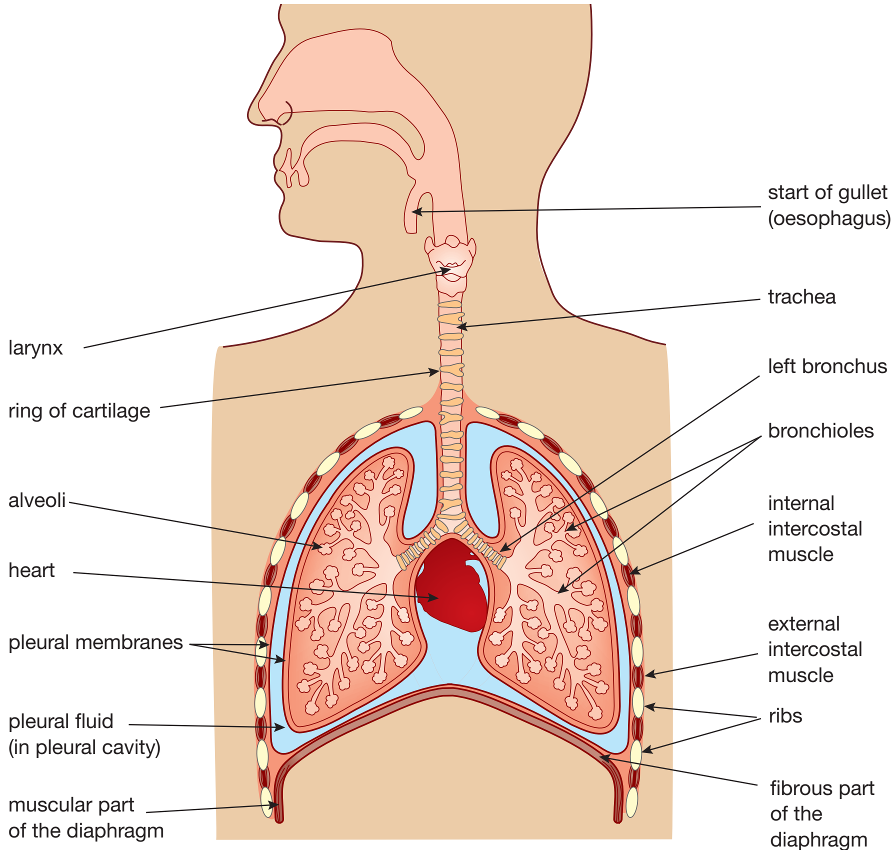
▲ Figure 3.2 This cast of the human lungs was made by injecting a pair of lungs with a liquid plastic. The plastic was allowed to set, then the lung tissue was dissolved away with acid.



▲ Figure 3.3 C-shaped cartilage rings in the trachea.

EXTENSION WORK

In the bronchi, the cartilage forms complete, circular rings. In the trachea, the rings are incomplete, and shaped like a letter 'C'. The open part of the ring is at the back of the trachea, next to where the oesophagus (gullet) lies as it passes through the thorax. When food passes along the oesophagus by peristalsis (see Chapter 4) the gaps in the rings allow the lumps of food to pass through more easily, without the peristaltic wave 'catching' on the rings (Figure 3.3).



▲ Figure 3.1 The human gas exchange system

The air passages of the lungs form a highly branching network (Figure 3.2). This is why it is sometimes called the **bronchial tree**.

When we breathe in, air enters our nose or mouth and passes down the windpipe or **trachea**. The trachea splits into two tubes called the **bronchi** (singular **bronchus**), one leading to each lung. Each bronchus divides into smaller and smaller tubes called **bronchioles**, eventually ending at microscopic air sacs, called **alveoli** (singular **alveolus**). It is here that gas exchange with the blood takes place.

The walls of trachea and bronchi contain rings of gristle or **cartilage**. These support the airways and keep them open when we breathe in. They are rather like the rings in a vacuum cleaner hose – without them the hose would squash flat when the cleaner sucks air in.

The inside of the thorax is separated from the lungs by two thin, moist membranes called the **pleural membranes**. They make up a continuous envelope around the lungs, forming an airtight seal. Between the two membranes is a space called the **pleural cavity**, filled with a thin layer of liquid called **pleural fluid**. This acts as lubrication, so that the surfaces of the lungs don't stick to the inside of the chest wall when we breathe.

KEEPING THE AIRWAYS CLEAN

The trachea and larger airways are lined with a layer of cells that have an important role in keeping the airways clean. Some cells in this lining secrete a sticky liquid called **mucus**, which traps particles of dirt or bacteria that are breathed in. Other cells are covered with tiny hair-like structures called **cilia** (Figure 3.4). The cilia beat backward and forward, sweeping the mucus and trapped particles out towards the mouth. In this way, dirt and bacteria are

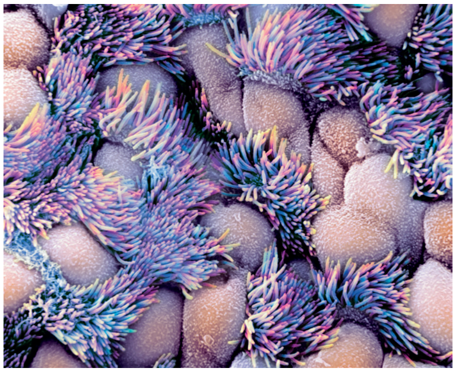


Figure 3.4 This electron microscope picture shows cilia from the lining of the trachea.

prevented from entering the lungs, where they might cause an infection. As you will see, one of the effects of smoking is that it destroys the cilia and stops this protection mechanism from working properly.

VENTILATION OF THE LUNGS

Ventilation means moving air in and out of the lungs. This requires a difference in air pressure – the air moves from a place where the pressure is high to one where it is low. Ventilation depends on the fact that the thorax is an airtight cavity. When we breathe, we change the volume of our thorax, which alters the pressure inside it. This causes air to move in or out of the lungs.

There are two movements that bring about ventilation: those of the ribs and the diaphragm. If you put your hands on your chest and breathe in deeply, you can feel your ribs move upwards and outwards. They are moved by the intercostal muscles (Figure 3.5). The outer (external) intercostals contract, pulling the ribs up. At the same time, the muscles of the diaphragm contract, pulling the diaphragm down into a more flattened shape (Figure 3.6a). Both these movements increase the volume of the chest and cause a slight drop in pressure inside the thorax compared with the air outside. Air then enters the lungs (inhalation).

EXTENSION WORK

During normal (shallow) breathing, the elasticity of the lungs and the weight of the ribs acting downwards is enough to cause exhalation. The internal intercostals are only really used for deep (forced) breathing out, for instance when we are exercising.

The opposite happens when you breathe out deeply. The external intercostals relax, and the internal intercostals contract, pulling the ribs down and in. At the same time, the diaphragm muscles relax and the diaphragm goes back to its normal dome shape. The volume of the thorax decreases, and the pressure in the thorax is raised slightly above atmospheric pressure. This time the difference in pressure forces air out of the lungs (Figure 3.6b). Exhalation is helped by the fact that the lungs are elastic, so that they have a tendency to collapse and empty like a balloon.

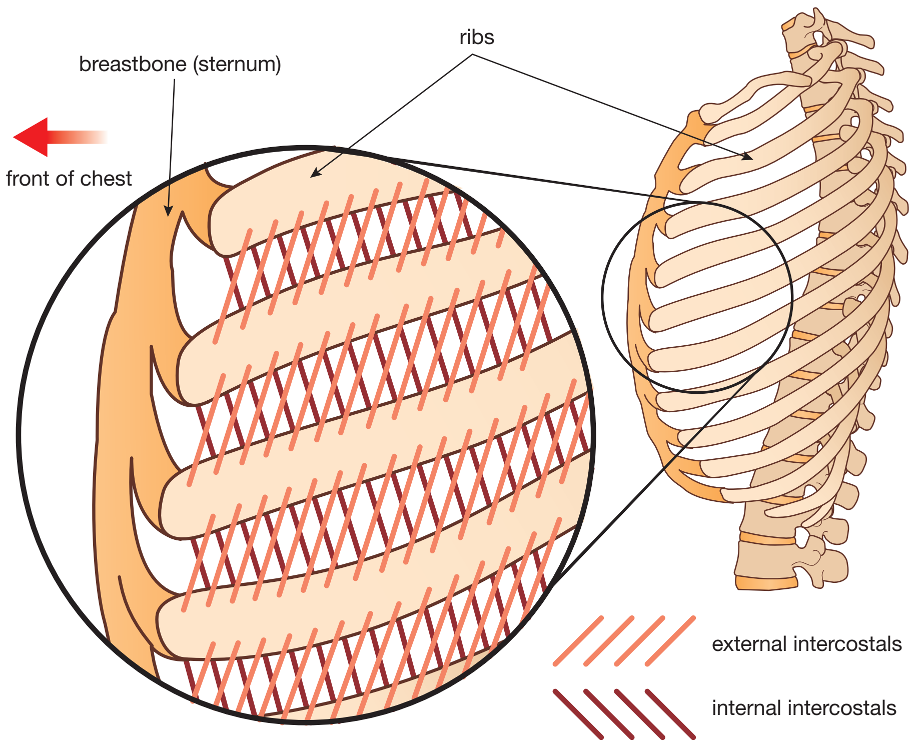
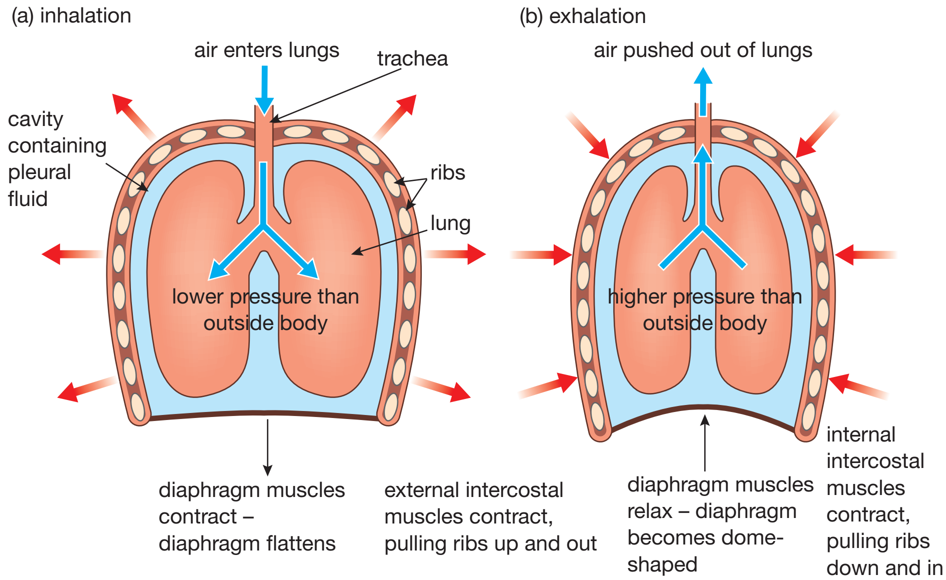


Figure 3.5 Side view of the chest wall, showing the ribs. The diagram shows how the two sets of intercostal muscles run between the ribs. When the external intercostals contract, they move the ribs upwards. When the internal intercostals contract, the ribs are moved downwards.



▲ Figure 3.6 Changes in the position of the ribs and diaphragm during breathing. (a) Breathing in (inhalation). (b) Breathing out (exhalation).

KEY POINT

It is important that you remember the changes in volume and pressure during ventilation. If you have trouble understanding these, think of what happens when you use a bicycle pump. If you push the pump handle, the air in the pump is squashed, its pressure rises and it is forced out of the pump. If you pull on the handle, the air pressure inside the pump falls a little, and air is drawn in from outside. This is similar to what happens in the lungs. In exams, students sometimes talk about the lungs *forcing* the air in and out – they don't!

GAS EXCHANGE IN THE ALVEOLI

You can tell what is happening during gas exchange if you compare the amounts of different gases in atmospheric air with the air breathed out (Table 3.1).

Table 3.1 Approximate percentage volume of gases in atmospheric (inhaled) and exhaled air.

Gas	Atmospheric air / %	Exhaled air / %
nitrogen	78	79
oxygen	21	16
carbon dioxide	0.04	4
other gases (mainly argon)	1	1

Exhaled air is also warmer than atmospheric air, and is saturated with water vapour. The amount of water vapour in the atmosphere varies depending on weather conditions.

Clearly, the lungs are absorbing oxygen into the blood and removing carbon dioxide from it. This happens in the alveoli. To do this efficiently, the alveoli must have a structure which brings the air and blood very close together, over a very large surface area. There are enormous numbers of alveoli. It has been calculated that the two lungs contain about 700 000 000 of these tiny air sacs, giving a total surface area of 60 m^2. That's bigger than the floor area of an average classroom! Viewed through a high-powered microscope, the alveoli look rather like bunches of grapes, and are covered with tiny blood capillaries (Figure 3.7).

HINT

Be careful when interpreting percentages! The *percentage* of a gas in a mixture can vary, even if the actual *amount* of the gas stays the same. This is easiest to understand from an example. Imagine you have a bottle containing a mixture of 20% oxygen and 80% nitrogen. If you used a chemical to absorb all the oxygen in the bottle, the nitrogen left would now be 100% of the gas in the bottle, despite the fact that the *amount* of nitrogen would still be the same. That is why the percentage of nitrogen in inhaled and exhaled air is slightly different.

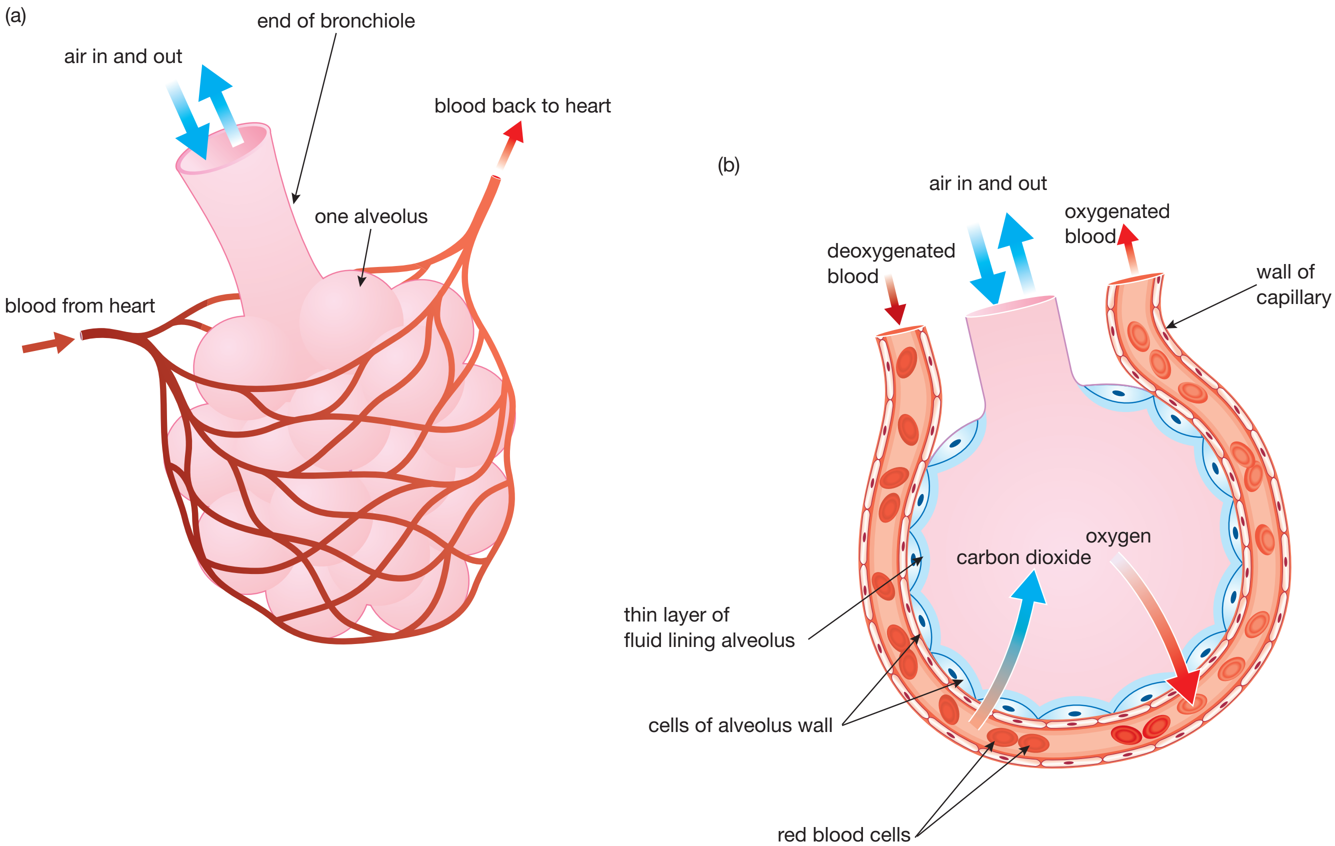


Figure 3.7 (a) Alveoli and the surrounding capillary network. (b) Diffusion of oxygen and carbon dioxide takes place between the air in the alveolus and the blood in the capillaries.

HINT

Be careful – students sometimes write 'The alveolus has *cell walls*'. This statement is not correct – a cell wall is part of a plant cell! The correct way to describe the structure is: 'The alveolus has *a wall made of cells*'.

Deoxygenated blood is pumped from the heart to the lungs and passes through the capillaries surrounding the alveoli. The blood has come from the respiring tissues of the body, where it has given up some of its oxygen to the cells, and gained carbon dioxide. Around the lungs, the blood is separated from the air inside each alveolus by only two cell layers; the cells making up the wall of the alveolus, and the capillary wall itself. This is a distance of less than a thousandth of a millimetre.

EXTENSION WORK

The thin layer of fluid lining the inside of the alveoli comes from the blood. The capillaries and cells of the alveolar wall are 'leaky' and the blood pressure pushes fluid out from the blood plasma into the alveolus. Oxygen dissolves in this moist surface before it passes through the alveolar wall into the blood.

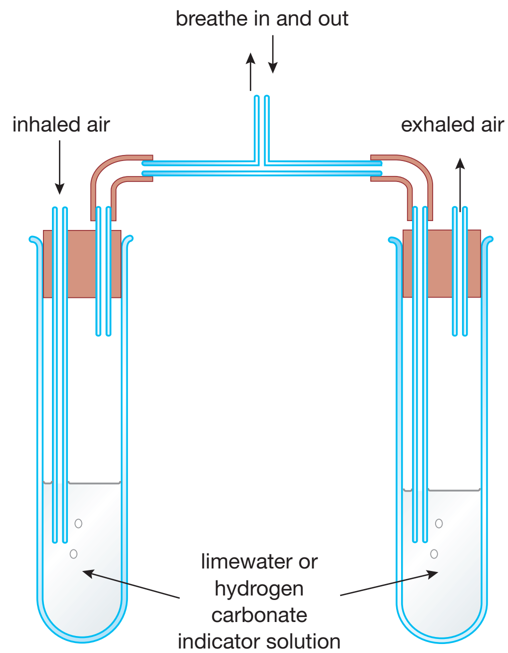
Because the air in the alveolus has a higher concentration of oxygen than the blood entering the **capillary** network, oxygen diffuses from the air, across the wall of the alveolus and into the blood. At the same time there is more carbon dioxide in the blood than there is in the air in the lungs. This means that there is a diffusion gradient for carbon dioxide in the other direction, so carbon dioxide diffuses the other way, out of the blood and into the alveolus. The result is that the blood which leaves the capillaries and flows back to the heart has gained oxygen and lost carbon dioxide. The heart then pumps the oxygenated blood around the body again, to supply the respiring cells (see Chapter 5).

Safety note: Wear eye protection and breathe gently; do not blow. A clean mouthpiece must be used for each person.

ACTIVITY 1

▼ PRACTICAL: COMPARING THE CARBON DIOXIDE CONTENT OF INHALED AND EXHALED AIR

The apparatus in Figure 3.8 can be used to compare the amount of carbon dioxide in inhaled and exhaled air. A person breathes gently in and out through the middle tube. Exhaled air passes out through one tube of indicator solution and inhaled air is drawn in through the other tube. If limewater is used, the limewater in the 'exhaled' tube will turn cloudy before the limewater in the 'inhaled' tube. (If hydrogen carbonate indicator solution is used instead, it changes from red to yellow.)



▲ Figure 3.8 Apparatus for Experiment 6.

Safety note: Wear suitable footwear for exercising and if doing step-ups use a sturdy secure low box or a PE bench.

ACTIVITY 2

▼ PRACTICAL: AN INVESTIGATION INTO THE EFFECT OF EXERCISE ON BREATHING RATE

It is easy to show the effect of exercise on a person's breathing rate. They sit quietly for five minutes, making sure that they are completely relaxed. They then count the number of breaths they take in one minute, recording their results in a table. They wait a minute, and then count their breaths again, recording the result, and repeating if necessary until they get a steady value for the 'resting rate'.

The person then carries out some vigorous exercise, such as running on the spot for three minutes. Immediately after they finish the exercise, they sit down and record the breathing rate as before. They then continue to record their breaths per minute, every minute, until they return to their normal resting rate.

The table shows the results from an investigation into the breathing rate of two girls, A and B, before and after exercise.

Time from start of experiment (min)	Breathing rate / breaths per min	
	A	B
1	13	13
2	14	12
3	14	12
Rate after 3 min vigorous exercise:		
7	28	17
8	24	13
9	17	12
10	14	12

Plot a line graph of these results, using the same axes for both subjects. Join the data points using straight lines, and leave a gap during the period of exercise, when no readings were taken.

Why does breathing rate need to rise during exercise? Explain as fully as possible. Why does the rate not return to normal as soon as a subject finishes the exercise? (see Chapter 1).

Describe the difference in the breathing rates of the two girls (A and B) after exercise. Which girl is more fit? Explain your reasoning.

THE EFFECTS OF SMOKING

In order for the lungs to exchange gases properly, the air passages need to be clear, the alveoli need to be free from dirt particles and bacteria, and they must have as big a surface area as possible in contact with the blood. There is one habit that can upset all of these conditions – smoking.

Links between smoking and diseases of the lungs are now a proven fact. Smoking is associated with lung cancer, bronchitis and emphysema. It is also a major contributing factor to other conditions, such as coronary heart disease and ulcers of the stomach and intestine. Pregnant women who smoke are more likely to give birth to underweight babies.

Coronary heart disease will be described in Chapter 5 after you have studied the structure of the heart. Here we will look at a number of other medical conditions that are caused by smoking.

EFFECTS OF SMOKE ON THE LINING OF THE AIR PASSAGES

You saw above how the lungs are kept free of particles of dirt and bacteria by the action of mucus and cilia. In the trachea and bronchi of a smoker, the cilia are destroyed by the chemicals in cigarette smoke.

The reduced numbers of cilia mean that the mucus is not swept away from the lungs, but remains to block the air passages. This is made worse by the fact that the smoke irritates the lining of the airways, stimulating the cells to secrete more mucus. The sticky mucus blocking the airways is the source of 'smoker's cough'. Irritation of the bronchial tree, along with infections from bacteria in the mucus, can cause the lung disease **bronchitis**. Bronchitis blocks normal air flow, so the sufferer has difficulty breathing properly.

EMPHYSEMA

Emphysema is another lung disease that kills about 20 000 people in Britain every year. Smoking is the cause of one type of emphysema. Smoke damages the walls of the alveoli, which break down and fuse together again, forming enlarged, irregular air spaces (Figure 3.9).

This greatly reduces the surface area for gas exchange, which becomes very inefficient. The blood of a person with emphysema carries less oxygen. In serious cases, this leads to the sufferer being unable to carry out even mild exercise, such as walking. Emphysema patients often have to have a supply of oxygen nearby at all times (Figure 3.10). There is no cure for emphysema, and usually the sufferer dies after a long and distressing illness.

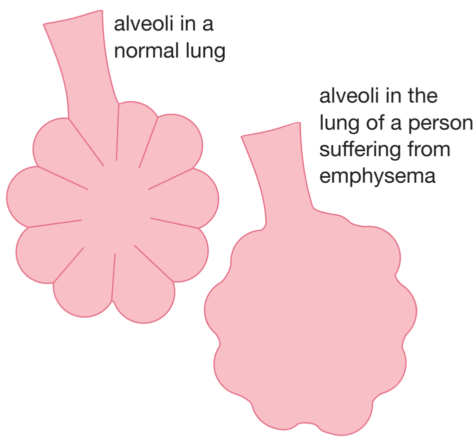


Figure 3.9 The alveoli of a person suffering from emphysema have a greatly reduced surface area and inefficient gas exchange.

Figure 3.10 Patients with emphysema often need to breathe air enriched with oxygen in order to stay alive.

EXTENSION WORK

A person who has chronic (long-term) bronchitis and emphysema is said to be suffering from chronic obstructive pulmonary disease, or COPD. COPD is a progressive disease for which there is no cure.

LUNG CANCER

Evidence of the link between smoking and lung cancer first appeared in the 1950s. In one study, a number of patients in hospital were given a series of questions about their lifestyles. They were asked about their work, hobbies, housing and so on, including a question about how many cigarettes they smoked. The same questionnaire was given to two groups of patients. The first group were all suffering from lung cancer. The second (**Control**) group were in hospital with various other illnesses, but not lung cancer. To make it a fair comparison, the Control patients were matched with the lung cancer patients for sex, age and so on.

When the results were compared, one difference stood out (Table 3.2). A greater proportion of the lung cancer patients were smokers than in the Control patients. There seemed to be a connection between smoking and getting lung cancer.

Table 3.2 Comparison of the smoking habits of lung cancer patients and other patients.

	Percentage of patients who were non-smokers	Percentage of patients who smoked more than 15 cigarettes a day
lung cancer patients	0.5	25
Control patients (with illnesses other than lung cancer)	4.5	13

Although the results didn't prove that smoking caused lung cancer, there was a statistically significant link between smoking and the disease: this is called a 'correlation'.

Over 20 similar investigations in nine countries have revealed the same findings. In 1962 a report called 'Smoking and health' was published by the Royal College of Physicians of London, which warned the public about the dangers of smoking. Not surprisingly, the first people to take the findings seriously were doctors, many of whom stopped smoking. This was reflected in their death rates from lung cancer. In ten years, while deaths among the general male population had risen by 7%, the deaths of male doctors from the disease had *fallen* by 38%.

Figure 3.11 This lung is from a patient with lung cancer.

Cigarette smoke contains a strongly addictive drug – **nicotine**. Smoke contains over 7000 chemicals, including; carbon monoxide, arsenic, ammonia, formaldehyde, cyanide, benzene, and toluene. More than 60 of the chemicals are known to cause cancer. These chemicals are called **carcinogens**, and are contained in the tar that collects in a smoker's lungs. Cancer happens when cells mutate and start to divide uncontrollably, forming a **tumour** (Figure 3.11). If a lung cancer patient is lucky, they may have the tumour removed by an operation before the cancer cells spread to other tissues of the body. Unfortunately tumours in the lungs usually cause no pain, so they are not discovered until it is too late – it may be inoperable, or tumours may have developed elsewhere.

If you smoke you are not *bound* to get lung cancer, but the risk that you will get it is much greater. In fact, the more cigarettes you smoke, the more the risk increases (Figure 3.12).

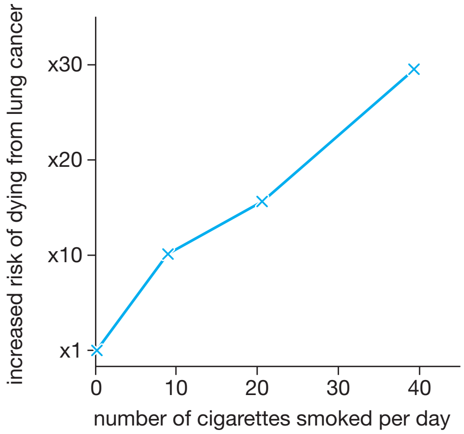


Figure 3.12 The more cigarettes a person smokes, the more likely it is they will die of lung cancer. For example, smoking 20 cigarettes a day increases the risk by about 15 times.

The obvious thing to do is not to start smoking. However, if you are a smoker, giving up the habit soon improves your chance of survival (Figure 3.13). After a few years, the likelihood of your dying from a smoking-related disease is almost back to the level of a non-smoker.

DID YOU KNOW?

People often talk about 'yellow nicotine stains'. In fact it is the *tar* that stains a smoker's fingers and teeth. Nicotine is a colourless, odourless chemical.

DID YOU KNOW?

Studies have shown that the type of cigarette smoked makes very little difference to the smoker's risk of getting lung cancer. Filtered and 'low tar' cigarettes only reduce the risk slightly.

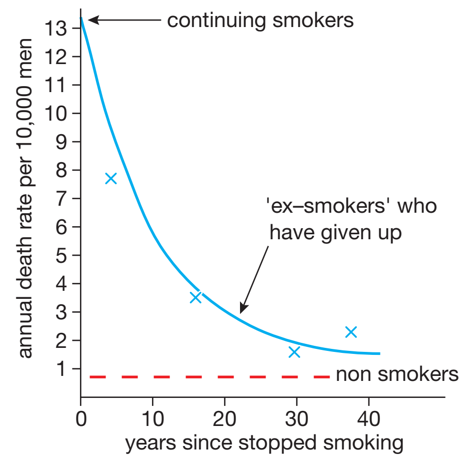


Figure 3.13 Death rates from lung cancer for smokers, non-smokers and ex-smokers.

CARBON MONOXIDE IN SMOKE

One of the harmful chemicals in cigarette smoke is the poisonous gas **carbon monoxide**. When this gas is breathed in with the smoke, it enters the bloodstream and interferes with the ability of the blood to carry oxygen. Oxygen is carried around in the blood in the red blood cells, attached to a chemical called **haemoglobin** (see Chapter 5). Carbon monoxide can combine with the haemoglobin much more tightly than oxygen can, forming a compound called **carboxyhaemoglobin**. The haemoglobin will combine with carbon monoxide in preference to oxygen. When this happens, the blood carries much less oxygen around the body. Carbon monoxide from smoking is also a major cause of heart disease (Chapter 5).

Figure 3.14 Smoking during pregnancy affects the growth and development of the baby.

If a pregnant woman smokes, she will be depriving her unborn **fetus** of oxygen (Figure 3.14). This has an effect on its growth and development, and leads to the mass of the baby at birth being lower, on average, than the mass of babies born to non-smokers.

SOME SMOKING STATISTICS

- It is estimated that there are over 1 billion smokers worldwide. In 2014 they consumed 5.8 *trillion* cigarettes.
- Every year nearly 6 million people are killed by tobacco-related illnesses. If the current trend continues, by 2030 this will rise to 8 million deaths per year and 80% of these premature deaths will be in developing countries.
- Smoking causes almost 80% of deaths from lung cancer, 80% of deaths from bronchitis and emphysema, and 14% of deaths from heart disease.
- More than a quarter of all cancer deaths are attributable to smoking. These include cancer of the lung, mouth, lip, throat, **bladder**, kidney, pancreas, stomach, liver and cervix.
- While demand for tobacco has steadily fallen in developed countries like the UK, cigarette consumption is being increasingly concentrated in the developing world.
- 9.6 million adults in the UK smoke cigarettes, 20% of men and 17% of women. However, 22% of women and 30% of men in the UK are now ex-smokers. Surveys show that about two-thirds of current smokers would like to stop smoking.
- It is estimated that worldwide, 31% of men and 8% of women are smokers. Consumption varies widely between different countries, but generally the areas of the world where there has been no change in consumption, or an increase, are southern and central Asia, Eastern Europe and Africa.

- In China alone there are about 350 million smokers, who consume about one-third of all cigarettes smoked worldwide. Large multinational tobacco companies have long been keen to enter the Chinese market.
- In China there are over a million deaths a year from smoking-related diseases. This figure is expected to double by 2025.
- In developing countries, smoking has a greater economic impact. Poorer smokers spend significant amounts of their income on cigarettes rather than necessities like food, healthcare and education.
- Tobacco farming uses up land that could be used for growing food crops. In 2012, 7.5 million tonnes of tobacco leaf were grown on almost 4.3 million hectares of land (an area larger than Switzerland).

Sources: Action on Smoking and Health (ASH) fact sheets (2015- 2016); ASH research reports (2014-2016)]

GIVING UP SMOKING

▲ Figure 3.15 An e-cigarette provides a smoker with an alternative source of nicotine.

▲ Figure 3.16 Nicotine patches release nicotine into the blood through the skin. When a smoker is trying to give up the habit, they reduce the craving for a cigarette.

Most smokers admit that they would like to find a way to give up the habit. The trouble is that the nicotine in tobacco is a very addictive drug, and causes withdrawal symptoms when people stop smoking. These include cravings for a cigarette, restlessness and a tendency to put on weight (nicotine depresses the appetite).

There are various ways that smokers can be helped to give up their habit. One method is 'vaping', which involves inhaling a vapour containing nicotine from an electronic cigarette or e-cigarette (Figure 3.15). Other methods use nicotine patches (Figure 3.16) or nicotine chewing gum. They all work in a similar way, providing the smoker with a source of nicotine without the harmful tar from cigarettes. The nicotine is absorbed by the body and reduces the craving for a cigarette. Gradually, the patient reduces the nicotine dose until they are weaned off the habit.

EXTENSION WORK

You could carry out an Internet search to find out about the different methods people use to help them give up smoking. Which methods have the highest success rate? Is there any evidence that suggests e-cigarettes are not safe?

There are several other ways that people use to help them give up smoking, including the use of drugs that reduce withdrawal symptoms, acupuncture and even hypnotism.

CHAPTER QUESTIONS

SKILLS CRITICAL THINKING

More questions on breathing can be found at the end of Unit 2 on page 116.

4th

1 The structures below are found in the human bronchial tree

1. alveoli 3. bronchioles
2. trachea 4. bronchi

Which of the following shows the route taken by air after it is breathed in through the mouth?

A 2 → 3 → 4 → 1 **C** 2 → 4 → 3 → 1
B 1 → 4 → 3 → 2 **D** 4 → 1 → 2 → 3

5th

2 Which of the following is *not* a feature of an efficient gas exchange surface?

A thick walls **C** close proximity to blood capillaries
B moist lining **D** large surface area

SKILLS CRITICAL THINKING

3rd

3 Which row in the table shows the correct percentage of oxygen in atmospheric and exhaled air?

	Atmospheric air / %	Exhaled air / %
A	78	21
B	21	16
C	16	4
D	4	0.04

4 Chemicals in cigarette smoke lead to the breakdown of the walls of the alveoli. What is the name given to this disease?

A bronchitis

B emphysema

C coronary heart disease

D lung cancer

4th

5 Copy and complete the table, which shows what happens in the thorax during ventilation of the lungs. Two boxes have been completed for you.

	Action during inhalation	Action during exhalation
external intercostal muscles	contract	
internal intercostal muscles		
ribs		move down and in
diaphragm		
volume of thorax		
pressure in thorax		
volume of air in lungs		

5th

6 A student wrote the following about the lungs.

When we breathe in, our lungs inflate, sucking air in and pushing the ribs up and out, and forcing the diaphragm down. This is called respiration. In the air sacs of the lungs, the air enters the blood. The blood then takes the air around the body, where it is used by the cells. The blood returns to the lungs to be cleaned. When we breathe out, our lungs deflate, pulling the diaphragm up and the ribs down. The stale air is pushed out of the lungs.

The student did not have a good understanding of the workings of the lungs. Re-write their description, using correct biological words and ideas.

SKILLS REASONING

7 Sometimes, people injured in an accident such as a car crash suffer from a *pneumothorax*. This is an injury where the chest wall is punctured, allowing air to enter the pleural cavity (see Figure 3.1). A patient was brought to the casualty department of a hospital, suffering from a pneumothorax on the left side of his chest. His left lung had collapsed, but he was able to breathe normally with his right lung.

6th

a Explain why a pneumothorax caused the left lung to collapse.

b Explain why the right lung was not affected.

c If a patient's lung is injured or infected, a surgeon can sometimes 'rest' it by performing an operation called an *artificial pneumothorax*. What do you think might be involved in this operation?

SKILLS CRITICAL THINKING

5th **8** Briefly explain the importance of the following.

a The trachea wall contains C-shaped rings of cartilage.

6th **b** The distance between the air in an alveolus and the blood in an alveolar capillary is less than 1/1000th of a millimetre.

c The lining of the trachea contains mucus-secreting cells and cells with cilia.

5th **d** Smokers have a lower concentration of oxygen in their blood than non-smokers.

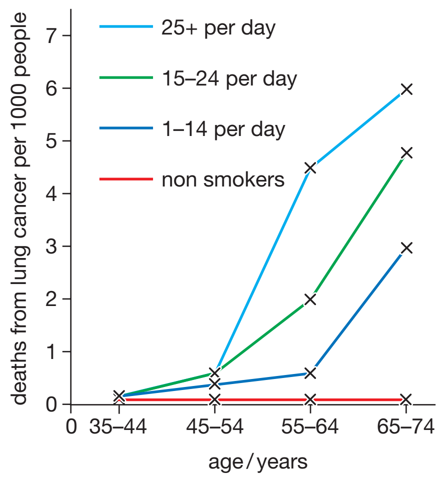
e Nicotine patches and nicotine chewing gum can help someone give up smoking.

7th **f** The lungs have a surface area of about 60 m^2 and a good blood supply.

6th **9** Explain the differences between the lung diseases bronchitis and emphysema.

SKILLS ANALYSIS

10 A long-term investigation was carried out into the link between smoking and lung cancer. The smoking habits of male doctors aged 35 or over were determined while they were still alive, then the number and causes of deaths among them were monitored over a number of years. (Note that this survey was carried out in the 1950s – very few doctors smoke these days!) The results are shown in the graph.



5th **a** Write a paragraph to explain what the researchers found out from the investigation.

SKILLS ANALYSIS, PROBLEM SOLVING

6th **b** How many deaths from lung cancer would be expected for men aged 55 who smoked 25 cigarettes a day up until their death? How many deaths from lung cancer would be expected for men in the same age group smoking 10 a day?

SKILLS ANALYSIS, REASONING

c Table 3.2 (page 43) shows the findings of another study linking lung cancer with smoking. Which do you think is the more convincing evidence of the link, this investigation or the findings illustrated in Table 3.2?

SKILLS CREATIVITY

7th **11** Design and make a hard-hitting leaflet explaining the link between smoking and lung cancer. It should be aimed at encouraging an adult smoker to give up the habit. You could use suitable computer software to produce your design. Include some smoking statistics, perhaps from an Internet search. However don't use too many, or they may put the person off reading the leaflet!

4 FOOD AND DIGESTION

Food is essential for life. The nutrients obtained from it are used in many different ways by the body. This chapter looks at the different kinds of food, and how the food is broken down by the digestive system and absorbed into the blood, so that it can be carried to all the tissues of the body.

LEARNING OBJECTIVES

- Identify the chemical elements present in carbohydrates, proteins and lipids (fats and oils)
- Describe the structure of carbohydrates, proteins and lipids as large molecules made up from smaller basic units – starch and glycogen from simple sugars, protein from amino acids, and lipids from fatty acids and glycerol
- Investigate food samples for the presence of glucose, starch, protein and fat
- Understand that a balanced diet should include appropriate proportions of carbohydrate, protein, lipid, vitamins, minerals, water and dietary fibre
- Identify the sources and describe the functions of carbohydrate, lipid, protein, vitamins A, C and D, the mineral ions calcium and iron, water, and dietary fibre as components of the diet
- Understand how energy requirements vary with activity levels, age and pregnancy
- Describe the structure and function of the human alimentary canal, including the mouth, oesophagus, stomach, small intestine (duodenum and ileum), large intestine (colon and rectum) and pancreas
- Understand how food is moved through the gut by peristalsis
- Understand the role of digestive enzymes, including the digestion of starch to glucose by amylase and maltase, the digestion of proteins to amino acids by proteases and the digestion of lipids to fatty acids and glycerol by lipases
- Understand that bile is produced by the liver and stored in the gall bladder, and understand the role of bile in neutralising stomach acid and emulsifying lipids
- Understand how the small intestine is adapted for absorption, including the structure of a villus

Figure 4.1 A balanced diet contains all the types of food the body needs, in just the right amounts.

We need food for three main reasons:

- to supply us with a ‘fuel’ for energy
- to provide materials for growth and repair of tissues
- to help fight disease and keep our bodies healthy.

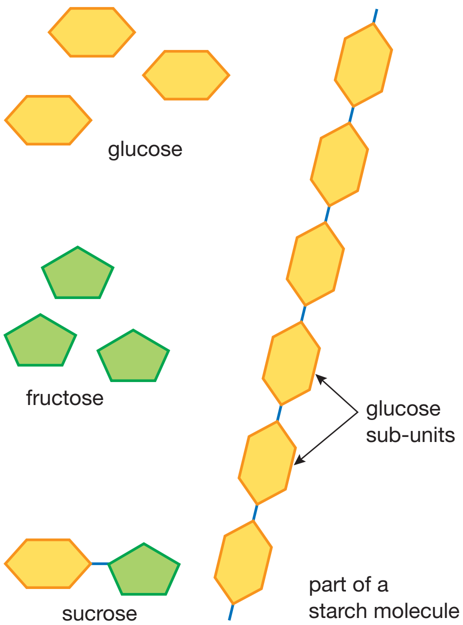
A BALANCED DIET

The food that we eat is called our diet. No matter what you like to eat, your diet must include the following five groups of food substances if your body is to work properly and stay healthy – **carbohydrates**, **lipids**, **proteins**, **minerals** and **vitamins** – along with **dietary fibre** and water. Food should provide you with all of these substances, but they must also be present in the *right* amounts. A diet that provides enough of these substances and in the correct proportions to keep you healthy is called a **balanced diet** (Figure 4.1). We will look at each type of food in turn, to find out about its chemistry and the role that it plays in the body.

CARBOHYDRATES

DID YOU KNOW?

The chemical formula for glucose is $C_6H_{12}O_6$. Like all carbohydrates, glucose contains only the elements carbon, hydrogen and oxygen. The 'carbo' part of the name refers to carbon, and the 'hydrate' part refers to the fact that the hydrogen and oxygen atoms are in the ratio two to one, as in water (H_2O).



▲ Figure 4.2 Glucose and fructose are 'single sugar' molecules. A molecule of glucose joined to a molecule of fructose forms the 'double sugar' called sucrose. Starch is a polymer of many glucose sub-units.

Carbohydrates only make up about 1% of the mass of the human body, but they have a very important role. They are the body's main 'fuel' for supplying cells with energy. Cells release this energy by oxidising a sugar called **glucose**, in the process called cell respiration (see Chapter 1). Glucose and other sugars belong to one group of carbohydrates.

Glucose is found naturally in many sweet-tasting foods, such as fruits and vegetables. Other foods contain different sugars, such as the fruit sugar called **fructose**, and the milk sugar, **lactose**. Ordinary table sugar, the sort some people put in their tea or coffee, is called **sucrose**. Sucrose is the main sugar that is transported through plant stems. This is why we can extract it from sugar cane, which is the stem of a large grass-like plant. Sugars have two physical properties that you will probably know: they all taste sweet, and they are all soluble in water.

We can get all the sugar we need from natural foods such as fruits and vegetables, and from the **digestion** of starch. Many processed foods contain large amounts of *added* sugar. For example, a typical can of cola can contain up to seven teaspoons (27 g) of sugar! There is hidden sugar in many other foods. A tin of baked beans contains about 10 g of added sugar. This is on top of all the food that we eat with a more obvious sugar content, such as cakes, biscuits and sweets.

In fact, we get most of the carbohydrate in our diet not from sugars, but from **starch**. Starch is a large, *insoluble* molecule. Because it does not dissolve, it is found as a storage carbohydrate in many plants, such as potato, rice, wheat and millet. The 'staple diets' of people from around the world are starchy foods like rice, potatoes, bread and pasta. Starch is a polymer of glucose – it is made of long chains of hundreds of glucose molecules joined together (Figure 4.2).

Starch is only found in plant tissues, but animal cells sometimes contain a very similar carbohydrate called **glycogen**. This is also a polymer of glucose, and is found in tissues such as liver and muscle, where it acts as a store of energy for these organs.

As you will see, large carbohydrates such as starch and glycogen have to be broken down into simple sugars during digestion, so that they can be absorbed into the blood.

Another carbohydrate that is a polymer of glucose is **cellulose**, the material that makes up plant cell walls. Humans are *not* able to digest cellulose, because our gut doesn't make the enzyme needed to break down the cellulose molecule. This means that we are not able to use cellulose as a source of energy. However, it still has a vitally important function in our diet. It forms **dietary fibre** or 'roughage', which gives the muscles of the gut something to push against as the food is moved through the intestine. This keeps the gut contents moving, avoiding constipation and helping to prevent serious diseases of the intestine, such as colitis and bowel cancer.

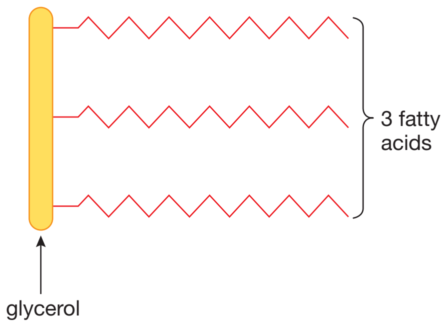
EXTENSION WORK

'Single' sugars such as glucose and fructose are called **monosaccharides**. Sucrose molecules are made of two monosaccharides (glucose and fructose) joined together, so sucrose is called a **disaccharide**. Lactose is also a disaccharide, made of glucose joined to another monosaccharide called galactose. Polymers of sugars, such as starch, glycogen and cellulose, are called polysaccharides.

LIPIDS (FATS AND OILS)

Lipids contain the same three elements as carbohydrates – carbon, hydrogen and oxygen – but the proportion of oxygen in a lipid is much lower than in a carbohydrate. For example, beef and lamb both contain a fat called tristearin, which has the formula $C_{51}H_{98}O_6$. This fat, like other animal fats, is a solid at room

▲ Figure 4.3 These foods are all rich in lipids.



▲ Figure 4.4 Lipids are made up of a molecule of glycerol joined to three fatty acids. The many different fatty acids form the variable part of the molecule.

KEY POINT

Cholesterol is a substance that the body gets from food such as eggs and meat, but we also make cholesterol in our liver. It is an essential part of all cells, but too much cholesterol causes heart disease.

temperature, but melts if you warm it up. On the other hand, plant lipids are usually liquid at room temperature, and are called oils. Meat, butter, cheese, milk, eggs and oily fish are all rich in animal fats, as well as foods fried in animal fat. Vegetable oils include many types used for cooking, such as olive oil, corn oil and rapeseed oil, as well as products made from oils, such as margarine (Figure 4.3).

Lipids make up about 10% of our body's mass. They form an essential part of the structure of all cells, and fat is deposited in certain parts of the body as a long-term store of energy, for example under the skin and around the heart and kidneys. The fat layer under the skin acts as insulation, reducing heat loss through the surface of the body. Fat around organs such as the kidneys also helps to protect them from mechanical damage.

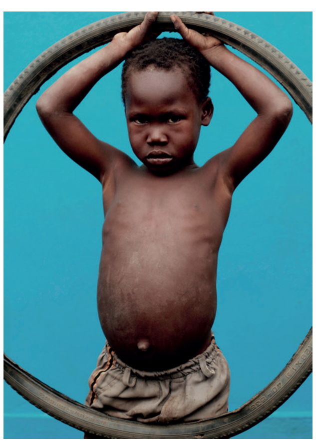
The chemical 'building blocks' of lipids are two types of molecule called **glycerol** and **fatty acids**. Glycerol is an oily liquid. It is also known as glycerine, and is used in many types of cosmetics. In lipids, a molecule of glycerol is joined to three fatty acid molecules. There are many different fatty acid molecules, which give us the many different kinds of lipid found in food (Figure 4.4).

Although lipids are an essential part of our diet, too much lipid is unhealthy, especially a type called *saturated* fat, and a lipid compound called **cholesterol**. These substances have been linked to heart disease (see Chapter 5).

DID YOU KNOW?

Saturated lipids (saturated fats) are more common in food from animal sources, such as meat and dairy products. 'Saturated' is a word used in chemistry, which means that the fatty acids of the lipids contain no double bonds. Other lipids are *unsaturated*, which means that their fatty acids contain double bonds. These are more common in plant oils. There is evidence that unsaturated lipids are healthier for us than saturated ones.

PROTEINS



▲ Figure 4.5 This child is suffering from a lack of protein in his diet, a disease called kwashiorkor. His swollen belly is not due to a full stomach, but is caused by fluid collecting in the tissues. Other symptoms include loss of weight, poor muscle growth, general weakness and flaky skin.

Proteins make up about 18% of the mass of the body. This is the second largest percentage after water. All cells contain protein, so we need it for growth and repair of tissues. Many compounds in the body are made from protein, including enzymes.

Most foods contain some protein, but certain foods such as meat, fish, cheese and eggs are particularly rich in it. You will notice that these foods are animal products. Plant material generally contains less protein, but some foods, especially beans, peas and nuts, are richer in protein than others.

However, we don't need much protein in our diet to stay healthy. Doctors recommend a maximum daily intake of about 70 g. In more economically developed countries, people often eat far more protein than they need, whereas in many poorer countries a protein-deficiency disease called **kwashiorkor** is common (Figure 4.5).

Like starch, proteins are also polymers, but whereas starch is made from a single molecular building block (glucose), proteins are made from 20 different sub-units called **amino acids**. All amino acids contain four chemical elements: carbon, hydrogen and oxygen (as in carbohydrates and fats) along with nitrogen. Two amino acids also contain sulfur. The amino acids are linked together in long chains, which are usually folded up or twisted into spirals, with cross-links holding the chains together (Figure 4.6).

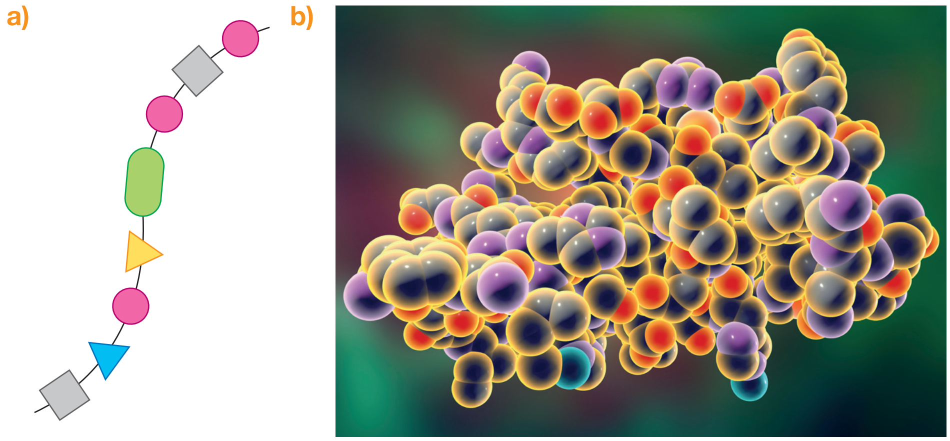


Figure 4.6 (a) A chain of amino acids forming part of a protein molecule. Each shape represents a different amino acid. (b) A computer model of the protein insulin. This substance, like all proteins, is made of a long chain of amino acids arranged in a particular order and folded into a specific shape.

EXTENSION WORK

Humans can make about half of the 20 amino acids that they need, but the other 10 have to be taken in as part of the diet. These 10 are called essential amino acids. There are higher amounts of essential amino acids in meat, fish, eggs and dairy products. If you are a vegetarian, you can still get all the essential amino acids you need, as long as you eat a varied diet that includes a range of different plant materials.

The *shape* of a protein is very important in allowing it to carry out its function, and the *order* of amino acids in the protein decides its shape. Because there are 20 different amino acids, and they can be arranged in any order, the number of different protein structures that can be made is enormous. As a result, there are thousands of different kinds of proteins in organisms, from structural proteins such as collagen and keratin in skin and nails, to proteins with more specific functions, such as enzymes and haemoglobin.

MINERALS

All the foods you have read about so far are made from just five chemical elements: carbon, hydrogen, oxygen, nitrogen and sulfur. Our bodies contain many other elements that we get from our food as ‘minerals’ or ‘mineral ions’. Some are present in large amounts in the body, for example calcium, which is used for making teeth and bones. Others are present in much smaller amounts, but still have essential jobs to do. For instance our bodies contain about 3 g of iron, but without it our blood would not be able to carry oxygen. Table 4.1 shows just a few of these minerals and the reasons they are needed.

Table 4.1 Some examples of minerals needed by the body.

Mineral	Approximate mass in an adult body / g	Location or role in body	Examples of foods rich in minerals
calcium	1000	making teeth and bones	dairy products, fish, bread, vegetables
phosphorus	650	making teeth and bones; part of many chemicals, e.g. DNA and ATP	most foods
sodium	100	in body fluids, e.g. blood	common salt, most foods
chlorine	100	in body fluids, e.g. blood	common salt, most foods
magnesium	30	making bones; found inside cells	green vegetables
iron	3	part of haemoglobin in red blood cells, helps carry oxygen	red meat, liver, eggs, some vegetables, e.g. spinach

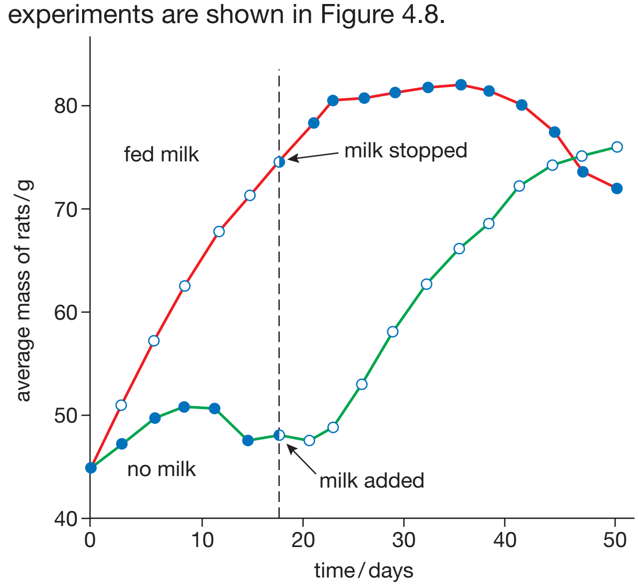
▲ Figure 4.7 An x-ray of the legs of a child showing the symptoms of rickets.

If a person doesn't get enough of a mineral from their diet, they will show the symptoms of a 'mineral deficiency disease'. For example, a one-year-old child needs to consume about 0.6 g (600 mg) of calcium every day, to make the bones grow properly and harden. Anything less than this over a prolonged period could result in poor bone development. The bones become deformed, a disease called rickets (Figure 4.7). Rickets can also be caused by lack of vitamin D in the diet (see below).

Similarly, 16-year-olds need about 12 mg of iron in their daily food intake. If they don't get this amount, they can't make enough haemoglobin for their red blood cells (see Chapter 5). This causes a condition called anaemia. People who are anaemic become tired and lack energy, because their blood doesn't carry enough oxygen.

VITAMINS

During the early part of the twentieth century, experiments were carried out that identified another class of food substances. When young laboratory rats were fed a diet of pure carbohydrate, lipid and protein, they all became ill and died. If they were fed on the same pure foods with a little added milk, they grew normally. The milk contained chemicals that the rats needed in small amounts to stay healthy. These chemicals are called vitamins. The results of one of these experiments are shown in Figure 4.8.



▲ Figure 4.8 Rats were fed a diet of pure carbohydrate, lipid and protein, with and without added milk. Vitamins in the milk had a dramatic effect on their growth.

At first, the chemical nature of vitamins was not known, and they were given letters to distinguish between them, such as vitamin A, vitamin B and so on. Each was identified by the effect a lack of the vitamin (vitamin deficiency) had on the body. For example, vitamin D is needed for growing bones to take up calcium salts. A deficiency of this vitamin can result in rickets (Figure 4.7), just as a lack of calcium can.

We now know the chemical structure of the vitamins and the exact ways in which they work in the body. As with vitamin D, each has a particular function. Vitamin A is needed to make a light-sensitive chemical in the retina of the eye (see Chapter 6). A lack of this vitamin causes night blindness, where the

DID YOU KNOW?

The cure for scurvy was discovered as long ago as 1753. Sailors on long voyages often got scurvy because they ate very little fresh fruit and vegetables (the main source of vitamin C). A ship's doctor called James Lind wrote an account of how the disease could quickly be cured by eating fresh oranges and lemons. The famous explorer Captain Cook, on his world voyages in 1772 and 1775, kept his sailors healthy by making sure that they ate fresh fruit. By 1804, all British sailors were made to drink lime juice to prevent scurvy. This is how they came to be called 'limeys', a word that was later used by Americans for all British people.

person finds it difficult to see in dim light. Vitamin C is needed to make fibres of a material called connective tissue. This acts as a 'glue', bonding cells together in a tissue. It is found in the walls of blood vessels and in the skin and lining surfaces of the body. Vitamin C deficiency leads to a disease called **scurvy**, where wounds fail to heal, and bleeding occurs in various places in the body. This is especially noticeable in the gums (Figure 4.9).

▲ Figure 4.9 Vitamin C helps lining cells such as those in the mouth and gums stick to each other. Lack of vitamin C causes scurvy, where the mouth and gums become damaged and bleed.

Vitamin B is not a single substance, but a collection of many different substances called the vitamin B group. It includes vitamins B1 (thiamine), B2 (riboflavin) and B3 (niacin). These compounds are involved in the process of cell respiration. Different deficiency diseases result if any of them are missing from the diet. For example, lack of vitamin B1 results in the weakening of the muscles and paralysis, a disease called **beri-beri**.

The main vitamins, their role in the body and some foods which are good sources of each, are summarised in Table 4.2.

Notice that the amounts of vitamins that we need are very small, but we cannot stay healthy without them.

Table 4.2 Summary of the main vitamins. Note that you only need remember the sources and functions of vitamins A, C and D.

Vitamin	Recommended daily amount in diet[1]	Use in the body	Effect of deficiency	Some foods that are a good source of the vitamin
A	0.8 mg	making a chemical in the retina; also protects the surface of the eye	night blindness, damaged cornea of eye	fish liver oils, liver, butter, margarine, carrots
B1	1.1 mg	helps with cell respiration	beri-beri	yeast extract, cereals
B2	1.4 mg	helps with cell respiration	poor growth, dry skin	green vegetables, eggs, fish
B3	16 mg	helps with cell respiration	pellagra (dry red skin, poor growth, and digestive disorders)	liver, meat, fish.
C	80 mg	sticks together cells lining surfaces such as the mouth	scurvy	fresh fruit and vegetables
D	5 μg	helps bones absorb calcium and phosphate	rickets, poor teeth	fish liver oils; also made in skin in sunlight

[1]Figures are the European Union's recommended daily intake for an adult (2012). 'mg' stands for milligram (a thousandth of a gram) and 'μg' for microgram (a millionth of a gram).

FOOD TESTS

It is possible to carry out simple chemical tests to find out if a food contains starch, glucose, protein or lipid. Practical 8 uses pure substances for the tests, but it is possible to do them on normal foods too. Unless the food is a liquid like milk, it needs to be cut up into small pieces and ground with a pestle and mortar, then shaken with some water in a test tube. This is done to extract the components of the food and dissolve any soluble substances such as sugars.

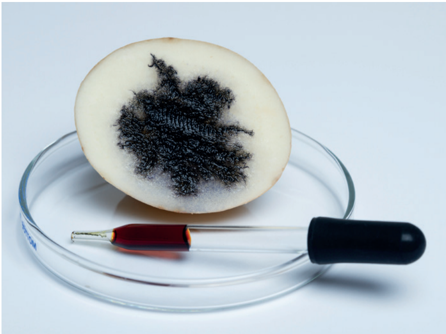


Figure 4.10a Testing for starch using iodine

Figure 4.10b Glucose with Benedict's solution, before and after heating

ACTIVITY 3

PRACTICAL: TEST FOR STARCH

A little starch is placed on a spotting tile. A drop of yellow-brown iodine solution is added to the starch. The iodine reacts with the starch, forming a very dark blue, or 'blue-black' colour (Figure 4.10 (a)). Starch is insoluble, but this test will work on a solid sample of food, such as potato, or a suspension of starch in water.

PRACTICAL: TEST FOR GLUCOSE

Glucose is called a reducing sugar. This is because the test for glucose involves reducing an alkaline solution of copper (II) sulfate to copper (I) oxide.

A small spatula measure of glucose is placed in a test tube and a little water added (about 2 cm deep). The tube is shaken to dissolve the glucose. Several drops of Benedict's solution are added to the tube, enough to colour the mixture blue (Figure 4.10 (b)).

A water bath is prepared by half-filling a beaker with water and heating it on a tripod and gauze. The test tube is placed in the beaker and the water allowed to boil (using a water bath is safer than heating the tube directly in the Bunsen burner). After a few seconds the clear blue solution gradually changes colour, forming a cloudy orange or 'brick red' precipitate of copper (I) oxide (Figure 4.10 (b)).

All other 'single' sugars (monosaccharides), such as fructose, are reducing sugars, as well as some 'double' sugars (disaccharides), such as the milk sugar, lactose. However, ordinary table sugar (sucrose) is not. If sucrose is boiled with Benedict's solution it will stay a clear blue colour.

PRACTICAL: TEST FOR PROTEIN

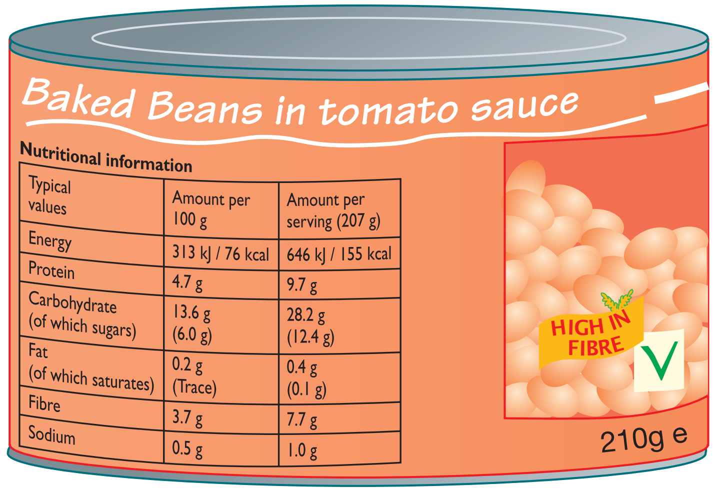
The test for protein is sometimes called the 'biuret' test, after the coloured compound that is formed.

A little protein, such as powdered egg white (albumen), is placed in a test tube and about 2 cm depth of water added. The tube is shaken to mix the powder with the water. An equal volume of dilute (5%) potassium hydroxide solution is added and the tube shaken again. Finally two drops of 1% copper sulfate solution are added. A purple colour develops. (Sometimes these two solutions are supplied already mixed together as 'biuret solution'.)

PRACTICAL: TEST FOR LIPID

Fats and oils are insoluble in water, but will dissolve in ethanol (alcohol). The test for lipid uses this fact.

A pipette is used to place one drop of olive oil in the bottom of a test tube. About 2 cm depth of ethanol is added, and the tube is shaken to dissolve the oil. The solution is poured into a test tube that is about three-quarters full with cold water. A white cloudy layer forms on the top of the water. The white layer is caused by the ethanol dissolving in the water and leaving the lipid behind as a suspension of tiny droplets, called an emulsion.



▲ Figure 4.11 Food packaging is labelled with the proportions of different food types that it contains, along with its energy content. The energy in units called kilocalories (kcal) is also shown, but scientists no longer use this old-fashioned unit.

ENERGY FROM FOOD

Some foods contain more energy than others. It depends on the proportions of carbohydrate, lipid and protein that they contain. Their energy content is measured in kilojoules (kJ). If a gram of carbohydrate is fully oxidised, it produces about 17 kJ, whereas a gram of lipid yields over twice as much as this (39 kJ). Protein can produce about 18 kJ per gram. If you look on a food label, it usually shows the energy content of the food, along with the amounts of different nutrients that it contains (Figure 4.11).

Foods with a high percentage of lipid, such as butter or nuts, contain a large amount of energy. Others, like fruits and vegetables, which are mainly composed of water, have a much lower energy content (Table 4.3).

Table 4.3 Energy content of some common foods

Food	kJ per 100g	Food	kJ per 100g
margarine	3200	fried beefburger	1100
butter	3120	white bread	1060
peanuts	2400	chips	990
samosa	2400	grilled beef steak	930
chocolate	2300	fried cod	850
Cheddar cheese	1700	roast chicken	770
grilled bacon	1670	boiled potatoes	340
table sugar	1650	milk	270
grilled pork sausages	1550	baked beans	270
cornflakes	1530	yoghurt	200
rice	1500	boiled cabbage	60
spaghetti	1450	lettuce	40

EXTENSION WORK

Food scientists measure the amount of energy in a sample of food by burning it in a calorimeter (Figure 4.12). The calorimeter is filled with oxygen, to make sure that the food will burn easily. A heating filament carrying an electrical current ignites the food. The energy given out by the burning food is measured by using it to heat up water flowing through a coil in the calorimeter.

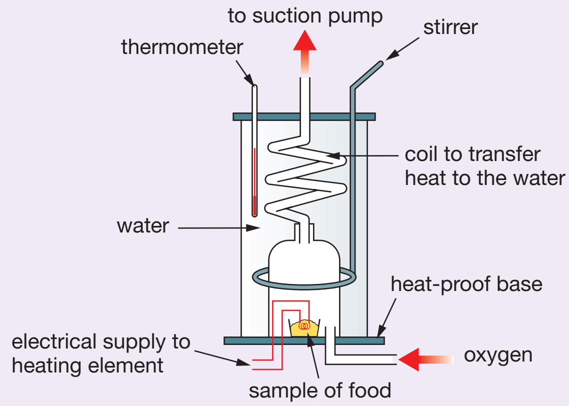


Figure 4.12 A food calorimeter

If you have samples of food that will easily burn in air, you can measure the energy in them by a similar method, using the heat from the burning food to warm up water in a test tube.

Even while you are asleep you need a supply of energy – in order to keep warm, for your heart to keep beating, to allow messages to be sent through your nerves, and for other body functions. However, the energy you need at other times depends on the physical work you do. The total amount of energy that a person needs to keep healthy depends on their age and body size, and also on the amount of activity they do. Table 4.4 shows some examples of how much energy is needed each day by people of different age, sex and occupation.

Table 4.4 The daily energy needs of different types of people.

Age/sex/occupation of person	Energy needed per day / kJ
newborn baby	2000
child aged 2	5000
child aged 6	7500
girl aged 12–14	9000
boy aged 12–14	11000
girl aged 15–17	9000
boy aged 15–17	12000
female office worker	9500
male office worker	10500
heavy manual worker	15000
pregnant woman	10000
breast-feeding woman	11300

Remember that these are approximate figures, and they are averages. Generally, the greater a person's weight, the more energy that person needs. This is why men, with a greater average body mass, need more energy than women. The energy needs of a pregnant woman are increased, mainly because of the extra weight that she has to carry. A heavy manual worker, such as a labourer, needs extra energy for increased muscle activity.

It is not only the recommended energy requirements that vary with age, sex and pregnancy, but also the *content* of the diet. For instance, during pregnancy a woman may need extra iron or calcium in her diet, for the growth of the fetus. In younger women, the blood loss during menstruation (periods) can result in anaemia, producing a need for extra iron in the diet.

DIGESTION

Food, such as a piece of bread, contains carbohydrates, lipids and proteins, but they are not the same carbohydrates, lipids and proteins as in our tissues. The components of the bread must first be broken down into their 'building blocks' before they can be absorbed through the wall of the gut. This process is called **digestion**. The digested molecules – sugars, fatty acids, glycerol and amino acids – along with minerals, vitamins and water, can then be carried around the body in the blood. When they reach the tissues they are reassembled into the molecules that make up our cells.

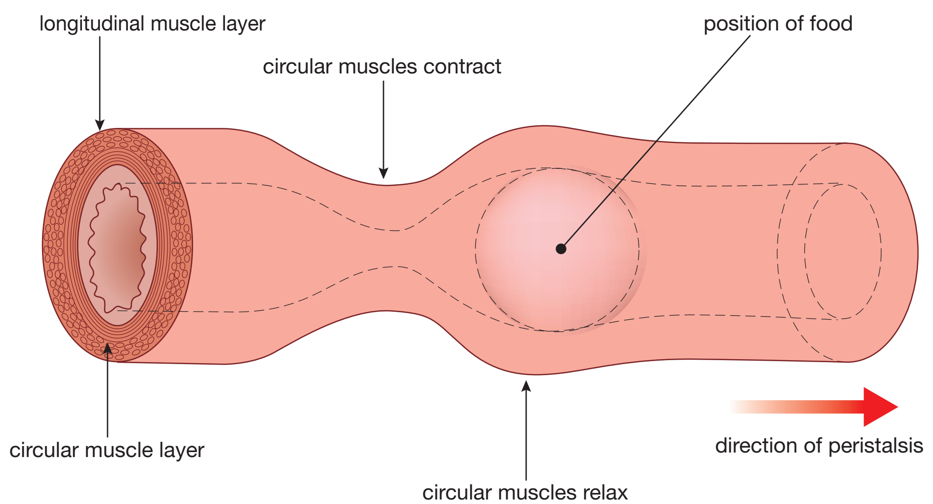
HINT

A good definition of digestion is: 'Digestion is the chemical and mechanical breakdown of food. It converts large insoluble molecules into small soluble molecules, which can be absorbed into the blood.'

Digestion is speeded up by **enzymes**, which are biological catalysts (see Chapter 1). Although most enzymes stay inside cells, the digestive enzymes are made by the tissues and glands in the gut and pass out of cells – on to the gut contents where they act on the food. This *chemical* digestion is helped by *mechanical* digestion. Mechanical digestion is the physical breakdown of food. The most obvious place where this happens is in the mouth, where the teeth bite and chew the food, cutting it into smaller pieces that have a larger surface area. This means that enzymes can act on the food more quickly. Other parts of the gut also help with mechanical digestion. For example, muscles in the wall of the stomach contract to churn up the food while it is being chemically digested.

PERISTALSIS

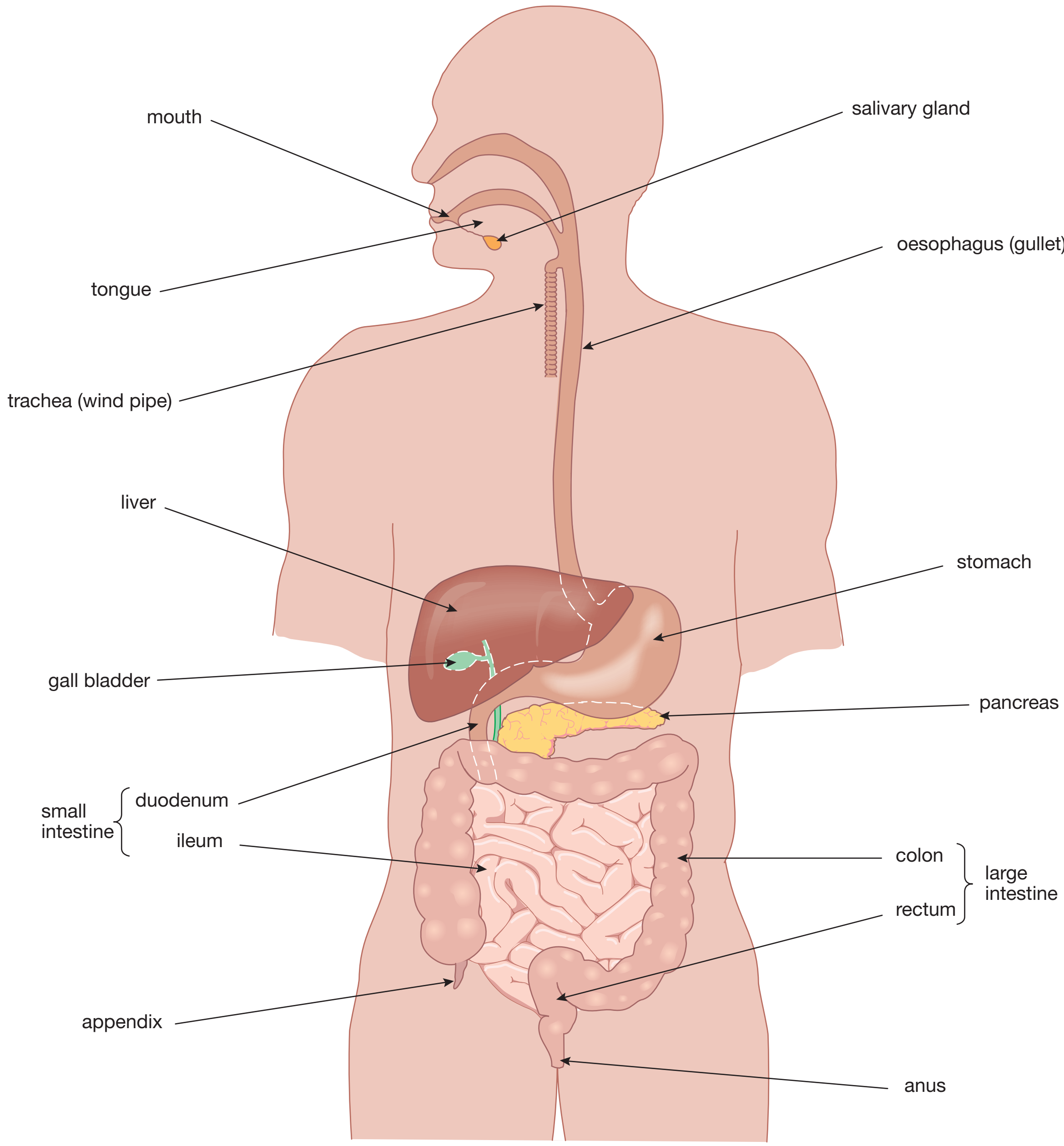
Muscles are also responsible for moving the food along the gut. The walls of the intestine contain two layers of muscles. One layer has fibres arranged in rings around the gut. This is the circular muscle layer. The other has fibres running along the length of the gut, and is called the longitudinal muscle layer. Together these two layers act to push the food along. When the circular muscles contract and the longitudinal muscles relax, the gut is made narrower. When the opposite happens, i.e. the longitudinal muscles contract and the circular muscles relax, the gut becomes wider. Waves of muscle contraction like this pass along the gut, pushing the food along, rather like squeezing toothpaste from a tube. This is called **peristalsis** (Figure 4.13). It means that movement of food in the gut doesn't depend on gravity – we can still eat standing on our heads!



▲ Figure 4.13 Peristalsis: contraction of circular muscles behind the food narrows the gut, pushing the food along. When the circular muscles are contracted, the longitudinal ones are relaxed, and vice versa.

THE DIGESTIVE SYSTEM

Figure 4.14 shows a simplified diagram of the human digestive system. It is simplified so that you can see the order of the organs along the gut. The real gut is much longer than this, and coiled up so that it fills the whole space of the abdomen. Overall, its length in an adult is about 8 m. This gives plenty of time for the food to be broken down and absorbed as it passes through the gut.



▲ Figure 4.14 The human digestive system

The mouth, stomach and the first part of the small intestine (called the **duodenum**) all break down the food using enzymes, either made in the gut wall itself, or by glands such as the **pancreas**. Digestion continues in the last part of the small intestine (the **ileum**) and it is here that the digested food is absorbed. The last part of the gut, the large intestine, is mainly concerned with absorbing water out of the remains, and storing the waste products (**faeces**) before they are removed from the body.

The three main classes of food are broken down by three classes of enzymes. Carbohydrates are digested by enzymes called **carbohydrases**. Proteins are acted upon by **proteases**, and enzymes called **lipases** break down lipids. Some of the places in the gut where these enzymes are made are shown in Table 4.5.

KEY POINT

Amylase digests starch into maltose. Amylase is the enzyme, starch is the substrate and maltose is the product.

Digestion begins in the mouth. **Saliva** helps moisten the food and contains the enzyme **amylase**, which starts the breakdown of starch. The chewed lump of food, mixed with saliva, then passes along the **oesophagus** (gullet) to the stomach.

Table 4.5 Some of the enzymes that digest food in the human gut. The substances shown in bold are the end products of digestion that can be absorbed from the gut into the blood.

Class of enzyme	Examples	Digestive action	Source of enzyme	Where it acts in the gut
carbohydrases	amylase amylase maltase	starch → maltose[1] starch → maltose maltose → **glucose**	salivary glands pancreas wall of small intestine	mouth small intestine small intestine
proteases	pepsin trypsin peptidases	proteins → peptides[2] proteins → peptides peptides → **amino acids**	stomach wall pancreas wall of small intestine	stomach small intestine small intestine
lipases	lipase	lipids → **glycerol** and **fatty acids**	pancreas	small intestine

[1]Maltose is a disaccharide made of two glucose molecules joined together.

[2]Peptides are short chains of amino acids.

The food is held in the stomach for several hours, while initial digestion of protein takes place. The stomach wall secretes hydrochloric acid, so the stomach contents are strongly acidic. This has a very important function. It kills bacteria that are taken into the gut along with the food, helping to protect us from food poisoning. The protease enzyme that is made in the stomach, called **pepsin**, has to be able to work in these acidic conditions, and has an optimum pH value of about 2. This is unusually low – most enzymes work best at near neutral conditions (see Chapter 1).

The semi-digested food is held back in the stomach by a ring of muscle at the outlet of the stomach, called a **sphincter muscle**. When this relaxes, it releases the food into the first part of the small intestine, called the duodenum (Figure 4.15).

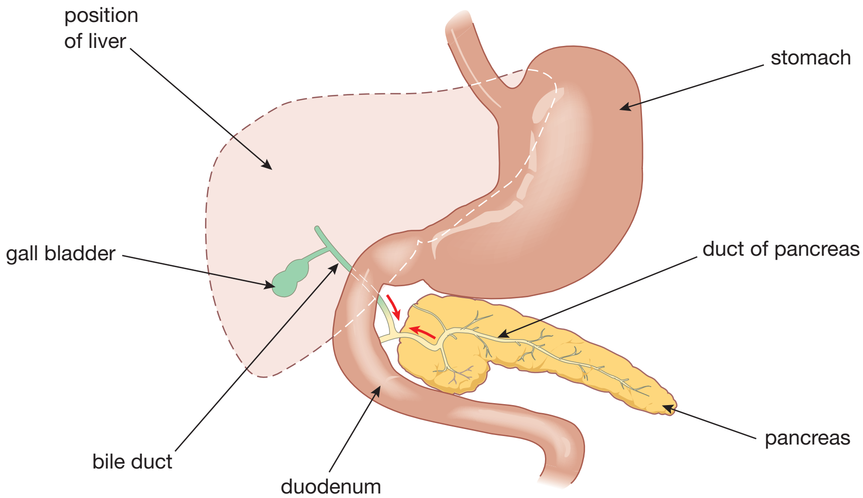


Figure 4.15 The first part of the small intestine, the duodenum, receives digestive juices from the liver and pancreas through tubes called ducts.

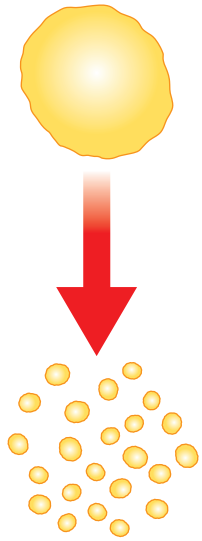


Figure 4.16 Bile turns fats into an emulsion of tiny droplets for easier digestion.

Several digestive enzymes are added to the food in the duodenum. These are made by the pancreas, and digest starch, proteins and lipids (Table 4.5). As well as this, the **liver** makes a digestive juice called **bile**. Bile is a green liquid that is stored in the **gall bladder** and passes down the **bile duct** on to the food. Bile does not contain enzymes, but has another important function. It turns any large lipid globules in the food into an emulsion of tiny droplets (Figure 4.16). This increases the surface area of the lipid, so that lipase enzymes can break it down more easily.

Bile and pancreatic juice have another function. They are both alkaline. The mixture of semi-digested food and enzymes coming from the stomach is acidic, and needs to be neutralised by the addition of alkali before it continues on its way through the gut.

As the food continues along the intestine, more enzymes are added, until the parts of the food that can be digested have been fully broken down into soluble end products, which can be absorbed. This is the role of the last part of the small intestine, the ileum.

ABSORPTION IN THE ILEUM

The ileum is highly adapted to absorb the digested food. The lining of the ileum has a very large surface area, which means that it can quickly and efficiently absorb the soluble products of digestion into the blood. The length of the intestine helps to provide a large surface area, and this is aided by folds in its lining, but the greatest increase in area is due to tiny projections from the lining, called **villi** (Figure 4.17).

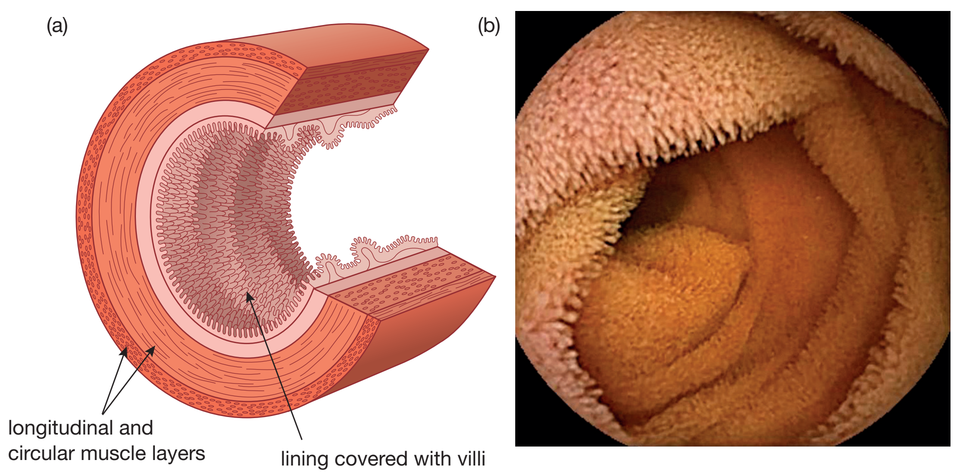
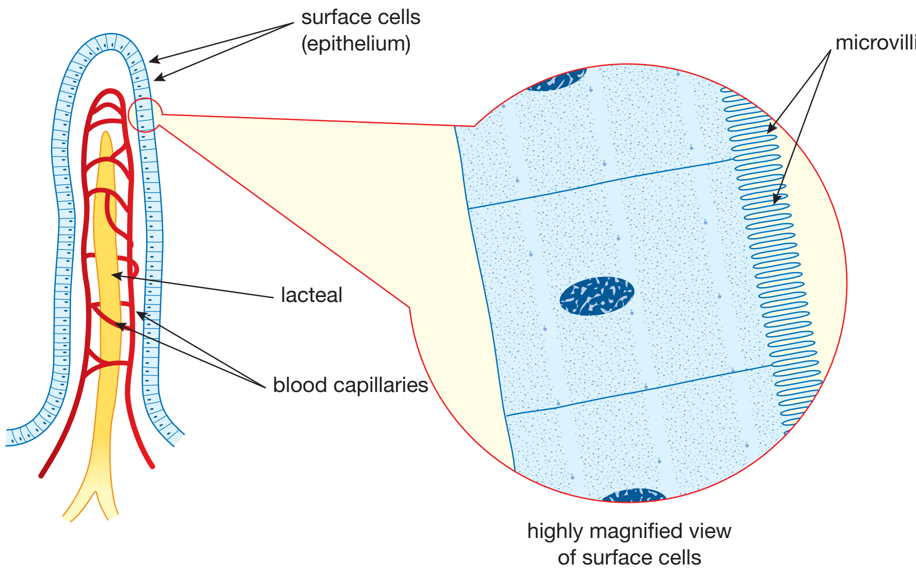


Figure 4.17 (a) The inside lining of the ileum is adapted to absorb digested food by the presence of millions of tiny villi. (b) Photo of the inside a patient's ileum, taken using a camera attached to an endoscope. You can see thousands of tiny villi covering the lining.

The singular of villi is 'villus'. Each villus is only about 1–2 mm long, but there are millions of them, so that the total area of the lining is thought to be about 300 m^2. This provides a massive area in contact with the digested food. As well as this, high-powered microscopy has revealed that the surface cells of each villus themselves have hundreds of minute projections, called **microvilli**, which increase the surface area for absorption even more (Figure 4.18).

Each villus contains a network of blood capillaries. Most of the digested food enters these blood vessels, but the products of fat digestion, as well as tiny fat droplets, enter a tube in the middle of the villus, called a **lacteal**. The lacteals form part of the body's lymphatic system, which transports a liquid called lymph. This lymph eventually drains into the blood system too.



▲ Figure 4.18 Each villus contains blood vessels and a lacteal, which absorb the products of digestion. The surface cells of the villus are covered with microvilli, which further increase the surface area for absorption.

The surface of a villus is made of a single layer of cells called an epithelium. This means that there is only a short distance between the digested food in the ileum and the blood capillaries making it easier for the products of digestion to diffuse through and enter the blood. The epithelium cells contain many mitochondria, which supply the energy needed for active transport of some substances.

In addition each villus contains muscle fibres which contract to move the villus. The villi are in constant motion, keeping them in contact with the contents of the ileum and maintaining a steep concentration gradient for diffusion of the products of digestion.

The blood vessels from the ileum join up to form a large blood vessel called the **hepatic portal vein**, which leads to the liver (see Chapter 5). The liver acts rather like a food processing factory, breaking some molecules down, and building up and storing others. For example, glucose from carbohydrate digestion is converted into glycogen and stored in the liver. Later, the glycogen can be converted back into glucose when the body needs it (see Chapter 7).

The digested food molecules are distributed around the body by the blood system (see Chapter 5). The soluble food molecules are absorbed from the blood into cells of tissues, and are used to build new parts of cells. This is called assimilation.

KEY POINT

Removal of faeces by the body is sometimes incorrectly called excretion. Excretion is a word that only applies to materials that are the waste products of cells of the body, such as carbon dioxide. Faeces are not products of cell metabolism – they consist of waste that has passed through the gut and left the body via the anus, without entering the cells. The correct name for this process is egestion.

THE LARGE INTESTINE – ELIMINATION OF WASTE

By the time that the contents of the gut have reached the end of the small intestine, most of the digested food, as well as most of the water, has been absorbed. The waste material consists mainly of cellulose (fibre) and other indigestible remains, water, dead and living bacteria and cells lost from the lining of the gut. The function of the first part of the large intestine, called the **colon**, is to absorb most of the remaining water from the contents, leaving a semi-solid waste material called faeces. This is stored in the **rectum**, until expelled out of the body through the **anus**.

CHAPTER QUESTIONS

More questions on food and digestion can be found at the end of Unit 2 on page 116.

SKILLS CRITICAL THINKING

6th

1 Which of the following organic molecules contains carbon, hydrogen, oxygen and nitrogen?

A glycogen
B lipid
C cellulose
D protein

5th

2 Which of the following substances would give a positive test when boiled with Benedict's solution?

A fructose
B lipid
C starch
D protein

6th

3 Which of the following statements about digestion is *not* correct?

A Digestion produces fatty acids and glycerol
B Digestion converts insoluble molecules into soluble molecules
C Digestion changes proteins into amino acids
D Digestion releases energy from food

4th

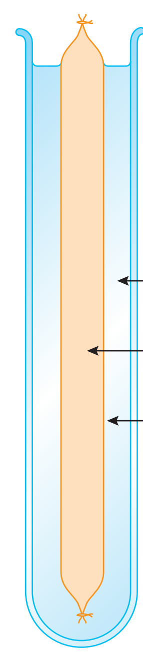
4 Which of the following organs does *not* produce digestive enzymes?

A salivary gland
B gall bladder
C stomach
D pancreas

SKILLS EXECUTIVE FUNCTION

5 The diagram shows an experiment that was set up as a model to show why food needs to be digested.

The Visking tubing acts as a model of the small intestine because it has tiny holes in it that some molecules can pass through. The tubing was left in the boiling tube for an hour, then the water in the tube was tested for starch and glucose.



5th

a Describe how you would test the water for starch, and for glucose. What would the results be for a 'positive' test in each case?

SKILLS REASONING

6th

b The tests showed that glucose was present in the water, but starch was not. Explain why.

5th

c If the tubing takes the place of the intestine, what part of the body does the water in the boiling tube represent?

SKILLS CRITICAL THINKING

6th

d What does 'digested' mean?

SKILLS DECISION MAKING

4th

6 A student carried out an experiment to find out the best conditions for the enzyme pepsin to digest protein. For the protein, she used egg white powder, which forms a cloudy white suspension in water. The table below shows how the four tubes were set up.

Tube	Contents
A	5 cm^3 egg white suspension, 2 cm^3 pepsin, 3 drops of dilute acid. Tube kept at 37 °C
B	5 cm^3 egg white suspension, 2 cm^3 distilled water, 3 drops of dilute acid. Tube kept at 37 °C
C	5 cm^3 egg white suspension, 2 cm^3 pepsin, 3 drops of dilute acid. Tube kept at 20 °C
D	5 cm^3 egg white suspension, 2 cm^3 pepsin, 3 drops of dilute alkali. Tube kept at 37 °C

The tubes were left for 2 hours and the results were then observed. Tubes B, C and D were still cloudy. Tube A had gone clear.

a Three tubes were kept at 37 °C. Why was this temperature chosen?

SKILLS REASONING

6th

b Explain what had happened to the protein in tube A.

7th

c Why did tube D stay cloudy?

SKILLS CRITICAL THINKING

5th

d Tube B is called a **Control**. Explain what this means.

SKILLS REASONING

8th

e Tube C was left for another 3 hours. Gradually it started to clear. Explain why digestion of the protein happened more slowly in this tube.

SKILLS CRITICAL THINKING

5th

f The lining of the stomach secretes hydrochloric acid. Explain the function of this.

4th

g When the stomach contents pass into the duodenum, they are still acidic. How are they neutralised?

6th

7 Copy and complete the following table of digestive enzymes.

Enzyme	Food on which it acts	Products
amylase		
trypsin		
		fatty acids and glycerol

7th

8 Describe four adaptations of the small intestine (ileum) that allow it to absorb digested food efficiently.

SKILLS CRITICAL THINKING, CREATIVITY

9th

9 Bread is made mainly of starch, protein and lipid. Imagine a piece of bread about to start its journey through the human gut. Describe what happens to the bread as it passes through the mouth, stomach, duodenum, ileum and colon. Explain how the bread is moved along the gut. Your description should be illustrated by two or three simplified diagrams.

5 BLOOD AND CIRCULATION

Large, multicellular animals need a circulatory system to transport substances to and from the cells of the body. This chapter looks at the structure and function of the circulatory systems of humans and other animals, the composition of mammalian blood, and disorders associated with the heart and circulation.

LEARNING OBJECTIVES

- Understand why simple unicellular organisms can rely on diffusion for movement of substances in and out of the cell
- Understand the need for a transport system in multicellular organisms
- Understand the general structure of the circulation system, including the blood vessels to and from the heart and lungs, liver and kidneys
- Describe the structure of the heart and how it functions
- Understand how factors may increase the risk of developing coronary heart disease
- Explain how the heart rate changes during exercise and under the influence of adrenaline
- Understand how the structures of arteries, veins and capillaries relate to their functions
- Describe the composition of blood: red blood cells, white blood cells, platelets and plasma
- Understand the role of plasma in the transport of carbon dioxide, digested food, urea, hormones and heat energy
- Understand how the adaptations of red blood cells make them suitable for the transport of oxygen, including shape, the absence of a nucleus and the presence of haemoglobin
- Understand how the immune system responds to infection using white blood cells, illustrated by phagocytes ingesting pathogens and lymphocytes releasing antibodies specific to the pathogen

THE NEED FOR CIRCULATORY SYSTEMS

Figure 5.1 shows the circulatory system of a mammal.

Blood is pumped around a closed circuit made up of the heart and blood vessels. As it travels around the body, it collects materials from some places and unloads them in others. In mammals, blood transports:

- oxygen from the lungs to all other parts of the body
- carbon dioxide from all parts of the body to the lungs
- nutrients from the gut to all parts of the body
- urea from the liver to the kidneys.

Hormones, antibodies and many other substances are also transported by the blood. It also distributes heat around the body.

Single-celled organisms, like the ones shown in Figure 5.2, do not have circulatory systems.

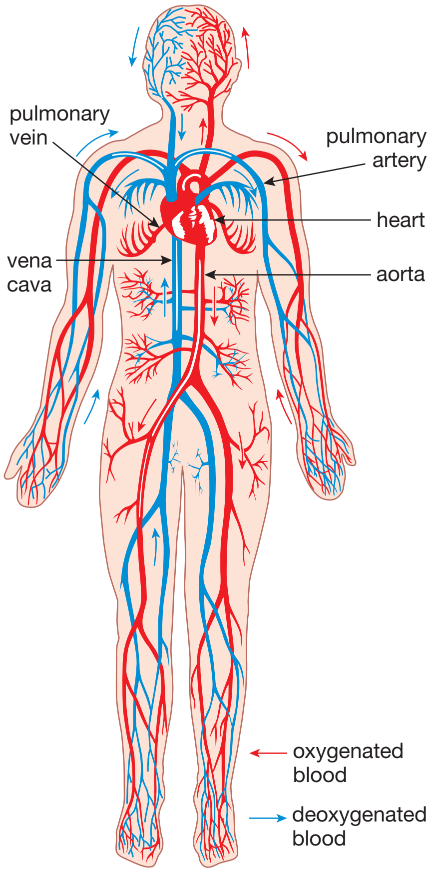


Figure 5.1 The human circulatory system.

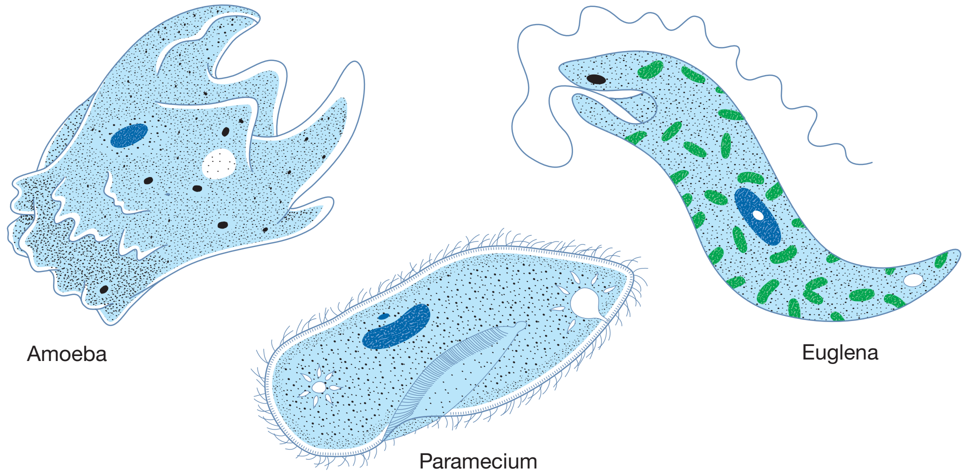


Figure 5.2 Unicellular organisms do not have circulatory systems.

There is no circulatory system to carry materials around the very small 'bodies' of these single-celled organisms. Materials can easily move around the cell without a special system. There is no need for lungs or gills to obtain oxygen from the environment either. Single-celled organisms obtain oxygen by diffusion through the surface membrane of the cell. The rest of the cell then uses the oxygen. The area of the cell's surface determines how much oxygen the organism can get (the supply rate), and the volume of the cell determines how much oxygen the organism uses (the demand rate).

The ratio of supply to demand can be written as: $\frac{\text{surface area}}{\text{volume}}$

This is called the 'surface area to volume ratio' and it is affected by the size of an organism (see Chapter 1, Activity 4). Single-celled organisms have a high surface area to volume ratio. Their cell surface membrane has a large enough area to supply all the oxygen that their volume demands. In larger animals, the surface area to volume ratio is lower.

Large animals cannot get all the oxygen they need through their surface (even if the body surface would allow it to pass through) – there just isn't enough surface to supply all that volume. To overcome this problem, large organisms have evolved special gas exchange organs and circulatory systems. The gills of fish and the lungs of mammals are linked to a circulatory system that carries oxygen to all parts of the body. The same idea applies to obtaining nutrients – the gut obtains nutrients from food and the circulatory system distributes the nutrients around the body.

THE CIRCULATORY SYSTEMS OF DIFFERENT ANIMALS

One of the main functions of a circulatory system in animals is to transport oxygen. Blood is pumped to a gas exchange organ to load oxygen. It is then pumped to other parts of the body where it unloads the oxygen. There are two main types of circulatory systems in animals.

- In a **single circulatory** system the blood is pumped from the heart to the gas exchange organ and then directly to the rest of the body.
- In a **double circulatory** system the blood is pumped from the heart to the gas exchange organ, back to the heart and then to the rest of the body.

Figure 5.3 shows the difference between these systems.

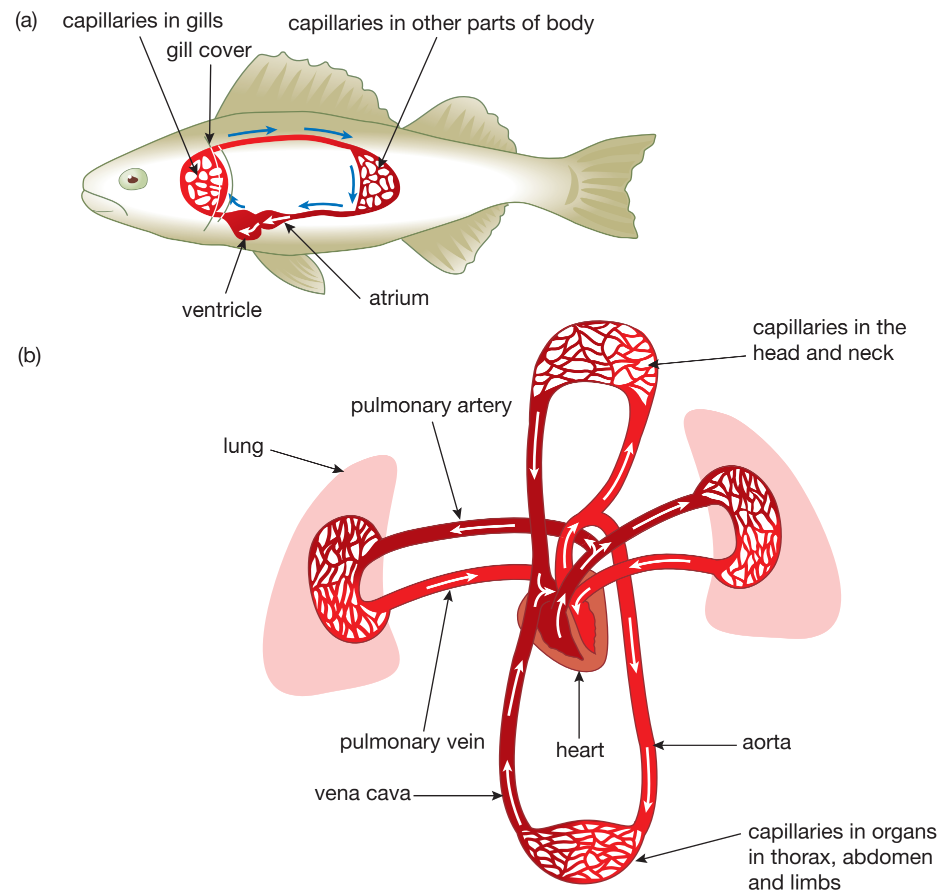


Figure 5.3 (a) The single circulatory system of a fish. The blood passes through the heart only once in a complete circuit of the body. (b) The double circulatory system of a human (and other mammals). The blood passes through the heart twice in one complete circuit of the body.

KEY POINT

'Pulmonary' means 'relating to the lungs'.

DID YOU KNOW?

There are actually two vena cavae (the plural of vena cava). One brings blood back from the head and arms and the other returns blood from the rest of the body (see Figure 5.4).

There are two parts to a double circulatory system:

- The **pulmonary circulation**. Deoxygenated blood leaves the heart through the pulmonary arteries, and is circulated through the lungs, where it becomes oxygenated. The oxygenated blood returns to the heart through the pulmonary veins.
- The **systemic circulation**. Oxygenated blood leaves the heart through the aorta and is circulated through all other parts of the body, where it unloads its oxygen. Deoxygenated blood returns to the heart through the vena cava.

A double circulatory system is more efficient than a single circulatory system. The heart pumps the blood twice, so higher pressures can be maintained. The blood travels more quickly to organs. In the single circulatory system of a fish, blood loses pressure as it passes through the gills. It then travels more slowly to the other organs.

The human circulatory system comprises:

- the heart – this is a pump
- blood vessels – these carry the blood around the body; **arteries** carry blood away from the heart and towards other organs, **veins** carry blood towards the heart and away from other organs and **capillaries** carry blood through organs, linking the arteries and veins
- blood – the transport medium.

Figure 5.4 shows the main blood vessels in the human circulatory system.

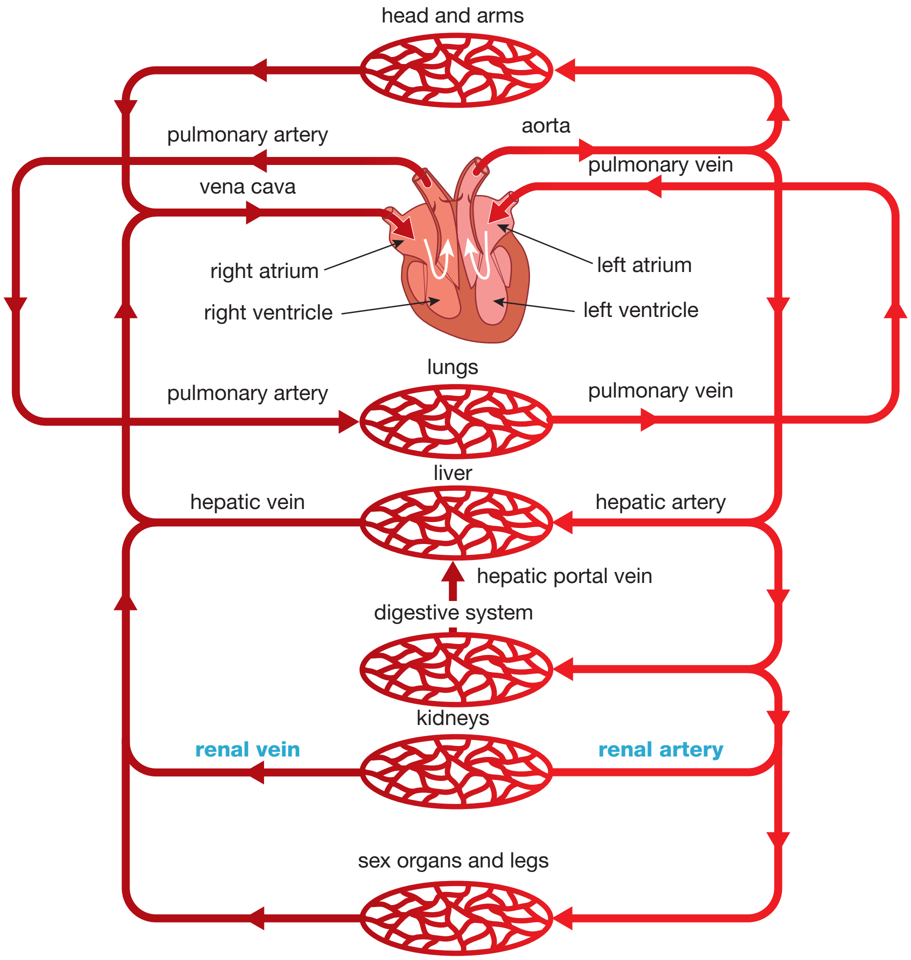


Figure 5.4 The main components of the human circulatory system

DID YOU KNOW?
'Cardiac' means 'related to the heart'.

DID YOU KNOW?
The **bicuspid** (mitral) and **tricuspid valves** are both sometimes called atrioventricular valves, as each controls the passage of blood from an atrium to a ventricle.

THE STRUCTURE AND FUNCTION OF THE HUMAN HEART

The human heart is a pump (Figure 5.5). It pumps blood around the body at different speeds and at different pressures according to the body's needs.

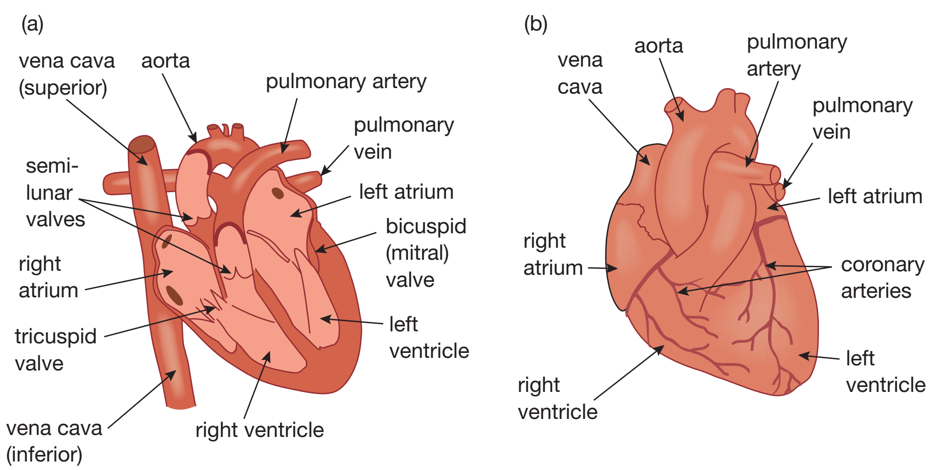
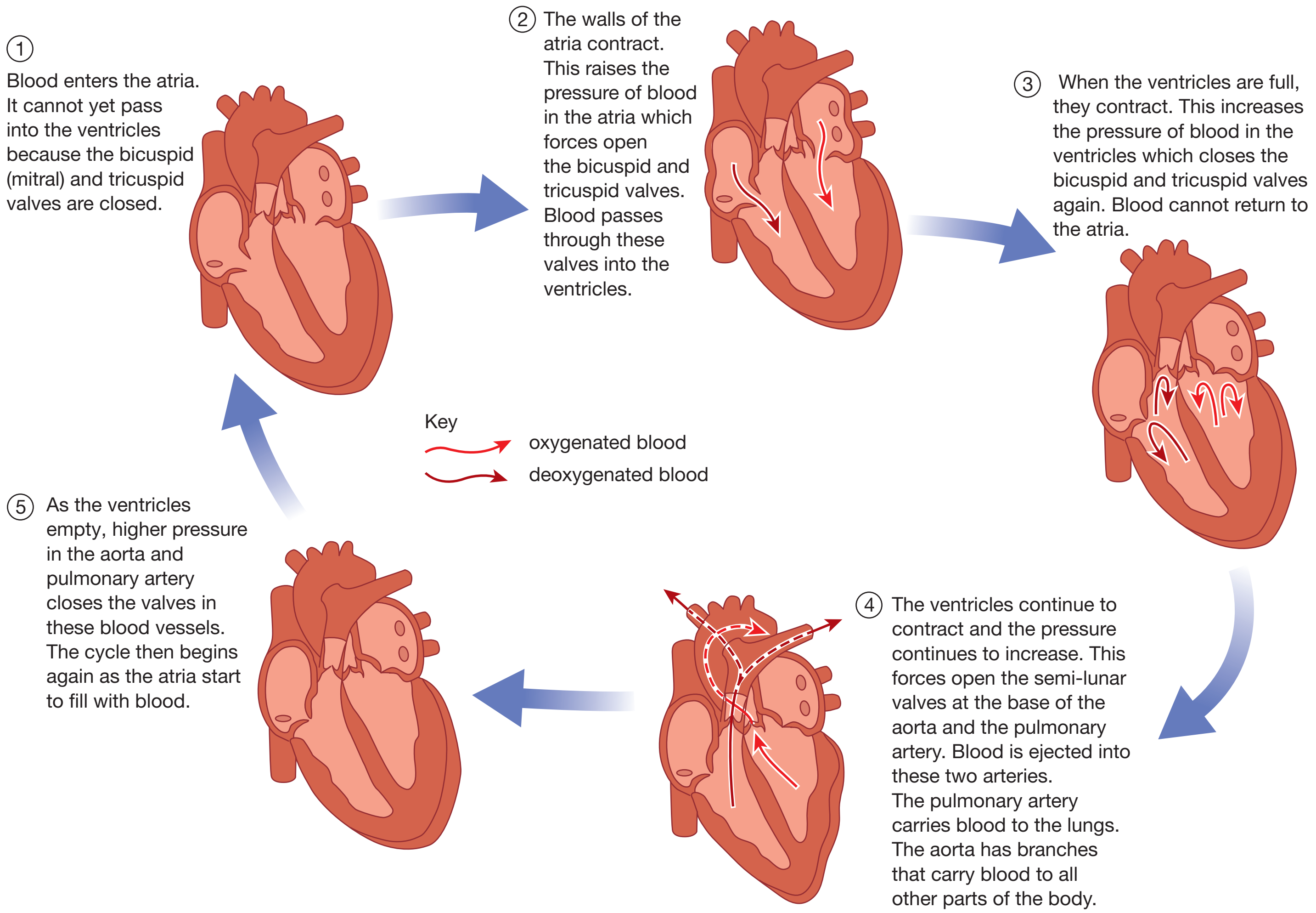


Figure 5.5 The human heart: (a) vertical section; (b) external view

Blood is moved through the heart by a series of contractions and relaxations of the muscle in the walls of the four chambers. These events form the **cardiac cycle**. The main stages are illustrated in Figure 5.6.



▲ Figure 5.6 The cardiac cycle.

HINT

Note that during the cardiac cycle both atria contract at the same time (and then relax). After this both ventricles contract at the same time (and then relax). Students are sometimes confused about this, and think that one ventricle contracts, followed by the other.

KEY POINT

Cardiac muscle is unlike any other muscle in our bodies. It never gets fatigued ('tired') like skeletal muscle. On average, cardiac muscle fibres contract and then relax again about 70 times a minute. In a lifetime of 70 years, this special muscle will contract over two billion times – without taking a rest!

The structure of the heart is adapted to its function in several ways:

- It is divided into a left side and a right side by a wall of muscle called the septum. The right **ventricle** pumps blood only to the lungs while the left ventricle pumps blood to all other parts of the body. This requires much more pressure, which is why the wall of the left ventricle is much thicker than that of the right ventricle.
- Valves ensure that blood can flow only in one direction through the heart.
- The walls of the **atria** are thin. They can be stretched to receive blood as it returns to the heart but can contract with enough force to push blood through the bicuspid and tricuspid valves into the ventricles.
- The walls of the heart are made of **cardiac muscle**, which can contract and then relax continuously without becoming fatigued.
- The cardiac muscle has its own blood supply – the coronary circulation. Blood reaches the muscle via **coronary arteries**. These carry blood to capillaries that supply the heart muscle with oxygen and nutrients. Blood is returned to the right atrium via **coronary veins**.