HUMAN PERSPECTIVES

ATAR

UNITS 3 & 4

TJ NEWTON
AP JOYCE

7ed

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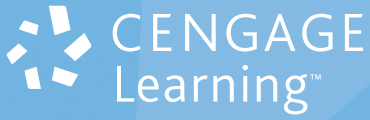

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TJ Newton
AP Joyce

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CONTENTS

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PREFACE

When *Human Perspectives* was first published in 1979, stem cells were found only in the stems of plants, AIDS were devices to make life easier, and fingerprints were made from fingers not from DNA. One of the exciting things about human biology is the continual accumulation of new knowledge about our species. This new knowledge is reflected in the many differences between this new edition of *Human Perspectives* and previous editions.

This seventh edition of *Human Perspectives Book 2* has been revised to suit the Year 12 syllabus of the new ATAR Human Biology course in Western Australia. The content has been rearranged to reflect the three outcomes of the course: 'Science Inquiry Skills', 'Science as a Human Endeavour' and 'Science Understanding'. The unit content that is addressed by each chapter is listed on the title page for that chapter. These content statements are taken directly from the unit content statements in the Year 12 Human Biology syllabus document published by the School Curriculum and Standards Authority of Western Australia. That syllabus covers the content for Units 3 and 4 of ATAR Human Biology.

We have tried to make the chapters as self-contained as possible so that teachers can follow a sequence different from that presented in the book.

In this edition, we have included *Science inquiry* activities to help address the required outcome of 'Science Inquiry Skills'. Although included in the chapter where the content is most relevant, many of them could be used to support other areas of content. This particularly applies to those activities relating to scientific method. Many *Science inquiry* activities could be used as assessment tasks.

Extension activities in each chapter involve the student in delving a little deeper into some of the material discussed in the chapter. They could be used for interest, homework or assessment, or they could be omitted altogether.

A NelsonNet website has been included with *Human Perspectives*. This website provides students with digital resources that supplement and complement material presented in the textbook. The textbook is also available as a NelsonNetBook. NelsonNetBook is a web-based ebook for secondary schools, friendly to interactive whiteboards, computers and iPads. Optional Web 2.0 functionality enables class groups and individuals to add highlights, annotations, audio clips and weblinks.

Whether you are a student or a teacher, we commend this book to you and wish you well in your studies of the biology of the human species.

Terry Newton
Ashley Joyce

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A great many people contributed to the writing and production of this book, and to all those people the authors express their sincere thanks.

Much of the content of this revision was presented in the previous editions. For those editions, we are particularly indebted to Pauline Charman, Helen Hawley, Ken Patterson, Peter Walster and Simone Sawiris, who reviewed parts of the manuscript and provided constructive criticism and suggestions.

We would also like to thank those people who provided information or photographs, or both, whether for earlier editions or for this seventh edition. In particular, a special expression of thanks must go to Geoff Meyer of the School of Anatomy, Physiology and Human Biology, University of Western Australia, for his contribution to past editions.

For this revised edition, we would like to thank Kay Waters for her skilled editing of the manuscript and her many useful suggestions. We are also grateful for the support and assistance of the editorial staff of Cengage Learning Australia. In this regard, special thanks are due to Eleanor Gregory and Nadine Anderson-Conklin for their tireless work in bringing this edition to fruition.

In addition, acknowledgement is due to Norbert Samuels of the School Curriculum and Standards Authority in Western Australia for his support and encouragement for the production of this seventh edition.

Finally, we would like to thank our families for their support and understanding during the preparation of this book.

Terry Newton
Ashley Joyce

DIGITAL RESOURCES

NelsonNet and NelsonNetBook

Please note that complimentary access to NelsonNet and the NelsonNetBook is only available to teachers who use the accompanying student textbook as a core educational resource in their classroom. Contact your sales representative for information about access codes and conditions.

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Students and teachers can link directly to external websites referred to in *Human Perspectives Units 3 & 4 ATAR* via the free, unprotected weblinks site located at http://hp3and4.nelsonnet.com.au.

UNIT 03 HOMEOSTASIS AND DISEASE

CHAPTER

01

SCIENCE INQUIRY

UNIT 3 AND 4 CONTENT

SCIENCE INQUIRY SKILLS

- identify, research and construct questions for investigation; propose hypotheses; and predict possible outcomes
- design investigations, including the procedure(s) to be followed, the materials required, and the type and amount of primary and/or secondary data to be collected; conduct risk assessments; and consider research ethics, including animal ethics
- conduct investigations, including the collection of data related to homeostasis and the use of models of disease transmission, safely, competently and methodically for the collection of valid and reliable data
- conduct investigations, including the use of virtual or real biotechnological techniques of polymerase chain reaction (PCR), gel electrophoresis for deoxyribose nucleic acid (DNA) sequencing, and techniques for relative and absolute dating, safely, competently and methodically for valid and reliable collection of data
- represent data in meaningful and useful ways, including the use of mean, median, range and probability; organise and analyse data to identify trends, patterns and relationships; discuss the ways in which measurement error, instrumental accuracy, the nature of the procedure and the sample size may influence uncertainty and limitations in data; and select, synthesise and use evidence to make and justify conclusions
- interpret a range of scientific and media texts, and evaluate models, processes, claims and conclusions by considering the quality of available evidence, including interpreting confidence intervals in secondary data; and use reasoning to construct scientific arguments
- select, use and/or construct appropriate representations, including diagrams, models and flow charts, to communicate conceptual understanding, solve problems and make predictions
- communicate to specific audiences, and for specific purposes, using appropriate language, nomenclature, genres and modes, including scientific reports

> In science the important thing is to modify and change one's ideas as science advances.
>
> Herbert Spencer

Herbert Spencer, an English philosopher who lived from 1820 to 1903, neatly summarised what science is all about. Science is a process of inquiry aimed at finding answers to problems and discovering new knowledge about the natural world. The knowledge discovered as a result of scientific inquiry becomes a part of science. That is, science means two things: a process of discovery and the knowledge that is discovered. The information presented in this book is science. It is some of our present knowledge about the human species, knowledge that has been obtained by scientific investigation.

Types of investigation

Observations

Observation is an essential part of science. Any investigation, regardless of the procedure used, will involve some form of observation. In investigations based on observation, scientists are looking for patterns. When a pattern becomes evident it may be possible to draw tentative conclusions.

An example of an investigation based on observation is the discovery that peptic ulcers are caused by a bacterial infection. In 1979 Dr Robin Warren, a pathologist at the Royal Perth Hospital, observed the presence of bacteria in samples of stomach tissue that he was examining. Continued observation over the next few years showed that the bacteria were often present in the stomachs of patients suffering from stomach inflammation. Warren's discovery was not taken seriously because, at the time, it was believed that the stomach contents were too acidic for bacteria to survive.

In collaboration with Dr Barry Marshall, a doctor specialising in stomach disease, Warren was able to show that a particular species of bacterium was present in the majority of cases of stomach and duodenal ulcers. They also found that it was rare to have an ulcer without being infected by the bacterium that Warren had discovered. Marshall and Warren went on to culture the bacterium and to show that it did indeed cause ulcers. As a result of their discovery it became easy to treat stomach and duodenal ulcers with antibiotics. The discovery that the bacterium *Helicobacter pylori* was the cause of ulcers began with simple observation and became one of the most significant events in Australian medical history. Robin Warren and Barry Marshall were awarded the Nobel Prize for Physiology or Medicine in 2005.

Another example of systematic observation is when it is used to gain knowledge of animal behaviour. Jane Goodall, the first person to observe the social organisation of chimpanzees in the wild, documented the interactions of chimps with one another, their social hierarchy, their tool making and many other features of their society. She began her observations in 1960, and her work is being continued today through the Jane Goodall Institute.

Controlled experiments

Controlled experiments, sometimes called fair tests, are designed to investigate relationships between factors (or variables). They involve changing one variable while all the other variables are kept the same. Any differences in the results should be due to the changed variable.

Howard Florey, an Australian working at Oxford in England, used controlled experiments to demonstrate the effectiveness of penicillin in treating bacterial infections. In 1940 a crucial experiment to test the effectiveness of penicillin as an antibiotic was carried out. Eight mice, all the same weight and age, were each injected with 100 million streptococci, a type of bacterium. Previous experiments had shown that an injection of that size would kill all mice injected. After the injection of streptococci, four of the mice were put back in their cages and given no further treatment. The other four mice were given injections of penicillin. The mice in the control group – those that did not receive penicillin – all died within 12 hours. Mice in the experimental group, which were given penicillin, survived for many days – one for more than six weeks.

Science Photo Library

Figure 1.1
All scientific investigation involves the collection of data. These students are collecting data on the pH of a liquid.

The only difference between the mice in the two groups was the injection of penicillin, so the survival of those mice was good evidence that penicillin was effective in combating bacterial infections. Further positive feedback from repeated controlled experiments gave Florey and his co-workers the confidence to try penicillin on humans suffering from bacterial infections. The results were outstanding. Florey and his colleague Ernst Chain were awarded the Nobel Prize in Physiology and Medicine in 1945.

Surveys

A **survey** is a process of systematically collecting, analysing and interpreting information about an aspect of a study. Surveys are usually designed to collect data from a large number of subjects. The information may be collected using a questionnaire or by interview. Using the large amount of information collected, the researcher can then look for patterns in the data.

Dr Karl Kruszelnicki was stimulated by a listener to his radio program to carry out a survey into the origins of belly button lint. The survey was conducted over the Internet, with 4799 people responding, and publicised on the radio station Triple J. The patterns in the responses revealed that people more likely to have belly button lint are male, hairy, with a concave belly button, and that the amount of lint increases with age. This was a light-hearted exercise but it does demonstrate the principles involved in conducting a survey. In 2002 'Dr Karl' received an Ig Nobel Prize for his efforts. Ig Nobel Prizes are awarded for research that makes people laugh and then makes them think.

Dr Karl's survey

Trial and error

Trial and error sounds like a random process but when used in scientific research it is systematic. The process involves one attempt to solve a problem being followed by another. Each trial is recorded and the results allow the investigator to gradually home in on the solution to a problem. Thomas Edison, who developed the electric light globe, had to find a suitable material for the filament in the light globe. Using trial and error, he examined more than 600 different materials before finding one that was satisfactory.

Many new drugs, such as antibiotics, have been discovered using trial and error. Chemical compounds extracted from plants can be tested on cultures of bacteria to see whether they have any effect. Those that show promise can then be subjected to further testing under different conditions. Meticulous records of the results of each trial must be kept. Such research is often prolonged and tedious but it is often the only way to find effective substances.

Case studies

A **case study** is an in-depth investigation of one particular person or situation. Case studies are frequently used in areas such as education and business management. However, they may also be useful in some areas of science. For example, in medicine the progress of a particular disease in one person may be documented. Such a case study can extend or help to confirm what is already known about the disease.

Longitudinal studies

A **longitudinal study** is conducted over a long period of time. It is similar to a case study but is more prolonged. Longitudinal studies may take place over many years, even decades. They can also be done retrospectively, which means that the researcher can examine records of past events to build up a picture of change over time.

The Busselton Health Study is a longitudinal study of the population of Busselton, a coastal town in the south-west of Western Australia. Begun in 1966 and continuing today, it is the world's longest-running study of the health of a population.

Busselton Health Study

A longitudinal study on a smaller scale was carried out by an American doctor, William Bean, who studied the growth of his fingernails for 35 years. He did this by filing a horizontal line on his thumbnail just above the cuticle and recording how long it took the mark to reach the tip of his thumbnail. From his records he was able to calculate the growth rate. In 1980, after 35 years of measurements, Bean was able to conclude that the growth of his nails had slowed from 0.123 mm a day when he was 32 years of age to 0.095 mm a day at the age of 67.

EXTENSION

1. A research method sometimes used by scientists is meta-analysis. Find out what is meant by meta-analysis and give an example of an investigation that used this method of research.
2. Some controlled experiments are said to be 'double-blind' experiments. Find out what is meant by a double-blind experiment and give examples of how such experiments might be used.

Scientific method

Scientists investigate in a methodical and systematic way. Wherever possible the data they collect is quantitative – that is, in the form of numbers. Detailed records are kept of the procedure followed and the results obtained.

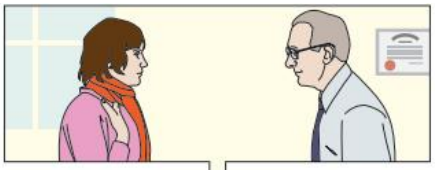
As we have seen, there are many ways of investigating in science. The method used will be the one that best suits the situation. However, many investigations lead to the testing of a hypothesis and will follow a pattern similar to the following.

1. Recognise a problem and define a question.
2. Collect as much information as possible relating to the problem.
3. Propose a hypothesis – a possible explanation for the problem.
4. Test the hypothesis using an experiment.
5. Analyse and interpret the data collected from the experiment.
6. Draw conclusions about whether the hypothesis was supported or disproved.
7. Report on the investigation.

Note that although a hypothesis may be disproved, it cannot be proved. The results of an experiment can only provide *support* for the hypothesis. As Albert Einstein said:

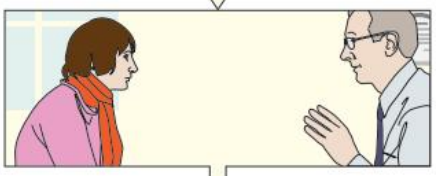
> No amount of experimentation can ever prove me right; a single experiment can prove me wrong.

The scientific method outlined above can be applied to many problem-solving situations. Figure 1.2 shows how a doctor uses the scientific method to arrive at a diagnosis. A mechanic would probably go about solving the problem of a car that would not start in the same way.

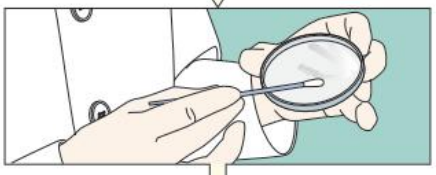


Problem
A patient with a sore throat visits a doctor. The doctor recognises the problem and formulates a question:
'What is causing the patient's sore throat?'

Collect information
The doctor asks the patient how long her throat has been sore; takes the patient's temperature; feels the throat for swelling; looks carefully inside the patient's mouth.

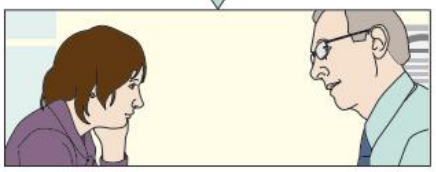


Propose a hypothesis
The doctor proposes a hypothesis:
'The sore throat is caused by a bacterial infection.'



Test the hypothesis
The doctor takes a swab from the patient's throat and sends it for testing at a laboratory.

Analyse and interpret data
The laboratory staff examine the culture from the patient's swab and check for disease-causing bacteria. They send their findings to the doctor.



Draw conclusions
As a result of the information from the pathology laboratory, the doctor decides that the patient's sore throat is caused by an infection of *Streptococcus*. The doctor's hypothesis is supported by the data collected from the test.

Figure 1.2 The scientific method

Scientific method
This website has one section that describes the scientific method and another that shows how it is applied in astronomy.

How science works
This website provides a series of modules designed to answer the question: 'What is science and how does it work?'

Some scientists are not happy with descriptions of the 'scientific method' because of the many different ways that can be used to gather data. One of the main criticisms of using this 'method' as a model of scientific investigation is that it does not give enough weight to the importance of observation as a means of obtaining knowledge. In some investigations, observation alone can lead to new understanding without the need for any experimentation.

Despite the criticisms, the scientific method is a useful model because it can be applied to many investigations. When you do investigations yourself, you will find the model a useful planning tool.

Planning an investigation

Literature review

One of the early steps in the scientific method described above is to 'collect as much information relating to the problem as possible'. One way of collecting the information is to carry out a literature review. A **literature review** is a survey of the material that has been written about the subject under consideration. Literature reviews used to involve long hours of library research but since the Internet was established they have become much easier.

The purposes of a literature review are as follows.

- To help the researcher define the problem: defining the problem carefully helps in the design of an investigation that will contribute to a solution of the problem.
- To find out what is already known about the problem: this prevents duplication of effort and allows the researcher to build on knowledge that is already available.
- To assess research methods: methods used by others may be used or adapted for the researcher's own investigation.
- To allow researchers to relate their findings to what is already known: this is particularly useful for the final report on an investigation. It is also helpful in considering areas for further research.

Safety

It is important that an investigation presents no danger to the participants or to the investigators. Examine the design of your investigation to make sure that there are no safety risks associated with any of the steps in the procedure. Consider the need for safety devices such as fire extinguishers, fire blankets, fume hoods and eye washes. Also assess the need for personal protection such as safety glasses, gloves, face masks and protective clothing. For some investigations it may be necessary to assess the participants. For example, do they have any allergies to the substances being used? Do they have health problems that could be affected by the activities involved?

Safety considerations should include not just the physical safety of the people involved, but also factors such as whether the participants will feel insecure, threatened or embarrassed.

Ethics

Ethics are a set of moral principles or values. They are standards that are observed by most people in our society. **Ethical behaviour** is behaviour that follows those principles or values. In scientific research, especially research involving human participants, there are many ethical issues.

Some of the principles that an investigation involving humans must satisfy if it is to be ethically sound are:

- *voluntary participation* – the subjects should not be pressured into taking part in the investigation
- *informed consent* – the subjects should be fully informed about the objectives of the research, the procedures to be followed, any possible risks and the potential benefits of the research; consent should only be sought after all information has been given
- *risk of harm* – as mentioned in the section on safety, there should be no risk of physical or psychological harm
- *confidentiality* – the identities of participants will not be revealed except to people directly involved in the study.

Just as humans must be treated in an ethical way, the same applies to animals. The requirements for investigations involving animals are set out in the *Australian code for the care and use of animals for scientific purposes 8th edition (2013)*. The code sets out detailed requirements, but in general terms any use of animals in research or teaching should be:

- valid
- humane
- justifiable
- considerate.

Controlling variables

A **variable** is any factor that may change during an experiment.

The **independent variable** is the factor that is being investigated – it is deliberately changed to determine its effect. This variable is deliberately made different in the control and the experimental groups in an experiment. By comparing the results from the control and experimental groups, the effect of the independent variable can be determined.

The independent variable may also be called the experimental variable or the manipulated variable.

The **dependent variable** is the factor that changes in response to the changes made to the independent variable. It is sometimes called the responding variable.

Controlled variables are the factors that are kept the same for both the control and the experimental groups in an experiment.

In any experiment it is important that, with the exception of the independent variable, all variables are kept the same for the control and the experimental group of subjects. If one or more is not kept the same, it is impossible to tell which variable is causing any difference between the two groups of subjects.

Sometimes it is difficult or impossible to keep all variables the same. **Uncontrolled variables** are variables that are not kept the same for the control and the experimental groups in an experiment. They may have been overlooked by the experimenter or they may have been impossible to control. If there are uncontrolled variables in an investigation, this must be taken into account when interpreting the results.

Repetition and replication

Scientific experiments always involve repetition or replication. **Repetition** means doing the same experiment many times. **Replication** means having a number of identical experiments running together or performing the experiment on a large number of subjects at the same time. Both repetition and replication help to demonstrate that results are consistent. If results are different each time an experiment is performed, they are of little value.

Repetition and replication can also help to overcome the effects of uncontrolled variables. For example, if 10 subjects are used in an experiment and one of them is unusual in some way, it will have a big effect on the overall result. If 100 subjects were used, one unusual person in 100 would not have much effect on the average result.

In designing any experiment, plan for as much repetition or replication as time and resources will allow.

Validity and reliability of results

An experiment is **valid** when it tests what it is supposed to test. Some scientists were testing the hypothesis that 'consumption of junk food affects people's memory'. They fed one group of young rats on fatty food for 12 weeks, and fed another group of older rats a low-fat diet. The rats' memories were then tested using an activity that involved pressing a lever. The rats fed on junk food were more forgetful, so it was concluded that the hypothesis was supported. This experiment did not test what it was supposed to test, for two reasons.

1. Testing one species, rats, will only demonstrate the effect on the memory of rats, not any other species.
2. Rats' memories may be affected by age. The two groups of rats should have been of the same age.

Experiments can also be invalid if there are uncontrolled variables – that is, if there are factors that could affect the result of an experiment that are not kept the same for the experimental and the control set-ups. When experimenting with humans, it is often very difficult to design a valid experiment because it is hard to control all the variables.

Reliability is the extent to which an experiment gives the same result each time it is performed. The measuring instruments used in the experiment must also be reliable; that is, they must give the same measurement each time they are used. For example, you may have a set of bathroom scales that give three different weights when you step on them three separate times. Those scales are unreliable, and if used in an experiment would make the results unreliable. The bathroom scales may give the same reading every time but it may be consistently higher or lower than the actual weight. In that case the scales are inaccurate.

Repetition and replication are used to make sure that results are reliable, but they do not improve the accuracy of the experiment.

Analysing results

Quantifying results

Data from an investigation can be one of two types:

- **quantitative data** – expressed in numbers and usually involving measurement; for example, 'the students are 174 and 176 cm in height'
- **qualitative data** – observations that do not involve numbers or measurement; for example, 'student A is taller than student B'.

Wherever possible, you should design an investigation so that the results are quantifiable (Figure 1.3). Numerical results can be ranked, averaged and manipulated in other ways. They can also be summarised using graphs.

Sometimes it is possible to quantify qualitative data. For example, if asking people's opinions on something, they can be asked 'Do you disagree strongly, disagree, agree or agree strongly?' or asked to answer using a numerical value such as 1 for 'disagree strongly' to 4 for 'agree strongly'.

Science Photo Library/Adam Gault

Figure 1.3 Where possible, design an experiment so that the results are expressed as measurements. Measuring height in millimetres is much more meaningful than observations such as 'tall' or 'short'.

Errors and limitations in data

It is important that data are checked carefully for errors. In science an error is not necessarily a mistake. It is any deviation from the result that should have been obtained. One of the reasons why scientists provide comprehensive reports on their investigations is so that others can check their data for errors.

Measurements made with any measuring instrument are approximate. For example, if you measure a person's height at several different times, the measurements are unlikely to be the same every time. This may be because there is natural variation in the subject, variation in the measurement process, or both. This uncertainty in measurement is called **measurement error**. In this case the word 'error' does not mean the same as 'mistake'. Your measurements are not wrong; the measurement error is the difference between the measurements you made and the true value of what you were measuring. Repetition can help to reduce measurement error but it cannot overcome error caused by the limitations or deficiencies of the measuring instrument.

It is also important to understand the limitations of data obtained from an investigation. You must not draw conclusions that go beyond the data. Sometimes it is difficult to look objectively at data, and even experienced scientists can draw conclusions that are not necessarily supported by their data.

One example of reading too much into the data obtained in an investigation arose from a report by Norwegian scientists on the incidence of breast cancer in 25 624 women. Published

in the *New England Journal of Medicine* (1997, volume 336, number 18, page 1269), a prestigious medical journal, the results of the scientists' survey showed that the incidence of breast cancer in women who exercise regularly was reduced by 37%. The media reported on the investigation with headlines stating that 'exercise prevents breast cancer'.

Other scientists pointed out that women who exercise regularly are also likely to be non-smokers, drink less alcohol, have healthier diets, and have higher levels of education and higher incomes than women who do not exercise. Which of these variables was actually contributing to the reduction in breast cancer? Was it really exercise, or could it be having a healthier diet, being a non-smoker, having a better education and so on? Could it be a combination of some of these factors? Each factor and combination of factors would have to be investigated before arriving at a firm conclusion. This example illustrates some of the pitfalls in analysing data.

Secondary data

Secondary data is data that has been collected by someone other than the people who are using the data. For example, earlier in this chapter we quoted the rate of growth of Dr William Bean's fingernails. This is secondary data – fingernail growth was measured by Dr Bean, not by the authors of this book.

Secondary data may sometimes include a *confidence interval*. A confidence interval is used to indicate the reliability of data. It is the range of values above and below a result in which the actual value is likely to fall. For example, opinion polls published in the media may say that 53% plus or minus 1.5% of people will vote for Party X. The confidence interval is 50.5 to 54.5%. A confidence *interval* should be quoted along with a confidence *level*. The *confidence level* most commonly used in research is 95%. This means that if the research were repeated a number of times, the range of values obtained would contain the true value 95% of the time. In the survey of voters, if the survey were repeated many times, the proportion of people who intend to vote for Party X would be between 50.5 and 54.5%, 95% of the time.

Another example may help clarify this concept. Suppose you wanted to find the average height of Year 12 students in Western Australia. You could measure the height of every Year 12 student in the state and then calculate the average height. This would give you an accurate result (the true value) but it would be impractical. A more practical method would be to measure a sample of Year 12 students. If you took a sample of 20 Year 12 students and calculated their average height it would give you an estimated result, but it would not tell you how certain you could be that your result was correct. Using a mathematical formula, a confidence interval could be calculated that would indicate the reliability of your estimate. The calculated confidence interval may show, for example, that using the same sampling method, the average height of Year 12 students will be between 167 and 179 cm 95% of the time.

Processing data

If you have designed an experiment to give quantitative data, you will end up with a mass of figures that you must interpret. In a controlled experiment you will have to compare the control and the experimental results. There are some simple calculations that you can do to make the numbers more meaningful.

Average

In science a description of a set of numbers almost always includes a measure of its centre, or its **average**. Averages are a very common and simple way of handling sets of numerical data. The average that is most often calculated is the **arithmetic mean**, often just called the **mean**. To calculate the mean of a group of measurements, you add up all the measurements in the group and divide by the total number of measurements.

Sometimes in a set of measurements there will be values that are well beyond the range of the rest of the measurements. These are called **outliers**. The mean is affected by outliers, because a very high

or very low outlier value will make the mean higher or lower than it would be without the outlier included. Outliers may result from mistakes in measurement, the failure of equipment or other errors. If the outliers clearly result from an error, they may be excluded when the mean is calculated.

Median

The **median** is the middle of a set of numbers. It divides the lower set of numbers from the upper set. For example, the heights of the members of a cricket team were measured and (in centimetres) they were: 164, 176, 177, 177, 178, 181, 182, 182, 183, 185, 191.

The median height of the team was 181 cm. 181 is the middle value – there are five team members with heights lower than 181 cm and five with heights higher. If there is an even number of measurements then the median is taken as the mean of the two values in the middle of the set of numbers.

Using the median of a set of numbers reduces the influence of outliers. Outliers due to measurement error could have a significant effect on the mean of a set of numbers, but would have much less effect on the median.

Range

A measure of the centre of a group of numbers can be misleading. The mean, or the median, gives us no idea about whether all the values are clustered around the centre or whether there is a very wide spread from highest to lowest value. Any description of a set of numbers should therefore include both a measure of centre and a measure of spread.

The simplest way to indicate the spread is to quote the **range** – that is, the highest and lowest measurements in the group. For example, we could say that the heights of students in a Year 12 class ranged from 151 to 183 cm with a mean of 171 cm.

Scientists use a number of other measures of spread, such as quartiles or standard deviation, but range should be sufficient for your investigations.

Ratios and rates

A **ratio** is a numerical statement of how one variable relates to another. That is, it is a comparison of two numbers. Ratios are written as two numbers separated by a colon. For example, on older TV screens the ratio of width to height was 4:3. If the width is 40 cm, the height is 30 cm; if the width is 60 cm, the height is 45 cm and so on. Modern, widescreen TVs have a ratio of 16:9.

A **rate** is a special kind of ratio that shows how long it takes to do something. For example, a good athlete can run 10 000 m (10 km) in around 30 minutes. This is a rate of 1 km per 3 minutes or 20 km per hour. Rate is much more meaningful than a simple count of how often something occurs. If you were investigating the effect of exercise on breathing, counting a person's breaths would be meaningless unless you knew how many breaths there were in a given time. That is, you need to know the rate in breaths per minute.

Percentages

Per cent means 'per hundred'. Percentages are used to express how large one variable is in relation to another. For example, if a breakfast cereal is labelled as containing 1.5% fat, it means that 100 g of the cereal contains 1.5 g of fat.

In Western Australia in 2011, males aged 15 to 19 years made up 6.7% of the population; females of the same age made up 6.4%. This means that for every 100 people in the population, 6.7 (or 67 per thousand) are 15 to 19 year-old males and 6.4 (64 per thousand) are 15 to 19 year-old females. Or we could say that for every 64 girls aged 15 to 19 in Western Australia, there are 67 boys aged 15 to 19.

Percentage change

Calculating a percentage increase or decrease is often a good way to understand changes in a variable over time. For example, if a person weighing 100 kg lost 10 kg after dieting for 6 months, we could say that the person had lost 10% of their body weight as a result of the diet. If another

person weighing 120 kg lost 13 kg after 6 months on the same diet, the percentage decrease would be 10.8%. Percentage change is helpful in making such comparisons.

To calculate percentage change:

1 *subtract* the old value (120 kg) from the new value (107 kg)
2 *divide* by the old value (120 kg)
3 *multiply* the result by 100 and add a per cent sign (%) to it.

This can be written as a formula:

$$\frac{\text{new value} - \text{old value}}{\text{old value}} \times 100 = \text{percentage change}$$

If the percentage change is positive, it indicates an increase; if the change is negative, it indicates a decrease.

Frequency

Frequency is the number of times an event occurs. For example, some students conducted a survey to find out how many drinks containing caffeine were consumed by the members of their class in a two-day period. The table of data they collected is called a **frequency distribution** or **frequency table**. A frequency table summarises the data by showing how often the variable in question occurs (Table 1.1). Frequencies can also be presented graphically as a histogram (Figure 1.4).

Table 1.1 Frequency table showing number of caffeine drinks consumed over a two-day period

Number of drinks consumed	Number of students
0	3
1	0
2	3
3	7
4	6
5	3
6	1
7	2

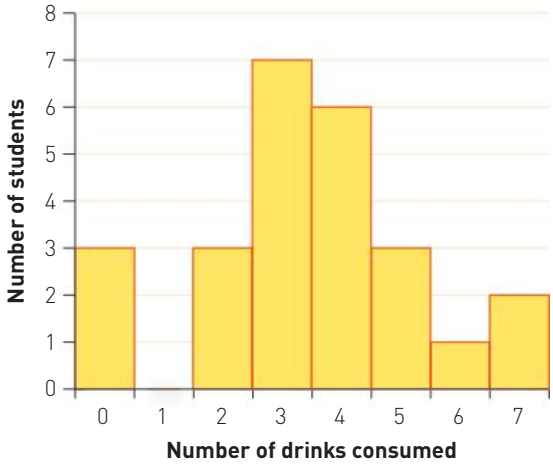


Figure 1.4 Histogram showing number of caffeine drinks consumed by students in a Year 12 class over a two-day period

Probability

Probability is the chance, or likelihood, that a particular event will occur. Many outcomes cannot be predicted with certainty. In such cases the best we can do is to say how likely it is that the event will occur. For example, the weather bureau cannot know with certainty when it will rain. If they forecast that there is a 20% chance of rain, they are stating a probability.

Often the probability of an event occurring can be expressed in more precise mathematical terms. Probability is the number of ways an event can occur divided by the number of possible outcomes. For example, what is the probability that when you throw a die you will get a three? There is only one way you can get a three but there are 6 possible outcomes. The probability of throwing a three is therefore $\frac{1}{6}$.

What is the probability of throwing an even number? There are three ways you can get an even number from 6 possible outcomes, so the probability of throwing an even number is $\frac{3}{6}$ or $\frac{1}{2}$. The probability can also be expressed as a percentage (50%) or as a decimal (0.5).

Probability is useful in many areas of science investigation. For example, in genetics (covered in Unit 2 of Human Biology) it is possible, in a simple cross, to state the probability that the offspring will inherit a certain characteristic.

Presentation of data

Tables

A convenient way to present numerical data is in the form of a table. The table of results for the students' survey of the number of caffeine drinks consumed in a Year 12 class over a two-day period could look something like Table 1.1.

Notice that the table follows these rules:

- It has a title. The title should state the variables represented by the data; in this case, the number of drinks consumed and the number of students are the two variables.
- The data are presented in columns. Usually the independent variable (in this case the number of drinks consumed) is in the left column and the dependent variable (number of students) is in the right column. This rule is not always applied – it is more important that the table be easily understood.
- Each column has a heading and, where appropriate, the heading must state the units in which the data have been measured.

Other examples of tables may be seen in Activity 9.1 on page 125.

Graphs

Graphs are a pictorial way of presenting numerical data. A graph shows how changes in one variable affect another variable. From a graph it is easy to see any trends in the data. It is also possible to predict what the values would have been between the points plotted (interpolation), or the trend beyond the data shown in the graph (extrapolation).

Figure 8.2 on page 103 is a typical *line graph*. When drawing any graph the following rules must be observed.

- The graph should have a title that states the two variables shown on the graph. For example, the title for Figure 8.2 describes what the graph is about.
- The independent variable ('Time' in Figure 8.2) is plotted on the horizontal axis and the dependent variable ('Blood glucose concentration') is plotted on the vertical axis.
- Each axis is labelled with one of the variables and the units in which it is measured.
- Equal intervals of units are used on each axis.

The most commonly used graphs are line graphs (e.g. Figure 3.9 on page 42), histograms, column graphs (e.g. Figure 17.18 on page 263) and bar graphs. Descriptions of how these graphs are used may be found in *Human Perspectives Units* 1 & 2 *ATAR*.

Tables and graphs
At the Australian Bureau of Statistics website you can find more information on graphs, and download the document 'What Graph or Display to Use When'.

Models

In science a **model** is a simplified representation of an idea or process. Figure 1.2 is a model of the scientific method. Once a model has been developed it can be applied to a number of situations. The model for scientific method can be applied to most scientific investigations. It can also be applied to other situations, as in Figure 1.2 where it is being applied to the steps a doctor may take in trying to diagnose an illness.

Figure 2.2 on page 23 is a model showing in simple diagram form how hormones may affect the functioning of a cell. The steady state control system described on page 76 is a model that can be applied to the regulation of body temperature, blood glucose and many other situations.

A model may be a diagram, a flow chart or a physical model such as a model of the atoms in a protein. Scientific models often have to be modified as new data are collected.

Flow charts

A flow chart is a diagram that shows the steps involved in a process. The steps are usually shown in boxes and the sequence of steps is indicated by arrows. Flow charts are very useful in summarising and visualising the steps in a complex process. Numerous flow charts are used in this book – for example, the flow chart illustrating the stimulus-response-feedback model on page 77 and the flow chart on page 90 showing how body temperature is regulated.

Reference to the work of others

An extensive examination of the literature at the start of an investigation allows the researcher to fully grasp the available information relating to the problem under consideration. This review also allows the results to be seen in the context of what is already known. Research done by others can also be used to support or confirm what has been discovered in the investigation. Demonstrating how your findings relate to what is already known will give credibility to your research and will add to the body of knowledge on the subject under review.

Reporting

When an investigation has been completed, the findings need to be made known to others. This is usually done by a written report. Reports are a very important part of communication in science. Scientists inform others of their research by publishing a report in a scientific journal. There are thousands of scientific journals, some of which deal with a very narrow field of science. Examples are *Nature*, *Science*, *Journal of Musculoskeletal Research* and *Journal of Genetics*.

The editors of scientific journals use a process called **peer review** to make sure that the report is worthy of publication. A submitted report is sent to one or more scientists who are experts in the field and who may or may not recommend publication. This process is important as it helps to keep scientific literature free of incorrect, bogus or misleading information.

A scientific **report** includes a description of an investigation, the results that were obtained and any conclusions that can be drawn from the results. The description of how the investigation was done must be sufficiently detailed to allow other scientists to repeat the experiment. It is common practice for scientists to repeat experiments that others have performed. If the results obtained are not the same as those for the original experiment, any conclusions that may have been drawn are questionable.

Reports follow a fairly standard format, similar to that described below.

Scientific report format

Reports may be written using the following headings.

- **Title** of the report and **name** of the author or authors
- **Introduction**, stating the nature of the problem investigated and the hypothesis tested
- **Materials and equipment**, listing the apparatus used, particularly any specialised items of equipment
- **Procedure**, describing the exact method used to carry out the investigation
- **Results**, often presented as tables, graphs, diagrams or photographs
- **Discussion**, including comments about the results and the way they relate to the hypothesis that was tested
- **Conclusion**, summarising the most important parts of the discussion and stating the success or otherwise of the investigation
- **Further research**, as scientific investigations often raise more questions than they answer – many reports suggest areas that need further investigation

- **References**, which list any reports, books, journal articles, websites or other sources of information referred to in the report
- **Acknowledgements**, of people who helped with the investigation or of organisations that provided funds for the research.

The discussion

The most important and longest part of a report is usually the discussion. The discussion is about the results and the method used to obtain the results. The discussion needs to be very thorough and to address all aspects of the research.

A checklist of questions that could be answered in the discussion section is as follows.

- Were there any defects in the design of the investigation or in the procedure?
- Were any results different from those expected?
- How do the results fit into the broader context of what is already known about the topic?
- Are there any practical applications for the results?
- Do the findings relate to any earlier work in the same area?
- Did the results support the hypothesis, or did they indicate that the hypothesis was incorrect?
- Were there any limitations in the research?
- Could the investigation have been improved in any way?
- Were there any variables that could not be controlled?
- Was there any bias in the results?
- Is there any information available from other reliable sources that would support the results?
- Is there a need for further research to clarify any of the results?

This is not an exhaustive list of questions; when writing a report, you will be able to think of other points that need to be discussed.

Report writing
This Monash University website gives detailed advice on report writing.

Report writing FAQ
This University of New South Wales website gives advice on report writing and links to other useful sites.

A case study of a scientific investigation

French scientist Louis Pasteur (1822–1895) conducted hundreds of investigations. His achievements include showing that micro-organisms cause disease, developing vaccines for rabies and some animal diseases, showing that micro-organisms are responsible for fermentation, and showing how the development of micro-organisms could be prevented by boiling and then cooling a liquid. This last process became known as pasteurisation.

Pasteur's investigations followed the scientific method. We can use aspects of his work as examples of many of the points discussed here. We will focus on Pasteur's demonstration that spontaneous generation does not occur. Spontaneous generation is the idea that living organisms can develop spontaneously from non-living matter.

Italian physician Francesco Redi had shown in 1668 that maggots develop from eggs laid by flies. Until that time it was believed that maggots formed naturally from rotting meat. Another Italian, Lazzaro Spallanzani, demonstrated 100 years later that micro-organisms come from the air and that boiling can kill them.

Despite the work of Redi and Spallanzani, the belief persisted that micro-organisms could spontaneously develop in decaying organic matter. The French Academy of Sciences arranged a contest for scientists to disprove the idea of spontaneous generation. Pasteur took up the challenge in 1859. This is a good example of how scientific

Getty Images/Science Photo Library

Figure 1.5 Louis Pasteur

Pasteur's reports
This website has one of Pasteur's research reports on the growth of micro-organisms, published in 1860.

knowledge builds over time. First Redi, then Spallanzani and later Pasteur and many others were involved in debunking the idea of spontaneous generation.

Pasteur had a problem to be solved and his hypothesis was 'that micro-organisms occur in sterile culture medium only when exposed to contaminated air from the outside'. To test the hypothesis he began a series of meticulous experiments. He opened flasks of sterile broth in the streets of Paris and found that after a time there was abundant growth of micro-organisms in the broth. He opened flasks high in the Alps and the broth nearly always remained sterile. Variables other than the location of exposure were kept the same: the flasks were the same size and shape, with the same volume of the same type of broth. All flasks were opened for the same period of time and kept at the same temperature, and so on. From his results Pasteur was able to conclude that the flasks exposed in Paris became infected because of the large numbers of micro-organisms in the air. The flasks exposed in the Alps remained free of micro-organisms because there are fewer micro-organisms in the air at high altitude.

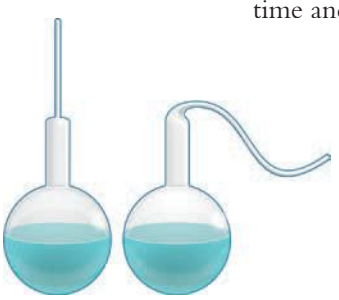


Figure 1.6 The types of flasks used by Pasteur in his experiment to demonstrate that spontaneous generation did not occur

Another experiment that Pasteur performed involved placing broth in flasks and heating them to kill micro-organisms. Some of the flasks then had their necks heated and drawn out into a long S-shaped curve (Figure 1.6). The necks of control flasks were heated but left straight. All flasks were left in the same location with their necks open to the air. After several weeks the broth in the flasks with straight necks had gone cloudy due to the activity of micro-organisms. Broth in the curved-neck flasks remained clear; the micro-organisms and dust in the air settled in the bend of the S-shaped tube and did not reach the broth in the flasks. In the straight-tubed flasks, micro-organisms and dust were able to reach the broth, where the micro-organisms multiplied and made the broth go cloudy. This experiment confirmed Pasteur's earlier conclusion that the air contains micro-organisms. Pasteur summarised his findings in a report titled, 'On the organised bodies that exist in the air. Examination of the doctrine of spontaneous generation'.

Getty Images/Science Photo Library

Figure 1.7 John Tyndall

Support for Pasteur's conclusions came from English physicist John Tyndall (Figure 1.7). He showed that sterile broth exposed to air but kept in a dust-free chamber remained sterile indefinitely. Tyndall and Pasteur were aware of each other's work – an example of one scientist producing evidence that supported the findings of another.

Despite the convincing evidence, the dispute over spontaneous generation continued. Many were not convinced and Pasteur often had to defend his research. At a lecture in 1864 he said:

> there is now no circumstance known in which it can be affirmed that microscopic beings came into the world without germs, without parents similar to themselves. Those who affirm it have been duped by illusions, by ill-conducted experiments, spoilt by errors that they either did not perceive or did not know how to avoid.

This situation persists in science today. The findings of scientists are subject to intense scrutiny by others and are often the subject of criticism – sometimes warranted, sometimes not. One reason for writing reports and presenting papers at conferences is so that other experts can examine the results. Many scientists have to vigorously defend their research in the face of criticism from peers and others.

Ideas about spontaneous generation were not finally laid to rest until 1876, when Pasteur and his assistant, Charles Chamberland, discovered that some bacteria produce spores that are resistant to high temperatures. These resistant spores accounted for the development of micro-organisms in cultures that had apparently been sterile for long periods. Some scientists had claimed that such development was the result of spontaneous generation. Spontaneous generation had finally been refuted 16 years after Pasteur's first convincing experiments and more than 200 years after Redi's research on spontaneous generation.

Pasteur made a great many discoveries about micro-organisms, but there was still a lot to find out. The scientific process of building knowledge continues in microbiology today.

Science inquiry

ACTIVITY 1.1 Validating Pasteur's experiment

You can repeat Pasteur's experiment in which he used flasks with S-shaped necks, to see whether you get the same results.

YOU WILL NEED

For each pair or group:

- beef cubes
- filter funnel and filter paper
- four 100 mL conical flasks
- four one-hole stoppers
- straight glass tubing and S-shaped glass tubing
- source of heat (hot plate or Bunsen burner)

WHAT TO DO

1. Make a broth using the beef cubes.
2. Filter the broth so that it is clear.
3. Place equal volumes of broth in each of the four flasks.
4. In two flasks place a stopper with straight glass tubing and in the other two flasks place a stopper with S-shaped tubing (Figure 1.8).
5. Gently boil the broth in each flask for 15 minutes.
6. Leave the flasks in a warm place and check every couple of days for evidence of the growth of micro-organisms, such as cloudiness, a scum or mould on the surface of the liquid, or bubbles. You may need to leave your flasks for several weeks before any changes are apparent.
7. At the conclusion of the investigation do not open any of the flasks. They must first be autoclaved at 120°C for 20 minutes under 100 kPa pressure to destroy any micro-organisms.

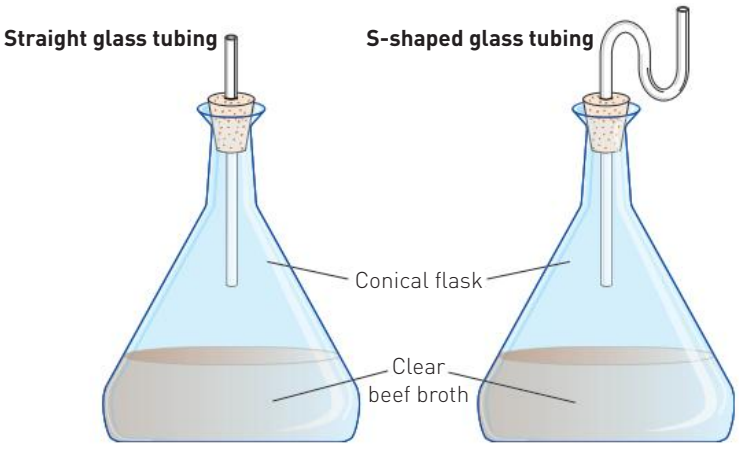


Figure 1.8 Flasks for validating Pasteur's experiment

STUDYING YOUR RESULTS

1. Describe your results, giving a description of the broth in each flask.
2. Combine your results with those of other groups in the class. What is the advantage of combining results?
3. Were your results similar to Pasteur's? Were the class results similar to Pasteur's?
4. If your results were not similar to Pasteur's, can you suggest any explanation?
5. If you were to repeat the experiment, how could you improve it?

ACTIVITY 1.2 Researching for Mightypharm

Researchers working for the pharmaceutical company Mightypharm were extracting chemicals from a new species of toadstool discovered in the rainforests of Brazil. Several of the chemicals were compounds that had never been found before. The researchers decided that the new compounds might have the potential to be used as antibiotics in the treatment of human bacterial infections.

Imagine that you are one of the Mightypharm researchers and your task is to test the new compounds with the goal of eventually producing an antibiotic that can be used to treat bacterial infections in human patients.

- *Stage 1:* Propose a hypothesis linking the two variables (chemical compounds and effect on bacteria). Describe how you would test the hypothesis to find out whether any of the compounds are effective in killing bacteria. Make your description detailed enough for someone else to follow and carry out the same tests that you propose. Describe how you would present your results and what sort of result would indicate that a compound had potential for use as an antibiotic.
- *Stage 2:* Suppose that one of the compounds tested in stage 1 showed promise as an antibiotic. Describe how you would test that compound on animals to find out whether it worked and whether there were any side effects from use of the compound. Make your description detailed enough for someone else to follow your procedure exactly, and remember that there are ethical considerations relating to the use of animals in research.
- *Stage 3:* The promising compound has successfully passed stages 1 and 2. Describe how you would carry out human trials on the compound. Also, describe how you would deal with any ethical issues that may arise.

In writing your descriptions of stages 1, 2 and 3 you may wish, or your teacher may ask you, to present your material as a paper to be published in a scientific journal. Refer to page 14 for the format of a scientific report.

FURTHER INVESTIGATION

You may wish to investigate how a prescription drug currently in use was discovered, developed and marketed.

Review questions

1 Explain the difference between:
- **a** observations and surveys
- **b** longitudinal studies and case studies.

2 What is a controlled experiment?

3 **a** What is a hypothesis?
- **b** Can a hypothesis be proved? Explain.

4 What is a literature review and what are some of the reasons for carrying out such a review?

5 List four principles that must be satisfied if an investigation is to be ethical.

6 **a** Explain the difference between the dependent and the independent variable in an experiment.
- **b** Explain the difference between controlled and uncontrolled variables.

7 What is the difference between the validity and the reliability of an investigation?

8 Explain the difference between qualitative and quantitative data.

9 Describe how you would calculate the mean of a set of measurements.

10 What are outliers? Should outliers be excluded when drawing conclusions from a set of data?

11 What is a peer review? Why are peer reviews used?

12 Describe some of the points that should be included in the discussion section of a scientific report.

13 What is an 'error' when discussing a scientific investigation?

Apply your knowledge

1 Re-read the account of Florey's experiment in which he injected mice with penicillin (pages 3–4). What variables did Florey control in his experiment?

2 What did Albert Einstein mean when he said: 'No amount of experimentation can ever prove me right; a single experiment can prove me wrong'?

3 What type of investigation would be best for finding a solution to the following problems? Explain the reasons for your choice in each case.
- **a** Can people taste the difference between two different brands of milk chocolate?
- **b** What proportion of students in your school are left-handed?
- **c** What is the ratio of males to females in your Human Biology class?
- **d** How has a particular person's growth rate changed from birth to age 15?

4 In addition to physical activity that is part of their job or daily routine, many people deliberately exercise by going to a gym or by walking or jogging. Describe how you would conduct a survey to find out the average amount of time the teachers at your school spend on deliberate exercise.

5 The table below shows the systolic blood pressure of students in a Year 12 Human Biology class.

Table 1.2 Systolic blood pressures of Year 12 students

Systolic blood pressure (mmHg)					
109	123	141	115	131	126
144	138	106	115	49	109
125	132	128	114	116	120
195	143	132	116	113	

a Are there any obvious outliers in the data in Table 1.2? If so, which are the outliers and why should they be regarded as outliers?
b Calculate the mean systolic blood pressure for the class, excluding any outliers.
c What is the range of blood pressures in the class?
d What percentage of students had a blood pressure of 130 mmHg or higher?
e The average systolic blood pressure for adults is 120 mmHg. What proportion of students have blood pressures above this average?

6 In 2003 a team of Australian anthropologists discovered skeletal remains on the Indonesian island of Flores. One skeleton was of a small human with a small brain, and dating showed it to be 18 000 years old. The team claimed it was a new species of human and named it *Homo floresiensis*. Experts are divided on whether the discovery is a new type of human or whether there is some other explanation for the small stature and small brain. This is a good example of scientific debate about the meaning of data. Use the Internet to find out some of the hypotheses put forward to explain why the skeleton is really our own species, *Homo sapiens*.

7 If you randomly draw a card from a standard pack of 52 playing cards,
a what is the probability that you will draw a spade?
b what is the probability that you will draw a king?

8 Researchers investigating the benefits of exercise in preventing heart disease studied the health outcomes for women after participating in an exercise program. They calculated the risk of heart disease at 0.18 with a confidence interval of 0.04 to 0.80 at the 95% confidence level. Explain what the data mean.

CHAPTER 02

CHEMICAL MESSENGERS

UNIT 3 CONTENT

SCIENCE AS A HUMAN ENDEAVOUR

- synthetic hormones may be developed to control or treat endocrine dysfunction, including diabetes mellitus, hypothyroidism and hyperthyroidism, to improve the quality of life for individuals

SCIENCE UNDERSTANDING

Endocrine system

- the hypothalamus, pituitary, thyroid, parathyroid, pancreas, thymus, gonads, pineal and adrenal glands are endocrine glands found in the human body
- hormones secreted from the hypothalamus, pituitary, thyroid, parathyroid, pancreas and adrenal glands are involved in homeostasis by affecting specific target organs
- the secretions of the pituitary gland are controlled by the hypothalamus through transport of hormones either via nerve cells or the vascular link between them
- hormones can be lipid-soluble and able to cross cell membranes to bind with and activate intracellular receptors or, water-soluble and able to bind with and activate receptors on cell membranes, and require secondary messengers to affect cell functioning

The body is composed of trillions of cells that are organised into tissues, organs and systems. All these structures must work together in a coordinated way. Coordination is achieved through the activities of the nervous system and the endocrine system. The nervous system exerts control by the transmission of nerve impulses to and from the various tissues. The endocrine system influences the activity of cells by the release of chemical messengers known as hormones. Much of the work of the endocrine system is concerned with keeping the environment inside the body fairly constant. Maintaining a stable internal environment is known as **homeostasis**. In this chapter we will discuss how the endocrine system maintains homeostasis and controls cellular activities through chemical messengers.

Feedback is very important in regulating the secretion of hormones from endocrine glands. When the body responds to a change, or **stimulus**, by secreting more or less of a hormone, that response changes the original stimulus. This is known as feedback. Feedback systems are discussed in more detail in Chapter 6.

Endocrine glands

There are two kinds of glands in the body.

- **Exocrine glands** secrete into a duct that carries the secretion to the body surface or to one of the body cavities. Sweat glands, mucous glands, salivary glands and the glands of the alimentary canal are examples of exocrine glands.
- **Endocrine glands** secrete hormones into the extracellular fluid that surrounds the cells that make up the gland. The secretion then usually passes into the capillaries to be transported by the blood. Endocrine glands are sometimes called ductless glands. The major endocrine glands are shown in Figure 2.1.

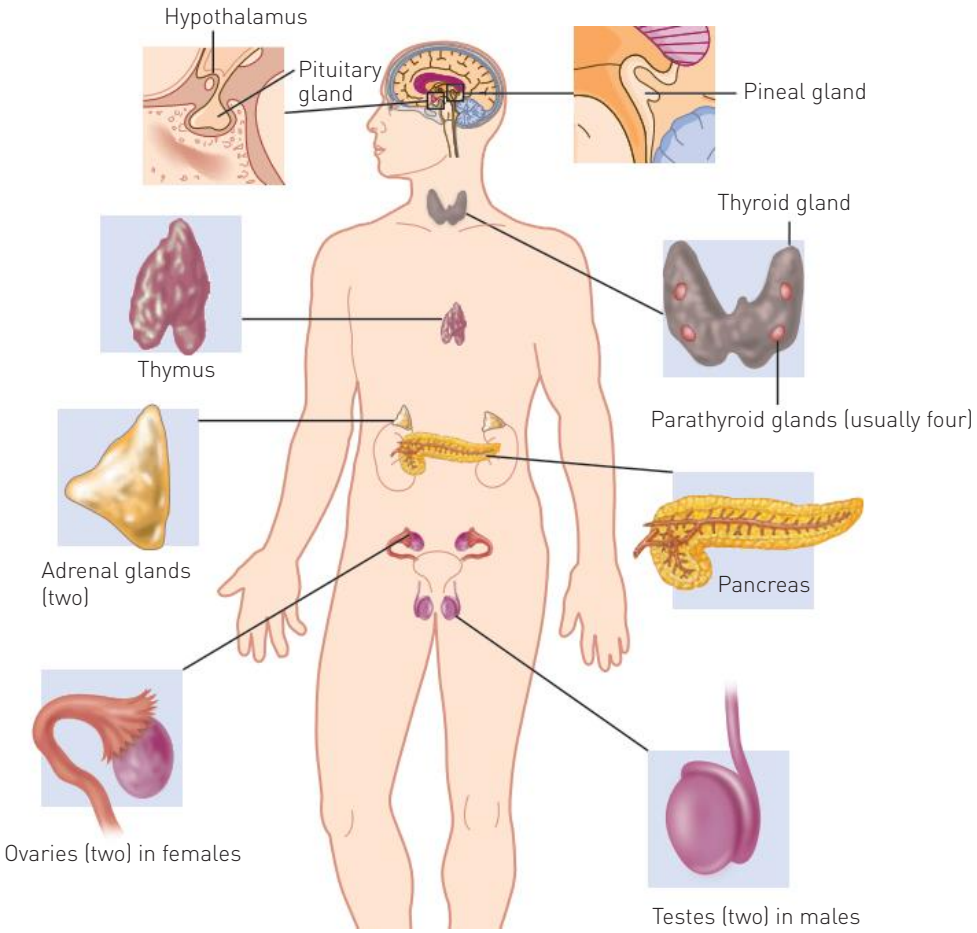


Figure 2.1 The major endocrine glands in the body

Hormones

As stated above, the secretion of an endocrine gland is called a **hormone**. Hormones may be proteins, steroids or amines. They are transported throughout the body in the blood. A hormone may affect all the cells of the body or only particular groups of cells, **target cells**, or particular organs, **target organs**.

Cells may communicate with other cells in the same tissue by secreting chemicals that diffuse to adjacent cells. These substances are called **paracrines** or sometimes *local hormones*. Paracrines are secreted by all cells in a particular tissue and move through the extracellular fluid. Hormones, however, are secreted only by specialised cells and are transported by the bloodstream.

Hormones are only able to influence cells that have the correct receptor for the hormone. That is, hormone receptors are *specific*. *Saturation* can also occur. Once all the receptor molecules are occupied by hormone molecules, the addition of more hormones does not produce any greater effect.

Protein and amine hormones work by attaching to receptor proteins in the membrane of the target cell. The combination of the hormone with the receptor causes a secondary messenger substance to diffuse through the cell and activate particular enzymes (Figure 2.2). For example, the hormone insulin binds to a receptor protein and this leads to an increase in glucose absorption by the cell. Receptor proteins are specific. Each type of receptor will bind with only one specific molecule. The lock and key analogy can be used to describe this interaction. The lock, the receptor protein, will only work with the correct key, the binding molecule.

There are also limited numbers of receptor proteins in the membrane of each cell, so when each receptor is bound to a molecule there can be no further increase in the rate of the cell's activity. For example, when each insulin receptor in the cell membrane is bound to insulin, the cell's rate of glucose uptake cannot increase any further, even if the amount of insulin increases.

Different cells have different types and numbers of receptor proteins. This is why there is variation in the sensitivities of cells to hormones and other substances.

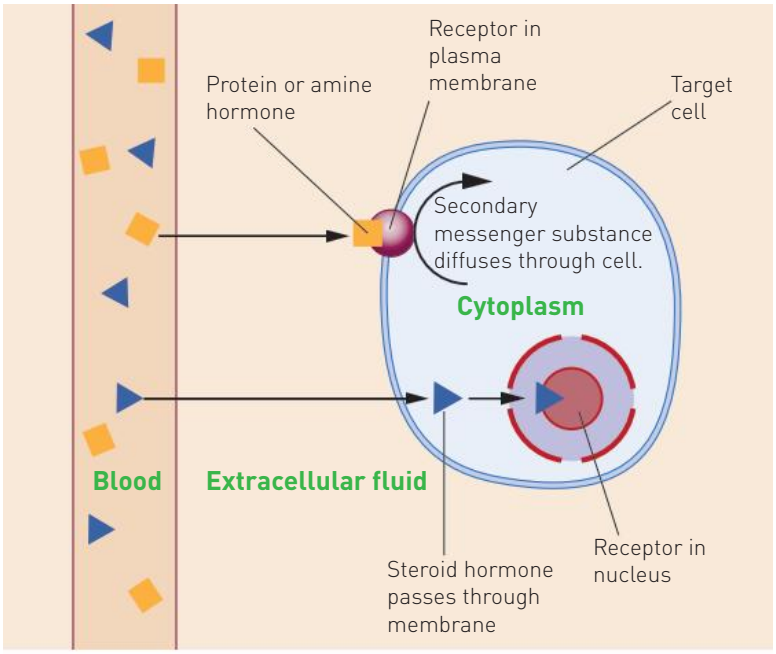


Figure 2.2 Hormones combine with receptors on the cell membrane or with receptors inside the cell.

Steroid hormones work by entering target cells and combining with a receptor protein inside the cell. The receptor may be on the mitochondria, on other organelles or in the nucleus. The hormone–receptor complex activates the genes controlling the formation of particular proteins (Figure 2.2).

Hormones change the functioning of cells by changing the type, activities or quantities of proteins produced. They are *not* enzymes, but in many cases hormones exert their influence by changing the activity of enzymes or by changing the concentration of enzymes. Hormones may:

- activate certain genes in the nucleus so that a particular enzyme or structural protein is produced
- change the shape or structure of an enzyme so that it is turned 'on' or 'off'
- change the rate of production of an enzyme or structural protein by changing the rate of transcription or translation during protein production.

Steroid hormones
This website provides an animation of the way steroid hormones work.

Enzyme amplification

One hormone molecule does not cause the manufacture or activation of just one enzyme molecule – it activates thousands of enzyme molecules. This is achieved through a process called **enzyme amplification**. The hormone triggers a cascading effect in which the number of reacting molecules involved is increased hundreds or thousands of times for each step along the metabolic pathway. One hormone molecule could trigger the production of more than a billion enzyme molecules. Thus, a very small stimulus can produce a very large effect.

Hormone clearance

Once a hormone has produced the required effect it must be turned off. This is done by breaking down the hormone molecules. Some hormones are broken down in the target cells but most are broken down in the liver and the kidneys. The degraded hormones are then excreted either in the bile or in the urine.

Control of hormone secretions

To maintain homeostasis, the amount of hormone produced by an endocrine gland must be very closely regulated. Any oversecretion or undersecretion of a hormone will cause the body to function abnormally.

Hormonal secretions are generally regulated by **negative feedback** systems whereby the response produced by the secretion of the hormone is the opposite of the stimulus that caused the secretion. Some negative feedback systems involve the nervous system through the release of regulating factors from the hypothalamus of the brain. These factors regulate the function of the pituitary gland. The hypothalamus can secrete **releasing factors**, which stimulate the release of a hormone, or **inhibiting factors**, which slow down the secretion of a hormone.

The hypothalamus and the pituitary gland

The **hypothalamus** is located at the base of the brain (Figure 2.3). This organ regulates many of the basic functions of the body, such as body temperature, water balance and heart rate. Many of the functions of the hypothalamus are carried out through the pituitary gland.

The **pituitary gland**, or **hypophysis**, lies just under the hypothalamus and is joined to the hypothalamus by a stalk called the **infundibulum**. It is not much bigger than a large pea, about 13 mm in diameter, but it is absolutely vital to the normal functioning of the body.

Hypothalamus and pituitary
This website provides more information on the relationship between the hypothalamus and the pituitary.

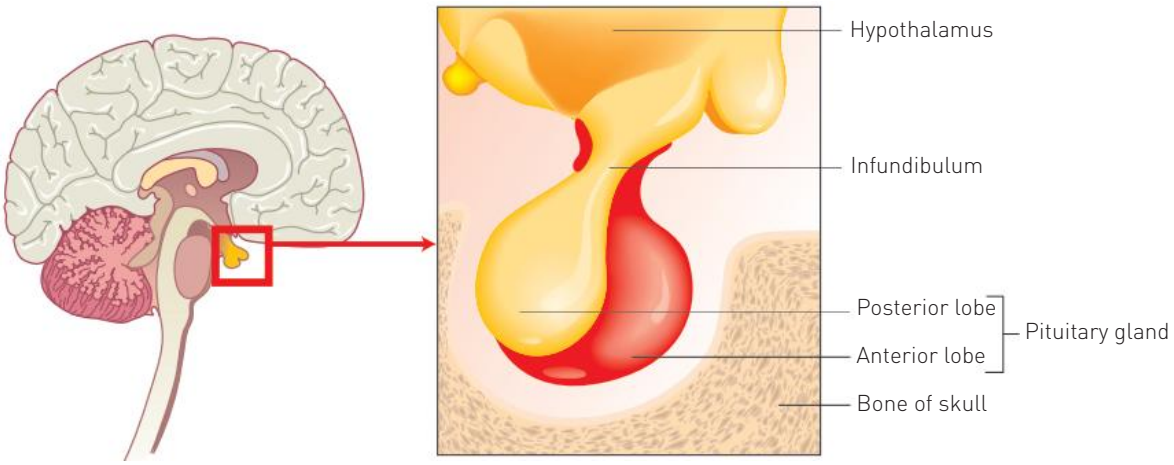


Figure 2.3 The location of the hypothalamus and the lobes of the pituitary gland

The pituitary consists of an anterior lobe and a posterior lobe, each of which functions separately (Figure 2.3). The anterior (front) lobe has no nerves connecting it to the hypothalamus but it is connected to it by a complex network of blood vessels. The posterior (rear) lobe is not a true gland because it does not secrete substances. It is joined to the hypothalamus by nerve fibres that come from nerve cell bodies in the hypothalamus and pass through the infundibulum to the posterior lobe.

The hypothalamus produces many different hormones. Some of them are carried by the blood to the anterior lobe of the pituitary, where they stimulate or inhibit the release of hormones made in the anterior lobe. Other hormones pass along the nerve fibres from the hypothalamus to the posterior lobe of the pituitary where they are then secreted.

Many pituitary hormones regulate the activity of other endocrine glands. For this reason the pituitary is sometimes referred to as the 'master gland'.

Anterior lobe of the pituitary

The anterior lobe of the pituitary (the adenohypophysis) releases a number of hormones that regulate a great range of bodily activities. Secretions of the anterior lobe are in turn controlled by releasing and inhibiting factors secreted by the hypothalamus. These factors are themselves hormones, because they are secreted into the extracellular fluid around the cells of the hypothalamus and are carried by the blood to the anterior lobe of the pituitary.

Hormones released by the anterior lobe of the pituitary include:

- **gonadotropins**, which are hormones that affect the gonads, the ovaries and testes. **Follicle-stimulating hormone (FSH)** in the ovary of the female stimulates development of the follicles that contain eggs. In the male, FSH stimulates the production and maturation of sperm in the testes. **Luteinising hormone (LH)** works with FSH in the female to bring about ovulation and to form a structure called the corpus luteum after ovulation. In the male, LH stimulates interstitial cells in the testes to secrete male sex hormones
- **growth hormone (GH)**, or somatotropin, which stimulates body growth, particularly growth of the skeleton. It increases the rate at which amino acids are taken up by cells and built into proteins. GH is secreted throughout life as it helps to maintain the size of organs once maturity is reached
- **thyroid-stimulating hormone (TSH)**, or **thyrotropin**, which stimulates production and release of hormones from the thyroid gland
- **adrenocorticotropic hormone (ACTH)**, or **adrenocorticotropin**, which controls production and release of some of the hormones from the cortex of the adrenal glands.
- **prolactin (PRL)**, or **lactogenic hormone**, which works with other hormones to initiate and maintain milk secretion in females.

Posterior lobe of the pituitary

The posterior lobe of the pituitary (the neurohypophysis) releases the hormones oxytocin and antidiuretic hormone, but neither is manufactured in the posterior lobe. Both hormones are produced in special nerve cells in the hypothalamus of the brain. These cells have long extensions that pass through the infundibulum to the posterior lobe. Hormones manufactured in the cells move down the extensions and are stored ready for release into the bloodstream. The release of the hormones is triggered by nerve impulses initiated in the hypothalamus and conducted along the cell extensions (Figure 2.4, page 26).

Oxytocin (OT) stimulates contraction of the muscles of the uterus. It is released in large quantities during labour. Oxytocin also stimulates contraction of cells in the mammary glands, resulting in release of milk during breastfeeding.

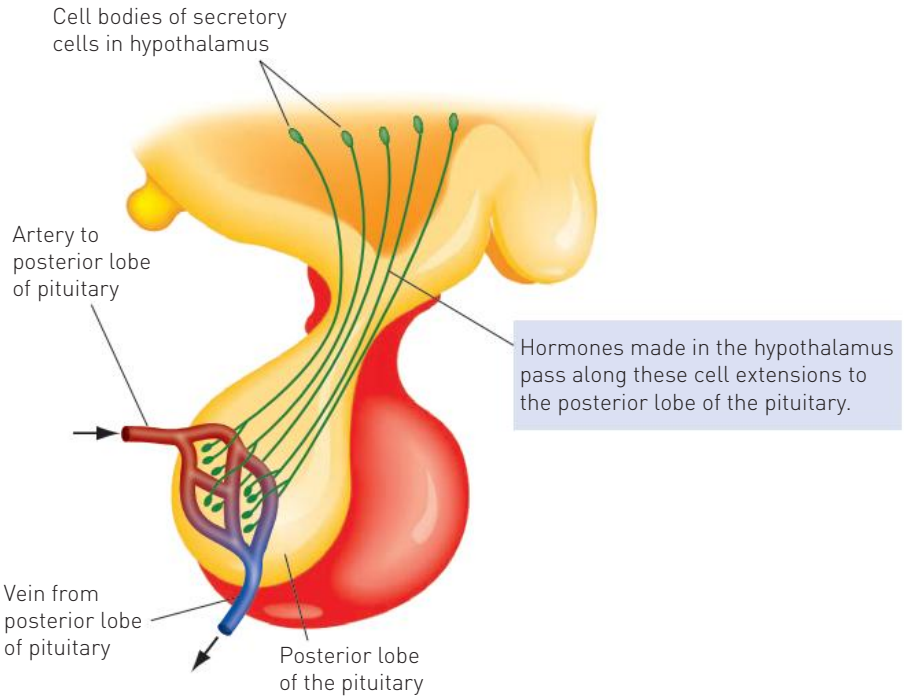


Figure 2.4 Hormones made in the hypothalamus are transported to the posterior lobe of the pituitary and can then be released into the bloodstream.

Antidiuretic hormone (ADH), or **vasopressin**, causes the kidneys to remove water from urine that is forming. This water is returned to the bloodstream. In this way, ADH helps to retain fluid within the body. At higher concentrations, ADH can also cause constriction of small arteries, the arterioles (giving rise to the alternative name, vasopressin).

Table 2.1 Hormones released by the pituitary gland

Hormone	Target organ	Main effects
Anterior lobe of the pituitary		
Follicle-stimulating hormone (FSH)	Ovaries (females) Testes (males)	Growth of follicles Production of sperm
Luteinising hormone (LH)	Ovaries (females) Testes (males)	Ovulation and maintenance of corpus luteum Secretion of testosterone
Growth hormone (GH)	All cells	Growth and protein synthesis
Thyroid-stimulating hormone (TSH)	Thyroid gland	Secretion of hormones from the thyroid
Adrenocorticotropic hormone (ACTH)	Adrenal cortex	Secretion of hormones from the adrenal cortex
Prolactin (PRL)	Mammary glands	Milk production
Posterior lobe of the pituitary		
Antidiuretic hormone (ADH)	Kidneys	Reabsorption of water
Oxytocin (OT)	Uterus Mammary glands	Contractions of uterus during childbirth Release of milk

The pineal gland

The **pineal gland** is found deep inside the brain and in children is about the size of a pea. After puberty it gradually decreases in size. Its role remains something of a mystery but it is known that it secretes the hormone **melatonin**, which is involved in the regulation of sleep patterns. Production of melatonin by the pineal gland is stimulated by darkness and inhibited by light.

EXTENSION

The French philosopher René Descartes (1596–1650) described the pineal gland as the 'seat of the soul'. Science cannot investigate beliefs such as the presence of a soul, but the role of the pineal gland has still not been defined and it continues to intrigue scientists.

Find out:

- the names of hormones secreted by the pineal gland
- some of the hypotheses that have been proposed for the function of the pineal gland
- the evidence on which these hypotheses have been based.

The thyroid gland

The **thyroid gland** is located in the neck, just below the larynx. It consists of two lobes that lie on either side of the trachea and are joined by a narrow piece of tissue that lies across the front of the trachea (Figures 2.5 and 2.6).

The main hormone secreted by this gland is **thyroxine**. It is made from iodine and an amino acid, and is continuously manufactured in the thyroid gland. Thyroxine controls body metabolism by regulating reactions in which complex molecules are broken down to release energy, and other reactions in which complex molecules are synthesised from simple ones. The overall effect of thyroxine is to bring about the release of energy and, because some of the energy released is in the form of heat, to maintain body temperature.

Thyroxine is secreted in response to thyroid-stimulating hormone from the anterior lobe of the pituitary.

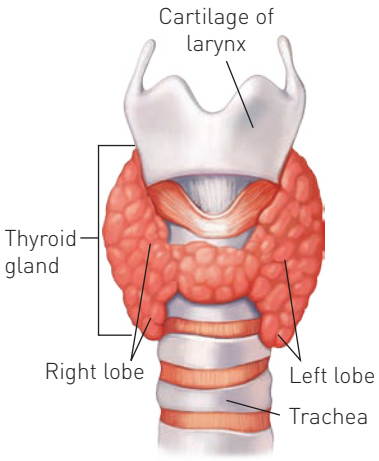
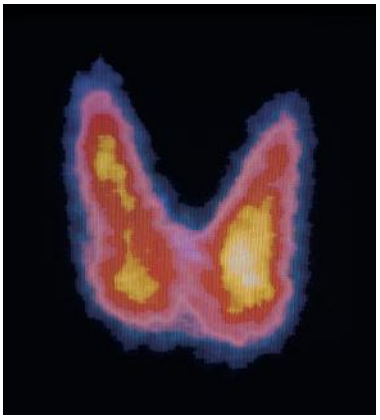


Figure 2.5 The location of the thyroid gland



Getty Images/Chris Priest/SPL

Figure 2.6 A scan of the thyroid gland, an endocrine gland in the neck. A radioactive tracer has been used to show the most active areas of the gland. These areas appear as yellow patches on the scan.

The parathyroid glands

There are usually four **parathyroid glands**, although some people have more. Each is about the size of a small pea and they are embedded in the rear surface of the lobes of the thyroid gland (Figure 2.7).

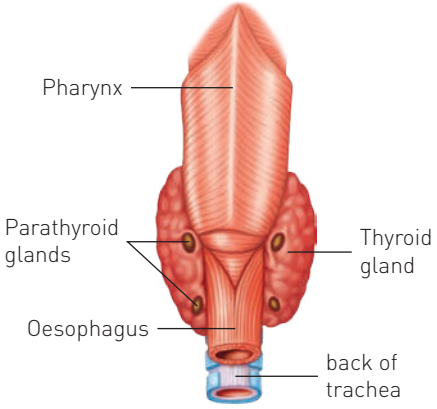


Figure 2.7 The location of the parathyroid glands (as seen from the rear of the body)

The parathyroid glands secrete **parathyroid hormone** (**PTH**, or **parathormone**), which controls calcium and phosphate levels in the blood (Figure 2.8).

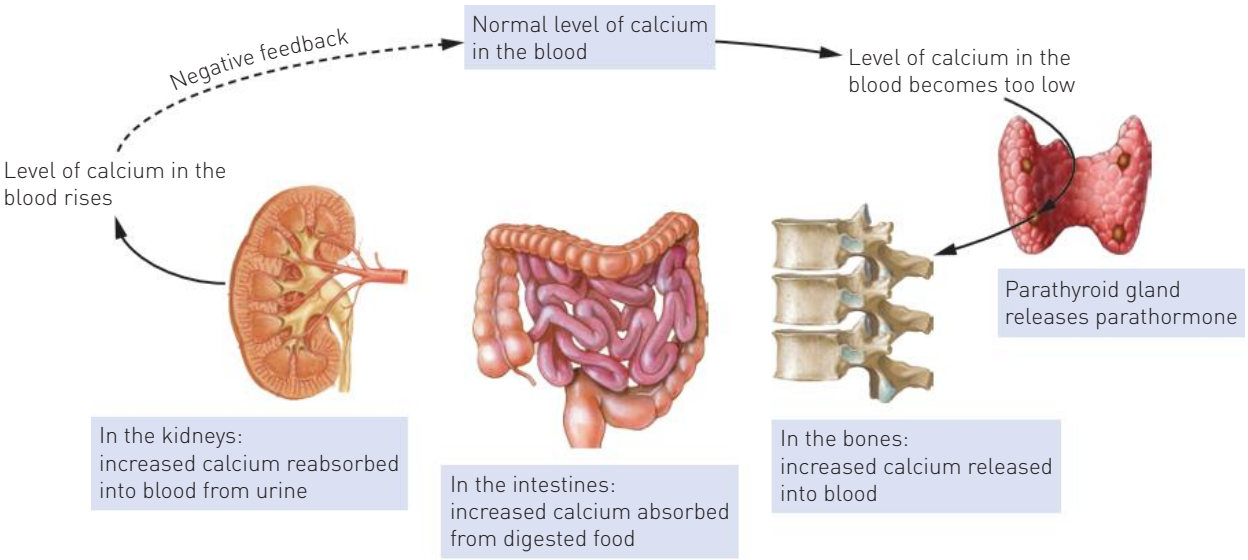


Figure 2.8 Regulation of blood calcium level by parathyroid hormone is a good example of negative feedback.

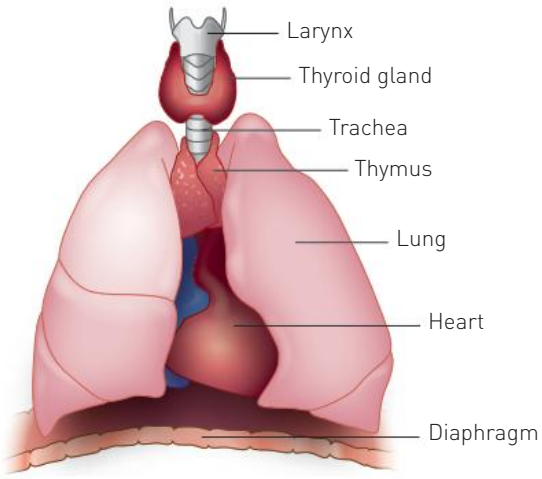


Figure 2.9 The location of the thymus

The thymus

The **thymus** is located in the chest just above the heart and just behind the sternum (breastbone) (Figure 2.9). Like the pineal gland, the thymus is largest in infants and children, and begins to shrink after puberty. The thymus secretes a group of hormones called **thymosins**. These hormones influence the maturation of disease-fighting cells called T lymphocytes. The role of T lymphocytes will be discussed in Chapter 11.

EXTENSION

In an average person the thymus weighs about 35 g just before puberty but by age 50 it has shrunk to around 12 g and by 75 to about 6 g. It has been suggested that this decline in size may be responsible for elderly people becoming more susceptible to disease.

Research the thymus and find out:

- how the role of the thymus was discovered
- the role of the thymus in providing defence against disease.

The adrenal glands

There are two **adrenal glands**, one immediately above each kidney, as shown in Figure 2.10. Each adrenal gland has an inner **adrenal medulla** and an outer **adrenal cortex**. These two parts are quite different in their structure and function. Thus, each adrenal gland is really two separate endocrine glands.

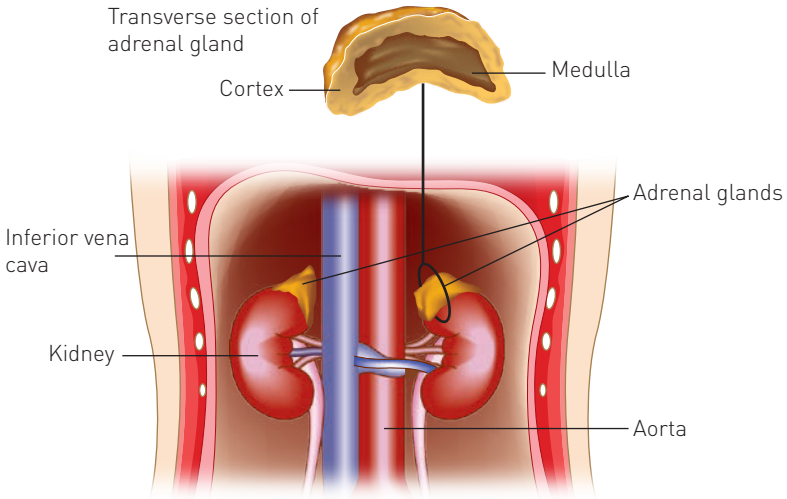


Figure 2.10 The location of the adrenal glands

Adrenal medulla

The hormones produced by the adrenal medulla are adrenaline and noradrenaline.

- **Adrenaline**, also called **epinephrine**, has an effect similar to that of the sympathetic division of the autonomic nervous system (Chapter 4). Adrenaline helps to prepare the body for reaction to a threatening situation; that is, it is concerned with fight-or-flight responses. These responses will be discussed in more detail in Chapter 4.
- **Noradrenaline**, also called **norepinephrine**, has effects similar to those of adrenaline. In particular, it increases the rate and force of the heartbeat.

Adrenal cortex

More than 20 different hormones are produced in the adrenal cortex and they are known collectively as **corticosteroids**. The two main ones are:

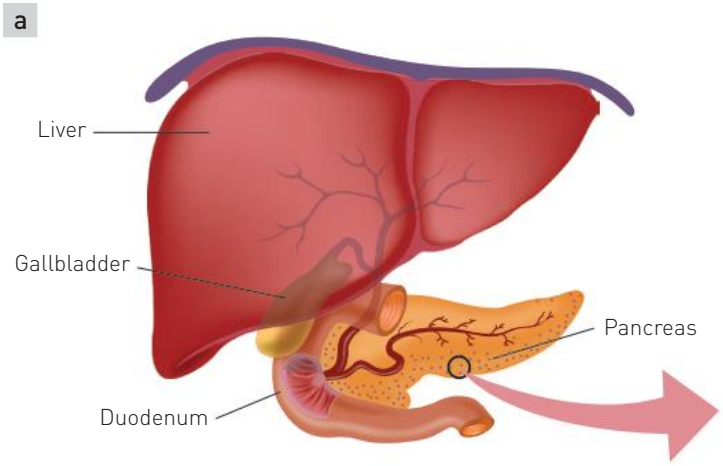
- **aldosterone**, which acts on the kidney to reduce the amount of sodium and increase the amount of potassium in the urine
- **cortisol**, which, with related hormones, promotes normal metabolism, helping the body to withstand stress, and also helps with repair of damaged tissues.

The pancreas

The **pancreas** lies just below the stomach and alongside the duodenum, the first part of the small intestine (see Figure 2.11a, page 30). It is both an exocrine gland and an endocrine gland. The exocrine part secretes digestive enzymes into the small intestine through the pancreatic duct. Within the pancreas are clusters of special cells called **islets of Langerhans** (also called **pancreatic islets**). The islets are the endocrine part of the pancreas (see Figure 2.11b, page 30). They secrete two important hormones.

- **Insulin** reduces the amount of glucose in the blood – that is, the blood sugar level. It does this by promoting the uptake of glucose from the blood by the cells of the body. In the liver, insulin causes the conversion of glucose to glycogen and fat; in skeletal muscles, it causes formation of glycogen from glucose; and in fat storage tissue, it causes glucose to be converted into fat. The level of secretion of insulin by the pancreas is determined by the amount of sugar in the blood and is controlled through a negative feedback system (see Figure 6.4 on page 76).
- **Glucagon** acts in the opposite way to insulin. It works to increase the blood sugar level, mainly by promoting the breakdown of glycogen to glucose in the liver. Glucagon also stimulates the breakdown of fat in the liver and in fat storage tissues.

The roles of insulin and glucagon in maintaining a constant level of glucose in the blood will be discussed in more detail in Chapter 8.



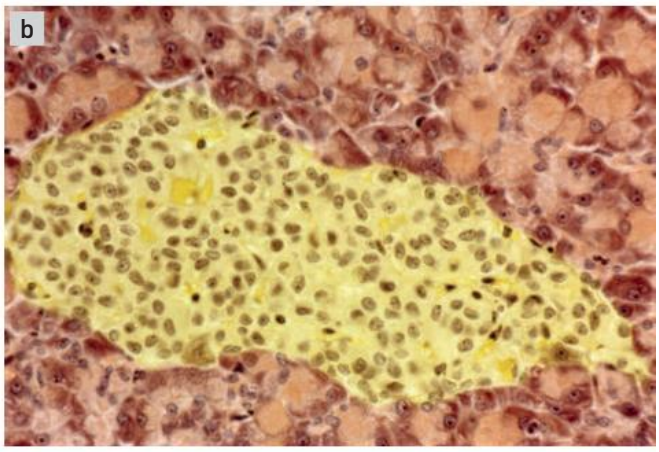


Figure 2.11 a The location of the pancreas **b** A micrograph of an islet of Langerhans within the pancreas

The gonads

The **gonads** are the testes and the ovaries. They produce hormones as well as sperm and eggs.

- **Androgens** are the male sex hormones produced by the testes. These hormones are responsible for the development and maintenance of the male sex characteristics.
- **Oestrogens** and **progesterone** are the female sex hormones produced by the ovaries. They stimulate the development and maintenance of the female sexual characteristics. Together with the gonadotropic hormones of the pituitary, they also regulate the menstrual cycle and are involved in changes that occur during pregnancy.

Other endocrine tissues

In addition to the major endocrine glands discussed above, there are other tissues, many of which are not called endocrine glands, that secrete hormones. Some of these are:

- the **stomach** and **small intestine**, which both secrete hormones that coordinate the exocrine glands of the digestive system
- the **kidneys**, which secrete hormones including **erythropoietin (EPO)**, a hormone that stimulates production of red blood cells by the bone marrow
- the **heart**, which secretes a hormone that helps to reduce blood pressure
- the **placenta**, which secretes a number of hormones during pregnancy that help to maintain the pregnancy, stimulate development of the foetus and stimulate the mother's mammary glands.

Major endocrine glands
This website provides further discussion of the major endocrine glands.

EXTENSION

New hormones are still being identified. One well-known example is the hormone leptin, discovered in 1994 through the study of obese mice. Leptin is secreted by fat storage tissues (adipose tissues).

Find out:

- how leptin was discovered
- the target cells for leptin
- the effect of the hormone.

Table 2.2 Hormones produced by endocrine glands other than the pituitary

Gland	Hormone	Target cells	Main effects
Thyroid	Thyroxine	Most cells	Increases metabolic rate and therefore oxygen consumption and heat production
Parathyroids	Parathyroid hormone	Bones Kidneys	Increases level of calcium in blood
Thymus	Thymosins	T lymphocytes	Stimulates development and maturation of T lymphocytes
Adrenal cortex	Corticosteroids, including:		
	Aldosterone	Kidney	Increases reabsorption of sodium ions and excretion of potassium ions
	Cortisol	Most cells	Promotes normal metabolism; helps the body deal with stress; promotes repair of damaged tissues
Adrenal medulla	Adrenaline and noradrenaline	Most tissues	Prepares the body for fight-or-flight responses; reinforces the effects of the sympathetic nervous system
Pancreas	Insulin	Most cells	Stimulates uptake of glucose; lowers blood glucose level
	Glucagon	Liver and fat storage tissues	Stimulates breakdown of glycogen and fat; increases blood glucose level
Testes	Androgens	Many tissues	Stimulate sperm production; growth of skeleton and muscles; male sexual characteristics
Ovaries	Oestrogens	Many tissues	Stimulate development of female characteristics; regulate the menstrual cycle
	Progesterone	Uterus and mammary glands	Regulates menstrual cycle and pregnancy; prepares mammary glands for milk secretion

Science inquiry

ACTIVITY 2.1 Endocrine dysfunction

Many disorders can be caused by oversecretion or undersecretion of one or more of the endocrine glands. Some hormonal problems are listed below.

Acromegaly	Gigantism
Addison's disease	Goitre
Androgen insensitivity syndrome	Graves' disease
Cushing's syndrome	Myxoedema
Exophthalmia	Phaeochromocytoma

Select one of these hormonal problems (or your teacher may assign one for you) and use references to find out:

- the cause of the problem – that is, the endocrine gland and hormone involved
- the symptoms of the disorder
- whether the disorder is caused by oversecretion or undersecretion of the hormone
- the treatment that is available for the disorder.

Write a brief report on the disorder that you chose. The report should be in a format that could be presented to the rest of your class.

ACTIVITY 2.2 The discovery of insulin

Insulin, a hormone secreted by the islets of Langerhans in the pancreas, was discovered in 1921–22 by researchers at the University of Toronto in Canada. The discovery is recognised as one of the greatest medical breakthroughs of all time.

1. Use the Internet to research the story of insulin's discovery. There are websites with biographies of the four researchers involved – Frederick Banting, Charles Best, J. J. R. Macleod and James Collip – and descriptions of the methods used to isolate insulin.
   Research into insulin continues to the present day. In the 1950s the full sequence of amino acids in the insulin molecule was determined, and in 1969 scientists worked out its three-dimensional structure.
2. In 2006 a research team at the CSIRO in Australia made another important discovery in the quest for a full understanding of how insulin works. Find out what the discovery was and its implications for the understanding of insulin.

Review questions

1 **a** What is a feedback system?
b Define 'negative feedback'.
2 Explain the difference between endocrine and exocrine glands and give five examples of each.
3 **a** What is a hormone?
b Explain the difference between a hormone and a paracrine.
4 Explain how hormones change the functioning of cells.
5 Hormones that are steroids work in a different way from those that are proteins or amines. Explain the difference.
6 Describe 'enzyme amplification'.
7 The hypothalamus and the pituitary gland are closely related. Describe their relationship in terms of:
a their location in the body
b the ways in which they function.
8 The pituitary gland is sometimes described as the 'master gland' because it secretes hormones that regulate the activity of other endocrine glands. Describe the pituitary hormones that are involved in the control of other endocrine glands.
9 Hormones secreted by the posterior lobe of the pituitary are not actually made in the posterior lobe. Describe the origin of these hormones and explain how they get to the posterior lobe of the pituitary gland.
10 **a** What is a target organ?
b How do hormones get from their source to the target organ?
c Describe target organ/cells and the role of the following hormones.
i Oxytocin
ii Antidiuretic hormone
iii Adrenaline
iv Parathyroid hormone
v Insulin
vi Glucagon
vii Thyroxine
11 **a** Which gland produces thymosins and what is the function of these hormones?
b Which gland secretes melatonin? What is the role of melatonin?

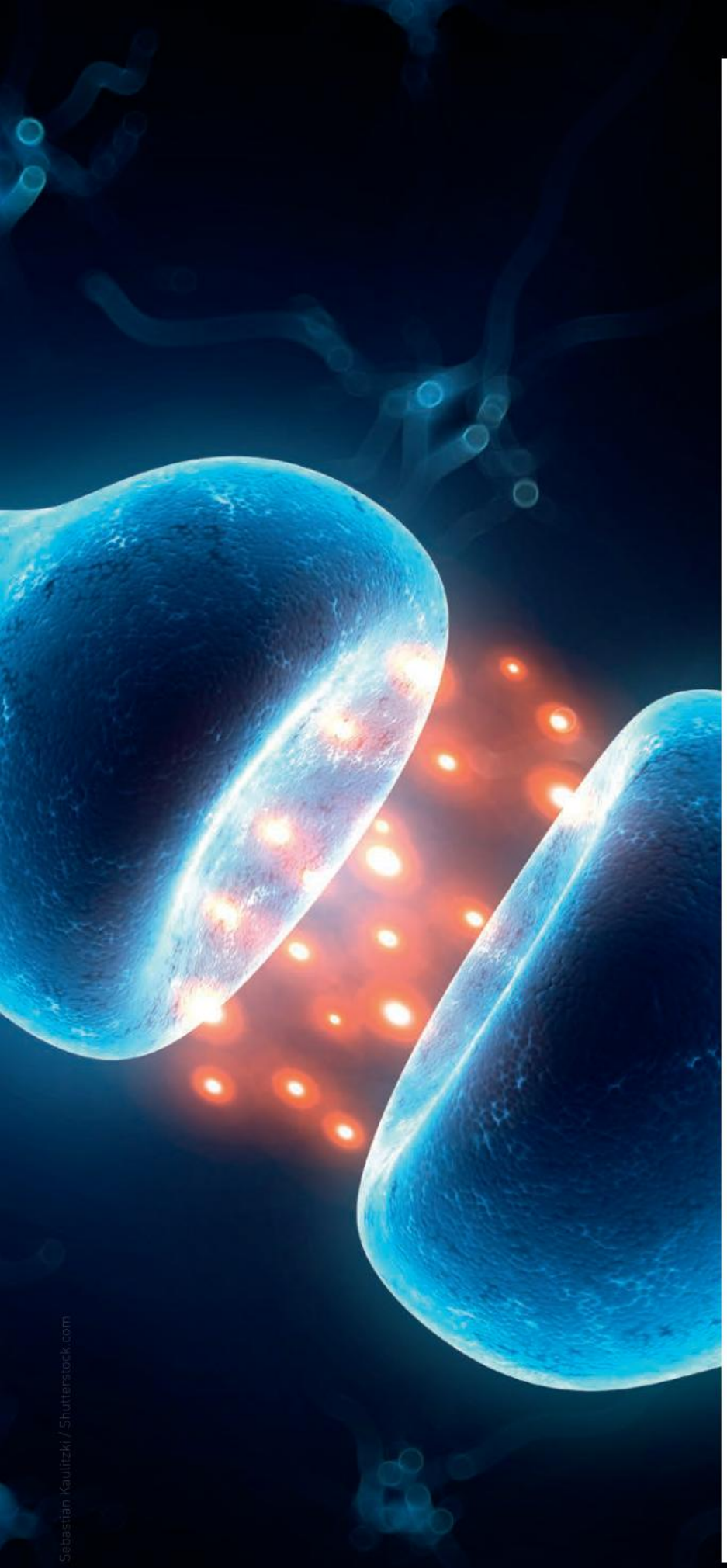
Apply your knowledge

1 Explain why endocrine glands are sometimes called ductless glands or glands of internal secretion.
2 Hormones are specific. What does this mean and how is specificity achieved?
3 Hormones affect the activity of their target cells. Explain why the addition of more and more hormone does not continue to increase the intensity or rate of the response.
4 Athletes have sometimes taken (illegally) the hormone erythropoietin in an effort to improve their performance. In what ways would this hormone improve sporting performance?
5 Many famous people have suffered from endocrine disorders.
a John F. Kennedy, President of the United States from 1960 until his assassination in 1963, suffered from Addison's disease. Consult references to see if you can find out some of Kennedy's medical history. How was he able to be President of the United States despite having such a serious illness?
b Napoleon Bonaparte is believed to have suffered from a disease of the hypothalamus that caused the pituitary gland to function abnormally. Because the anterior pituitary regulates the functioning of the gonads and the adrenal and thyroid glands, these organs were also affected. See if you can find out the symptoms of Napoleon's disorder.

c Akhenaton, an Egyptian pharaoh who lived 3500 years ago, is portrayed in statues made later in his life with feminine features – prominent breasts, hips wider than the shoulders, and a large amount of fat on the buttocks and thighs. It has been suggested that Akhenaton may have been afflicted with a disorder of one of the endocrine glands. Which gland, or glands, could it have been and what hormones could have been involved?

6 Construct a diagram similar to Figure 2.8 on page 28 using the hormone ADH and its role in water balance as the example. Be sure to include the role of feedback in your diagram.

7 Thyroid-stimulating hormone (TSH) is secreted by the anterior lobe of the pituitary gland. If a cancer patient had their thyroid gland removed, would you expect the level of TSH in the person's blood to rise or fall? Explain your answer.



Sebastian Kaulitzki / Shutterstock.com

CHAPTER

03

NERVE CELLS AND NERVE IMPULSES

UNIT 3 CONTENT

SCIENCE INQUIRY SKILLS

- select, use and/or construct appropriate representations, including diagrams, models and flow charts, to communicate conceptual understanding, solve problems and make predictions

SCIENCE UNDERSTANDING

Central and peripheral nervous system

- the reflex arc comprises of specially structured neurons, including sensory, interneuron and motor neurons, to transmit information from the receptor to the effector to respond rapidly to stimuli
- transmission of nerve impulses is via electro-chemical changes that occur at the generation of the impulse, the propagation of the impulse along the nerve fibre, and the transfer of the impulse across the synapse

The trillions of cells that make up the human body all work together in an integrated and coordinated way. To achieve integration and coordination, cells must communicate with one another. The **nervous system** is the communication network and control centre of the body. It is also involved in maintaining a constant environment inside the body, a task it shares with the **endocrine system** (see Chapter 2).

The nervous system can be divided into two main parts: the central nervous system and the peripheral nervous system. Although these two parts are themselves called 'nervous systems', they are in fact both part of the one nervous system.

The **central nervous system (CNS)** consists of the brain and spinal cord. It is the control centre for the whole nervous system. The nerves that connect the central nervous system with the receptors, muscles and glands make up the **peripheral nervous system (PNS)**. In this chapter we will discuss the specialised cells that make up both the central and peripheral nervous systems and the way in which those cells transmit information.

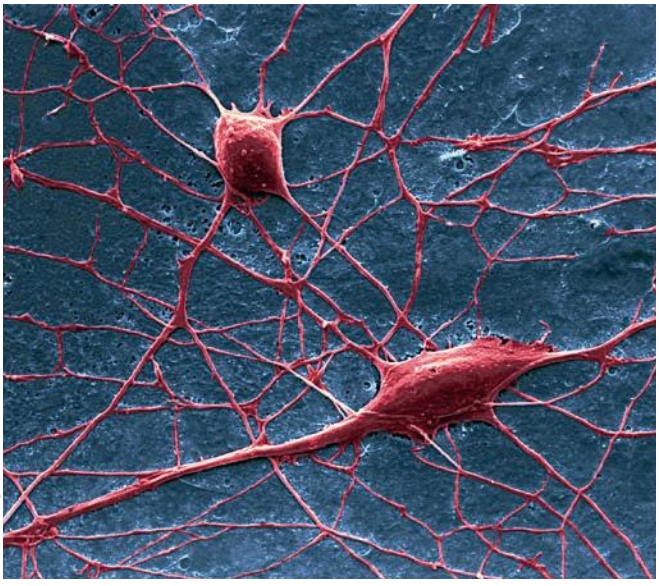
Nerve cells

Nerve cells, or **neurons**, are the basic structural and functional units of the whole nervous system. Neurons vary in size and shape, but they all consist of a cell body and two different types of extension from the cell – the dendrites and the axon (Figures 3.1 and 3.2).

Most of the neurons in the brain and many in the spinal cord are **interneurons** (also called **connector neurons** or **association neurons**), as shown in Figure 3.3. They have many branches that are able to send or receive messages to or from adjacent neurons.

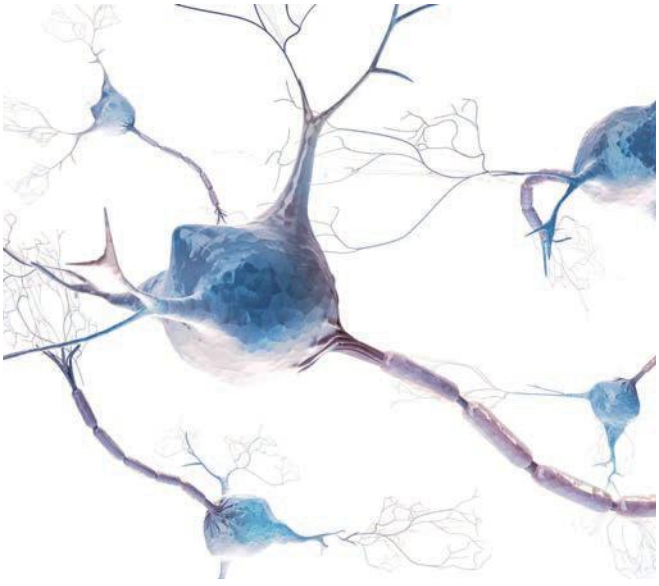
The **cell body** is the part of the neuron that contains the nucleus. Around the nucleus is cytoplasm containing the organelles that are found in most cells – mitochondria, endoplasmic reticulum, ribosomes and Golgi apparatus.

Dendrites are usually fairly short extensions of the cytoplasm of the cell body. They are often highly branched and they carry messages, or **nerve impulses**, into the cell body. The **axon** is often a single, long extension of the cytoplasm. It usually carries nerve impulses away from the cell body. Although usually longer than the dendrites, the length of axons varies enormously. Those in the brain may be only a few millimetres long, while the axons that run from the spinal cord to the foot may be a metre or so in length. Most axons are covered with a layer of fatty material



Getty Images/Science Photo Library

Figure 3.1 A coloured scanning electron micrograph of two nerve cells from the brain. The cell bodies can be clearly seen with many extensions, called dendrites, branching from them.



Andrii Muzyka / Shutterstock.com

Figure 3.2 Nerve cells showing cell body, dendrites and axon

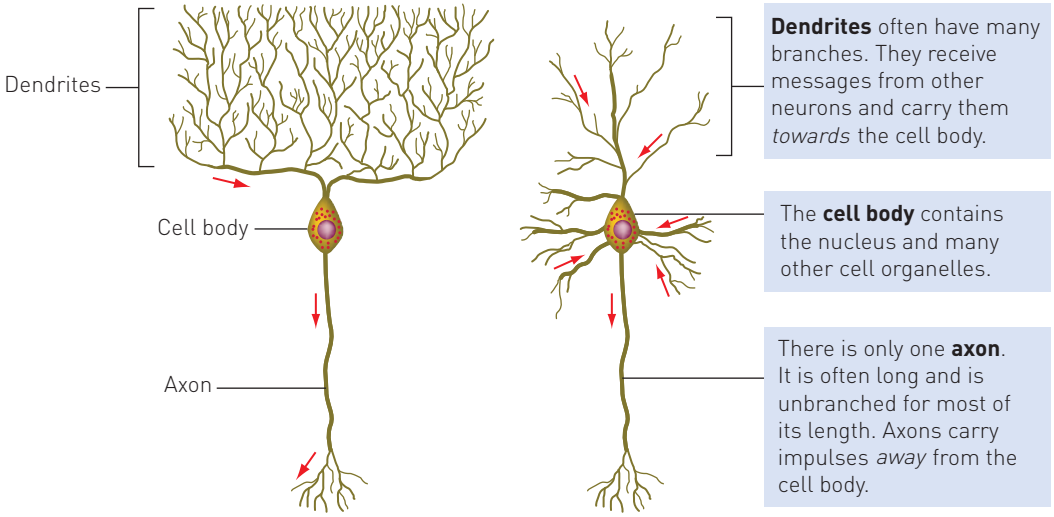


Figure 3.3 Interneurons. The arrows show the direction in which nerve impulses travel.

called the **myelin sheath**. The term **nerve fibre** is used for any long extension of a nerve cell, but usually refers to an axon. Those that have a myelin sheath are called **myelinated fibres** and those that don't are said to be **unmyelinated**.

When parts of the central nervous system of a mammal are cut open, they are seen to consist of some areas that are greyish in colour and others that are white. The grey areas, known as **grey matter**, consist of nerve cell bodies and unmyelinated fibres. The white areas, or **white matter**, are composed of myelinated fibres (the lipid myelin that covers these fibres is white).

Outside the brain and spinal cord the myelin sheath is formed by special cells called **Schwann cells**, which wrap around the axon. At intervals along the axon are gaps in the myelin sheath, called **nodes of Ranvier**. The sheath has three important functions: it acts as an insulator; it protects the axon from damage; and it speeds up the movement of nerve impulses along the axon. Around the myelin sheath the outermost coil of the Schwann cell forms a structure called the **neurilemma**, which helps in the repair of injured fibres (see Figure 3.4, and Figure 3.5 on page 38).

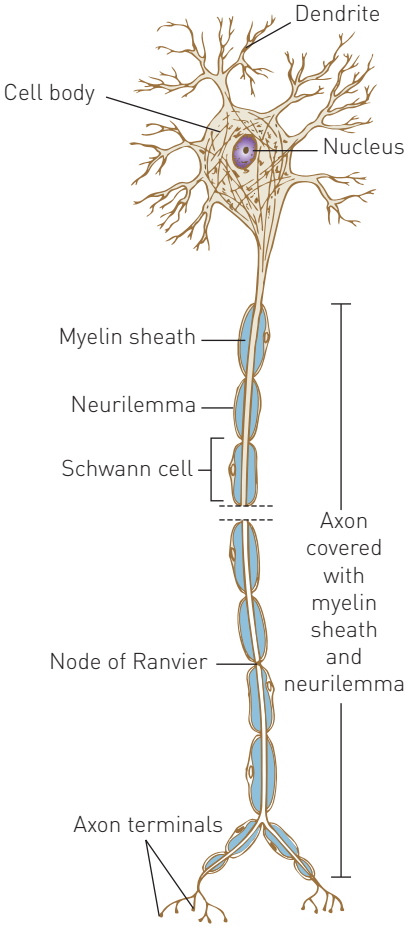


Figure 3.4 Structure of a typical neuron with a myelinated axon

Types of neurons

Functional types

Neurons may be classified into three types depending on the *function* each performs.

- **Sensory** (or **receptor**) **neurons** carry messages from receptors in the sense organs, or in the skin, to the central nervous system (brain and spinal cord).
- **Motor** (or **effector**) **neurons** carry messages from the central nervous system to the muscles and glands – the effectors. A typical motor neuron is shown in Figure 3.4.
- Interneurons are located in the central nervous system and are the link between the sensory and motor neurons. Interneurons may also be called association neurons, connector neurons or **relay neurons**. Typical examples can be seen in Figure 3.3.

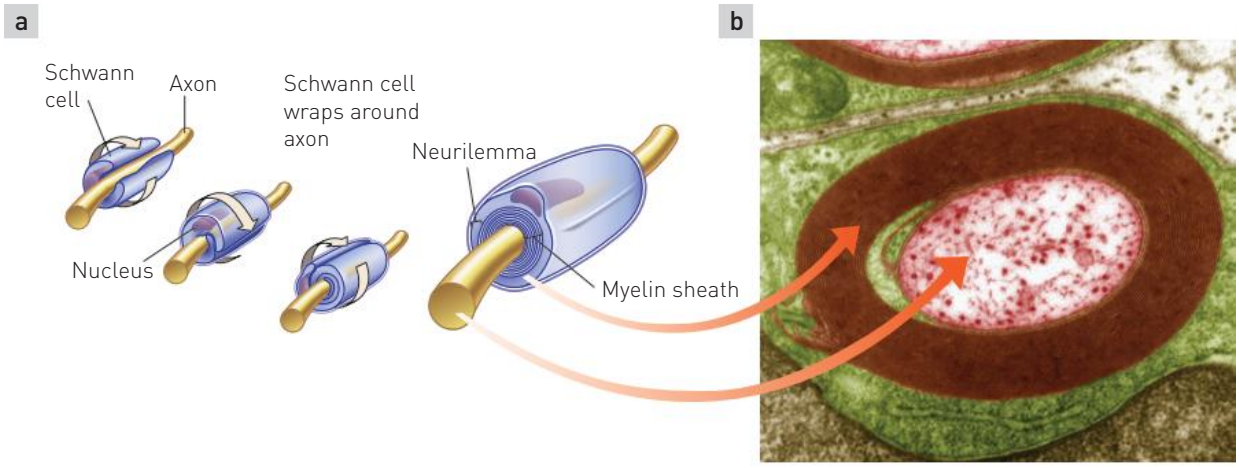


Figure 3.5 a Schwann cells form the sheath of a myelinated axon by wrapping around the axon. **b** Coloured transmission electron micrograph of a transverse section of a myelinated axon. The myelin sheath (brown) is formed when Schwann cells wrap around the axon and deposit layers of myelin between each coil. The outermost layer (green) is the cytoplasm of the Schwann cell – the neurilemma.

Structural types

Another way of classifying neurons is by their *structure*. This classification is based on the number of extensions from the cell body (see Figure 3.6).

- **Multipolar neurons** have one axon and multiple dendrites extending from the cell body. This type of neuron is the most common, and includes most of the interneurons in the brain and spinal cord and also the motor neurons that carry messages to the skeletal muscles.
- **Bipolar neurons** have one axon and one dendrite. Both axon and dendrite may have many branches at their ends. Bipolar neurons occur in the eye, ear and nose, where they take impulses from the receptor cells to other neurons.
- **Unipolar neurons** have just one extension, an axon. The cell body is to one side of the axon. Most sensory neurons that carry messages to the spinal cord are of this type.

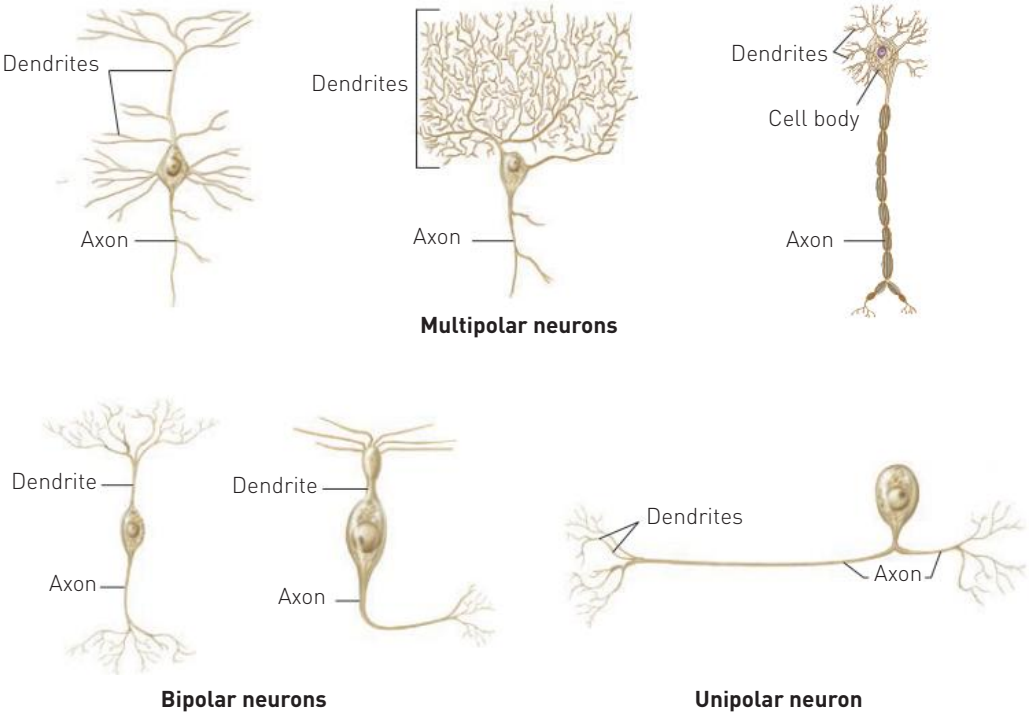


Figure 3.6 The structure of different types of neurons

As mentioned, the axons and dendrites of nerve cells are known collectively as nerve fibres. Outside the central nervous system, nerve fibres are arranged into bundles called **nerves**. In a nerve the fibres are held together by sheaths of connective tissue.

Table 3.1 The difference between neurons, nerve fibres and nerves

Neuron	A nerve cell
Nerve fibre	Any long extension of cytoplasm of a nerve cell body, although the term usually refers to an axon
Nerve	A bundle of nerve fibres held together by connective tissue

Synapses

Nerve impulses have to be passed from neuron to neuron. The junction between the branches of adjacent neurons is called the **synapse**. At the synapse the neurons do not actually join – there is a very small gap between them. Most synapses occur between the end branches of an axon of one neuron and a dendrite or the cell body of another neuron (Figure 3.7). Messages have to be carried across the synapse.

A similar synapse exists where an axon meets a skeletal muscle cell. This tiny gap is called the **neuromuscular junction**.

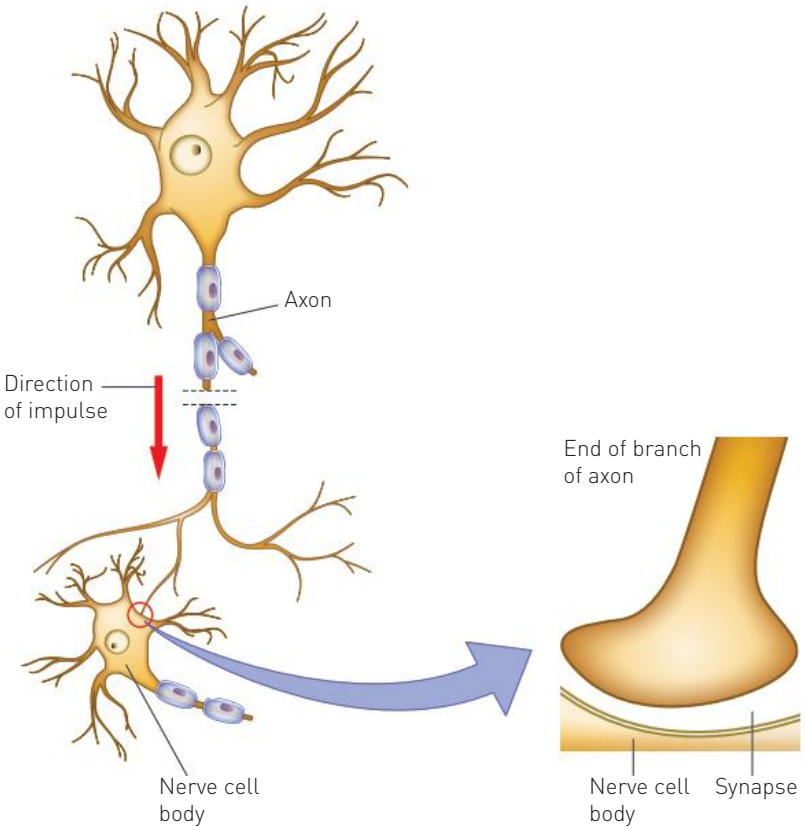


Figure 3.7 A synapse is a small gap between one neuron and the next.

Nerve impulses

The message that travels along a nerve fibre is called a **nerve impulse**. Nerve impulses are transmitted very quickly, making it possible for the body to respond rapidly to any change in the internal or external environment.

A nerve impulse is an **electrochemical change** that travels along a nerve fibre. It is described as electrochemical because it involves a change in electrical voltage that is brought about by changes in the concentration of ions inside and outside the cell membrane of the neuron.

Although all nerve impulses travel quickly, there is a lot of variation in speed of transmission. The speed at which an impulse travels depends on whether the nerve fibre is myelinated or unmyelinated and also on the diameter of the fibre. In unmyelinated fibres the impulse travels steadily along the fibre. The maximum speed of this type of transmission is 2 m/s, which is equivalent to about 7 km/h.

In myelinated fibres the myelin sheath is not continuous. It is punctuated by the gaps called the nodes of Ranvier. The nerve impulses jump from one node to the next. This jumping conduction, known as **saltatory conduction**, allows the nerve impulse to travel much faster. Depending on the diameter of the fibre, impulses can travel at speeds from 18 m/s (65 km/h) up to 140 m/s (500 km/h).

When you consider the short distances involved, some responses are almost instantaneous. Blinking when something is coming towards the eye is an example. The eye senses the approaching object, sends a message to the brain, which then sends a message to the muscles of the eyelid. The distance travelled is very small and the response, therefore, very rapid.

The nature of a nerve impulse – an action potential

Sending messages in the form of nerve impulses is the quickest way the body has of responding to changes in the internal and external environment. To understand the nature of a nerve impulse we must first understand some basic electrical concepts. Many of these you will recall from other science courses you have done.

There are two types of electrical charges: positive and negative. Two positive or two negative charges *repel* each other. A positive and a negative charge *attract* each other. That is, like charges repel and unlike charges attract.

When unlike charges are separated, an electrical force tends to pull them together. The force that pulls unlike charges together can be measured and its strength increases as the charges get closer. When positive and negative charges come together, energy is released. If a group of positive and negative charges are separated they have the potential to come together and release energy. The **potential**, or potential difference, between two places can be measured. It is called the voltage and is measured in volts (V) or millivolts (mV) (1000 mV = 1V).

What do these electrical charges have to do with nerve impulses and nerve cells? When some chemical substances are dissolved in water, they break up into electrically charged particles called ions. This happens to some of the substances dissolved in the fluid around and inside cells.

Extracellular fluid (outside the cell) contains a high concentration of sodium chloride, and so most of its charged particles are positive sodium ions (Na^+) and negative chloride ions (Cl^-). In the intracellular fluid (inside the cell) these ions are in very low concentration. Here the main positive ions are potassium (K^+) and the negative ions come from a variety of organic substances made by the cell. Thus, if there were a difference between the concentration of ions inside and outside a cell, there would be a potential between the inside and the outside of the cell membrane. This occurs in all body cells: there is a difference in the ion concentration on either side of the cell membrane.

The potential difference created is called the **membrane potential** and it is particularly large in nerve and muscle cells. The membrane potential of unstimulated nerve cells, known as the **resting membrane potential**, can be measured and is about –70 mV. This means that the potential of the inside of the membrane is 70 mV less than that of the outside.

The resting membrane potential of neurons is due mainly to differences in the distribution of potassium ions (K^+) and sodium ions (Na^+) on either side of the cell membrane. The concentration of sodium ions is about 10 times higher outside the neuron than within, and that of potassium ions is about 30 times greater inside the neuron than outside. The cell membrane is highly permeable to potassium and chloride ions, only slightly permeable to sodium ions and impermeable to the large negatively charged organic ions.

There is a tendency for potassium ions to diffuse out of the cell, resulting in the inside of the cell becoming electrically negative. The cell membrane maintains this potential difference in two ways. First, it actively moves ions across the membrane. This activity is described as a **sodium–potassium pump** and it transports sodium ions out of the cell and potassium ions in. Second, the cell membrane is not equally permeable to all ions and there are large numbers of negatively charged ions trapped inside the cell. Although sodium and potassium ions are both positively charged, there are not enough potassium ions inside the cell to counteract the effect of the large number of negative ions. Thus, the membrane is maintained so that the inside is negative in relation to the outside. In this state the membrane is said to be **polarised** (Figure 3.8).

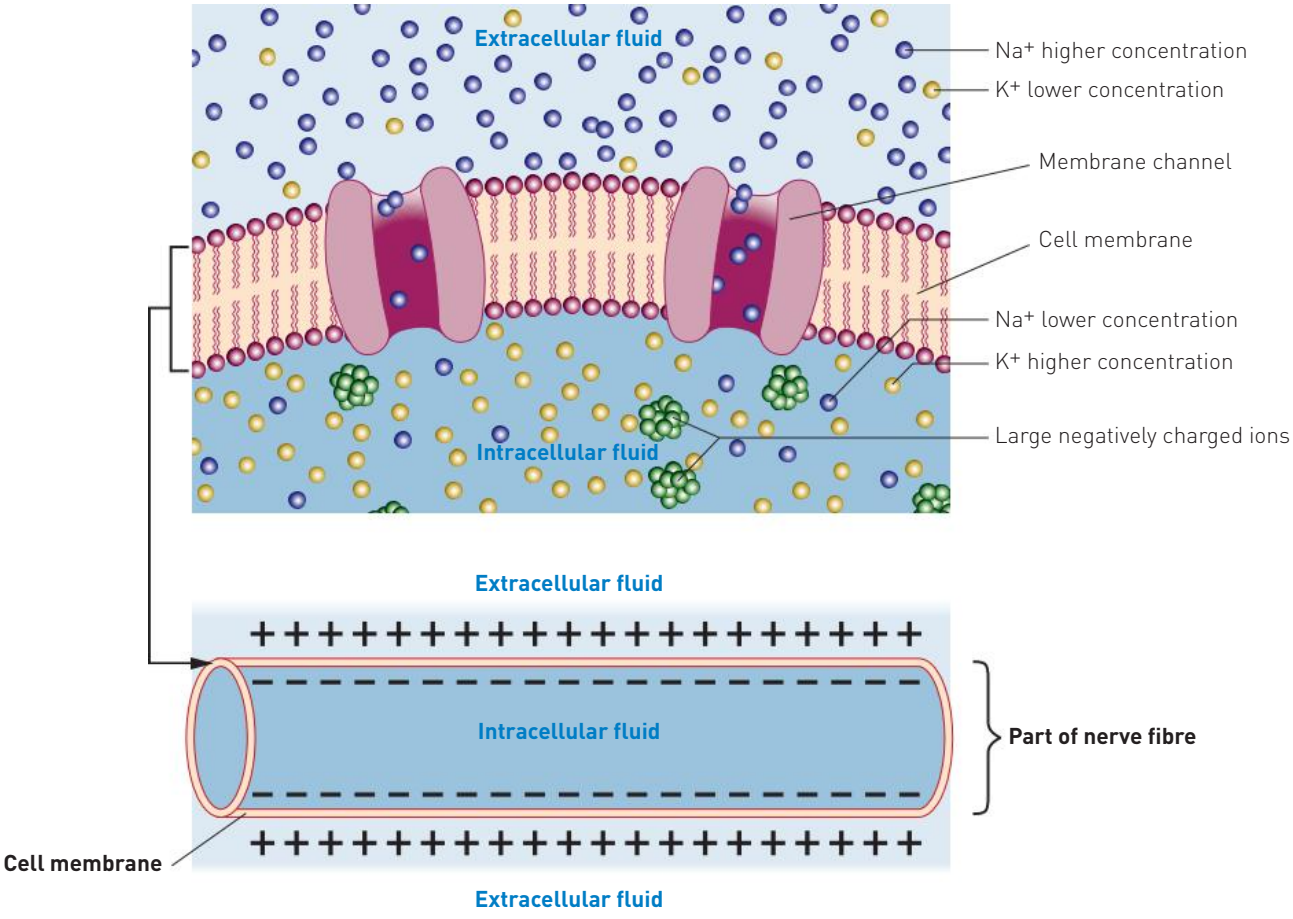


Figure 3.8 Sodium ions are much more concentrated outside the cell than inside, while the reverse is true for potassium ions. Large negatively charged ions that are unable to pass through the cell membrane give the inside of the cell a negative charge.

If a sufficiently strong stimulus is applied to a nerve fibre, the membrane becomes more permeable to sodium ions and so sodium ions move across the membrane and into the cell. This inward movement is too great to be balanced by an outward movement of potassium ions and the membrane becomes **depolarised**. Depolarisation occurs only if the level of stimulation exceeds a certain threshold. If the stimulus is strong enough to cause a change of about 15 mV, then the movement of sodium ions proceeds independently of the stimulus; that is, the size of the response is not related to the strength of the stimulus. This is known as an **all-or-none response**.

Because of the movement of sodium ions, the original polarity of the membrane decreases to zero and then the inside actually becomes positive relative to the outside. Almost as quickly, the membrane is restored to its original condition. This rapid depolarisation and repolarisation of the membrane is called an **action potential** and involves a change in the membrane voltage lasting only 1 millisecond (ms) (Figure 3.9). The movement of the action potential along a nerve fibre is the nerve impulse.

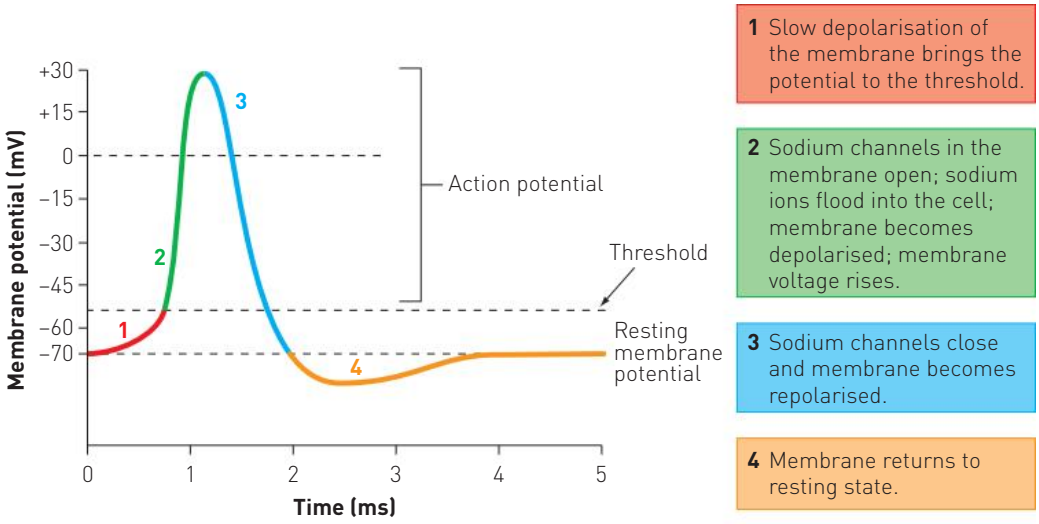


Figure 3.9 Development of an action potential on a nerve cell membrane

During an action potential, and for a very brief time afterwards, that part of the nerve fibre cannot be stimulated to respond again. This is called the **refractory period** (Figure 3.10). The refractory period of an action potential is important in the transmission of an impulse along a fibre.

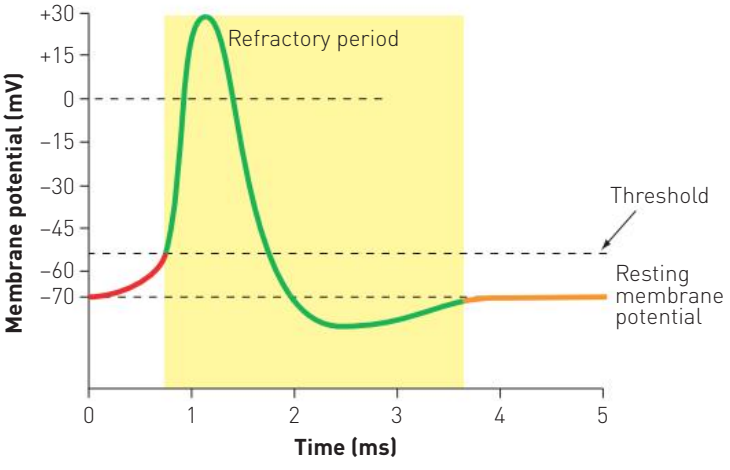


Figure 3.10 The refractory period is the time during which another action potential cannot be generated.

Action potentials
This website provides another explanation of action potentials.

EXTENSION

Cell membranes contain gated channels – channels that can open or close under the influence of particular stimuli. Such channels regulate the flow of ions from one side of the cell membrane to the other.

Find out about:

- the different types of gated channels
- the role of gated channels in establishing an action potential.

Transmission of the nerve impulse

Conduction along unmyelinated fibres

In an unmyelinated nerve fibre, depolarisation of one area of the membrane causes a local current flow between neighbouring areas on the membrane. This current flow causes depolarisation immediately adjacent to the site of the original stimulus. The process repeats itself along the whole length of the membrane so that the action potential moves along the membrane away from the point of stimulation. If the stimulus should occur in the middle of a fibre, impulses will travel in both directions along the fibre, away from the point of stimulation. However, in the body this would be unusual as stimulation normally occurs at the end of a fibre.

Figure 3.11 shows how a nerve impulse is transmitted. Each action potential generates another action potential just in front of it. Thus, an action potential does not travel along the nerve fibre; it is the message, or nerve impulse, that travels along the fibre. This situation has been likened to a line of dominoes. When the first domino falls it pushes over the second, which in falling pushes over the third, and so on. No one domino travels along the line, but the energy that triggers the fall is transmitted from the first domino to the last.

The nerve impulse is prevented from going backwards along the fibre by the refractory period (Figure 3.10). During the refractory period of an action potential, another action potential cannot be generated at that point on the fibre.

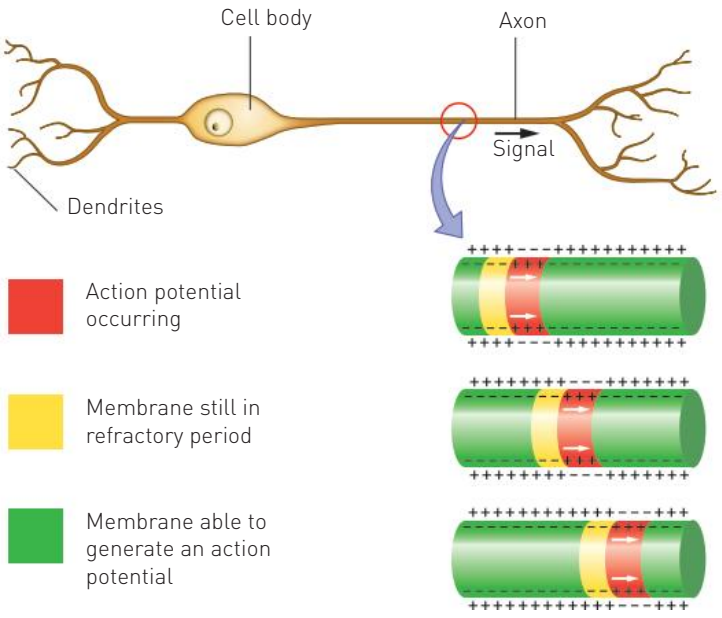


Figure 3.11 Transmission of a nerve impulse along an unmyelinated fibre. Successive action potentials are generated along the membrane of the nerve fibre.

Nerve impulse animation
Go to this website for an animation of the nerve impulse. Click on Neurobiology – teacher animations, then on Action Potential.

Transmission along myelinated fibres

In a myelinated fibre, the nerve fibres are insulated from the extracellular fluid except at the nodes of Ranvier. Because of this, ions cannot flow between the inside and outside of the membrane and an action potential cannot form. In this case, the action potential jumps from one node of Ranvier to the next because the myelin sheath is absent from the nodes (Figure 3.12). Because of this 'jumping conduction', known as saltatory conduction, the nerve impulse travels much faster along myelinated fibres than along unmyelinated ones. A large myelinated fibre can conduct impulses at a speed of up to 140 m/s; in an unmyelinated fibre the maximum speed of transmission is 2 m/s.

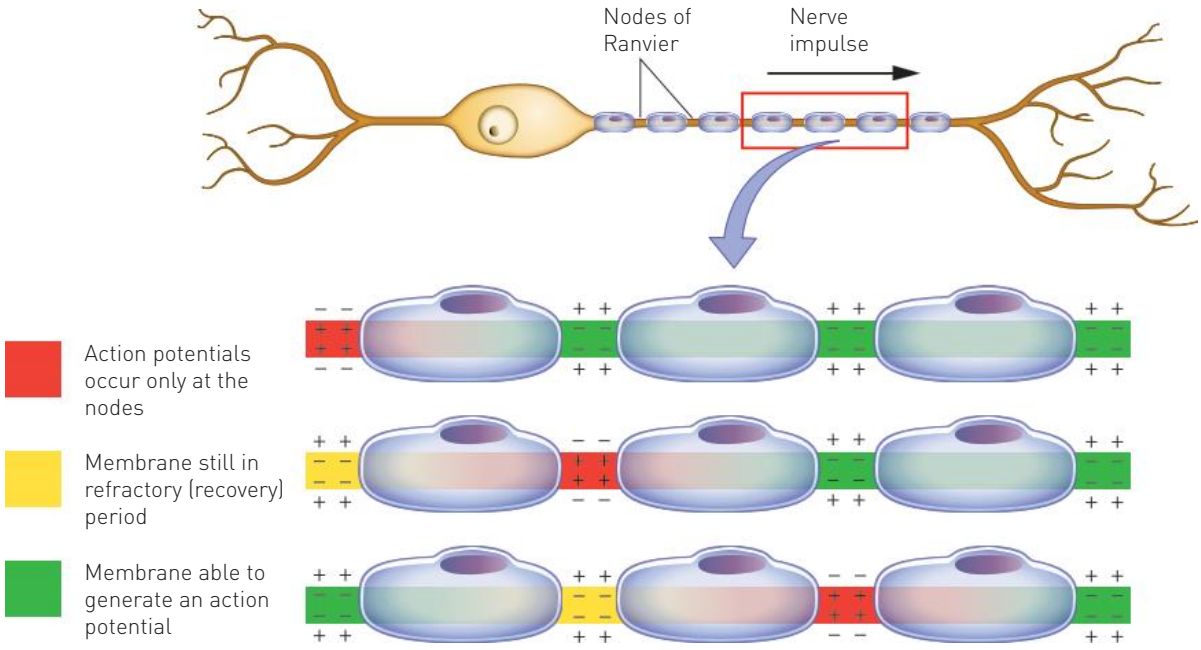


Figure 3.12 Saltatory conduction along a myelinated fibre. The nerve impulse jumps from node to node.

The size of a nerve impulse that travels along a fibre is always the same, regardless of the size of the stimulus. A weak stimulus, provided it exceeds the threshold, produces the same action potential as a strong one. As mentioned before, this is called an all-or-none response – a stimulus is either strong enough to trigger an impulse, or it is not. The magnitude of the impulse is always the same. If you stub your toe, nerve impulses will be generated that travel along an axon all the way up to your spinal cord. The voltage of the impulses arriving at the spinal cord will be the same as the voltage of those generated at the toe. This situation has been likened to a burning fuse. When the fuse is lit, the heat generated ignites the next part of the fuse, which then produces enough heat to light the next part, and so on. The end of the fuse burns with the same amount of heat as the beginning. Like the heat in a burning fuse, a nerve impulse does not become weaker with distance.

How is it then that we are able to distinguish stimuli of different intensity? For example, how do we tell a light tap on the shoulder from a heavy slap on the back? Two things enable us to determine the strength of a stimulus. First, a strong stimulus causes depolarisation of more nerve fibres than a weak stimulus; second, a strong stimulus produces more nerve impulses in a given time than a weak stimulus.

Transmission across a synapse

The synapse is the very small gap between one neuron and the next. We have seen how the nerve impulse is transmitted along the membrane of a neuron by a change in the ion concentration on each side of the membrane, but at the synapse there is no membrane and so some other method of transmission must be involved. At the synapse, special chemicals are released from the ends of the axon. These diffuse across the gap and attach to receptors on the membrane of the next neuron (Figure 3.13). Substances that diffuse across the synapse in this way are called **neurotransmitters**.

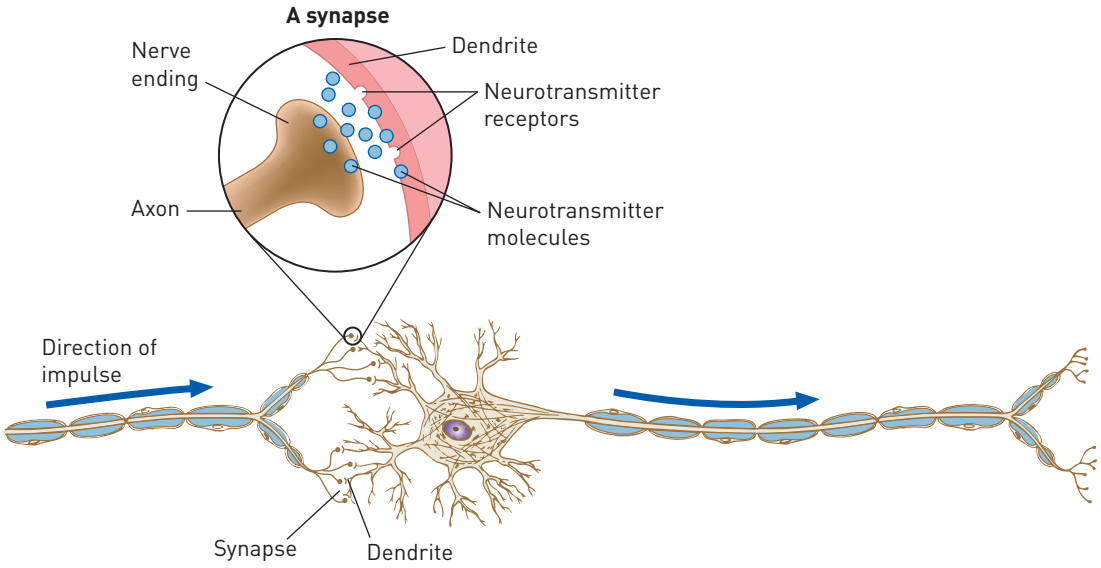


Figure 3.13 Transmission of a nerve impulse across a synapse

Neurotransmitters were discovered by Otto Loewi in 1921 (see Activity 3.3 on page 46). More than 100 different substances are either confirmed or suspected of being neurotransmitters. Some that you may have heard of are acetylcholine, adrenaline, dopamine and histamine.

The transmission of nerve impulses across a synapse occurs in only one direction – from axon to dendrite or from axon to cell body. Thus, there must be separate pathways for impulses that are carried from receptors into the brain and spinal cord, and for impulses that are carried out of the brain and spinal cord to effector organs.

Neurotransmitter transmission
This website provides an explanation and animation of transmission across a synapse.

Chocolate and neurotransmitters
Do you like chocolate? This website explores how chocolate may have an effect on neurotransmitters in the brain.

Effect of chemicals on the transmission of nerve impulses

There are many chemicals, both natural and synthetic, that influence the transmission of nerve impulses. Most of these work by affecting transmission at the synapse or at the neuromuscular junction. Stimulants such as caffeine and benzedrine stimulate transmission at the synapse. Other drugs, such as anaesthetics or hypnotics, depress the transmission. Venom from certain species of snakes and spiders also affects the neuromuscular junction.

Nerve agents (also called nerve gases) used during World War II contained organophosphates, which cause the build-up of acetylcholine at the neuromuscular junction. All muscles in the body then try to contract and the loss of muscle control prevents breathing. Organophosphates are used in some insecticides.

Nerve agents
This website provides more information about nerve agents.

Science inquiry

ACTIVITY 3.1 A neuron tour

Imagine that you are the size of a sodium ion and that you have been given the task of taking a group of tiny tourists on a guided tour of a motor neuron. You need to write a commentary to use on your tour.

As the guide you need to tell the tourists what they are seeing and the role of each part you encounter along the way. Clearly describe what you would tell them about the structure and function of the various parts of the neuron. Introduce them to the scientific terms that are used for the parts of the neuron and their functions.

Start your tour by gathering the group at a synapse and then enter the neuron via a dendrite. Conduct your tour all the way through the neuron until you exit at an axon terminal.

ACTIVITY 3.2 A model of a neuron

In this activity you will create a model of a multipolar neuron with a myelinated axon. In a small group, think about the various components that you will need to show in your model and the materials you will need to construct your neuron. Play dough or plasticine, and pipe cleaners, may be good starting points. Use different-coloured material for the different structures. To ensure the accuracy of your model, you may need to refer to some of the figures in this chapter.

Label all the structures that make up your model of a neuron. Be prepared to explain the functions of the various parts of your model to other class members.

ACTIVITY 3.3 The discovery of neurotransmitters

Neurotransmitters are chemicals released from a neuron that cause a response in an adjacent neuron, muscle or organ. A German pharmacologist, Otto Loewi, was the first person to demonstrate that nerve impulses exert their effect on muscles through the secretion of a neurotransmitter. In 1921 he performed an experiment that showed conclusively the effect of neurotransmitters. The idea for Loewi's experiment came to him in a dream. In his book *From the Workshop of Discoveries* (1953, University of Kansas Press), he said:

> In the night of Easter Saturday, 1921, I awoke, turned on the light, and jotted down a few notes on a tiny slip of paper. Then I fell asleep again. It occurred to me at six o'clock in the morning that during the night I had written down something most important, but I was unable to decipher the scrawl. That Sunday was the most desperate day in my whole scientific life. During the next night, however, I awoke again, at three o'clock, and I remembered what it was. This time I did not take any risk; I got up immediately, went to the laboratory, made the experiment on the frog's heart, described above, and at five o'clock the chemical transmission of nervous impulse was conclusively proved.

The experiment that Loewi performed involved the use of two hearts from freshly killed frogs. The still beating hearts were placed in separate beakers of salt solution. Heart A still had the vagus nerve attached; heart B did not. When the vagus nerve of heart A was electrically stimulated the heart slowed down. Loewi then took a dropper of the salt solution from around the slowly beating heart A and placed the fluid into the salt solution surrounding heart B. After a short time heart B slowed down (Figure 3.14). Loewi concluded that a chemical produced by the vagus nerve of heart A had caused heart B to slow down. In 1936 Loewi was awarded a Nobel Prize for his discovery.

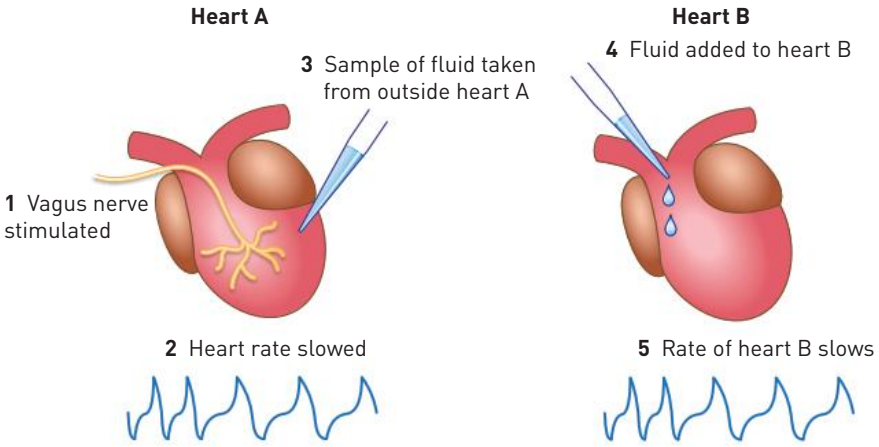


Figure 3.14 Loewi's experiment

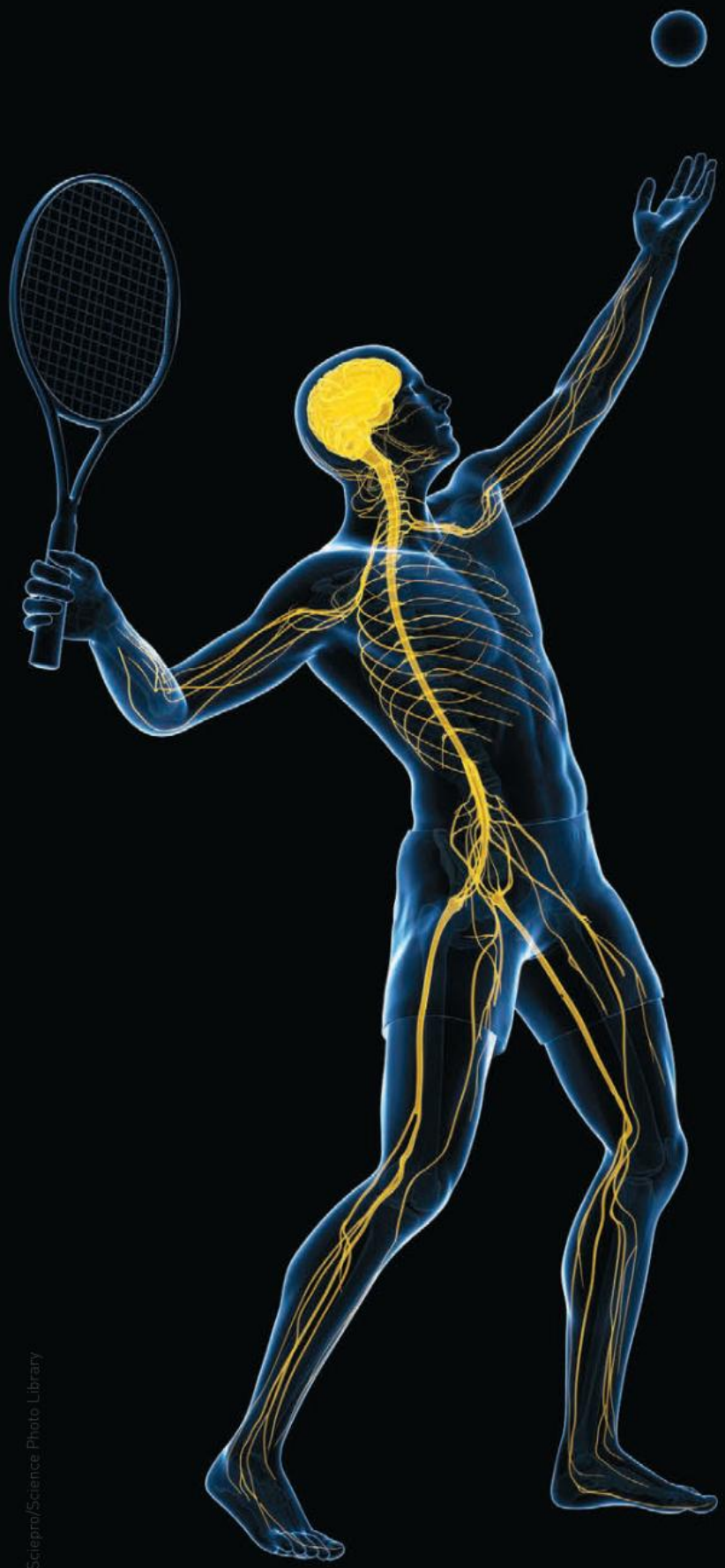
1. Explain how the result of Loewi's experiment enabled him to claim that a chemical was involved in slowing the rate of beating of the hearts.
2. Would Loewi have got the same result if he had placed both hearts in the same beaker of salt solution?
3. What control experiments would have been necessary before Loewi could claim that a chemical secreted by nerve cells was involved in slowing the hearts?
4. Loewi called the chemical 'vagusstoff' (or 'vagus stuff' when translated into English). Find out what we now call the neurotransmitter that is released at neuromuscular junctions.
5. If Loewi was doing such an experiment today, what do you think he would write down as his:
   - **a** hypothesis?
   - **b** testable prediction?

Review questions

1 Explain the difference between the central nervous system and the peripheral nervous system.
2 a Explain the difference between a myelinated fibre and an unmyelinated fibre.
b Describe how the sheath of a myelinated fibre is formed.
3 Depending on their functions there are three different types of neuron. Name the three types and describe the function of each.
4 Explain the difference between multipolar, bipolar and unipolar neurons. In what part of the nervous system is each type of neuron found?
5 Explain the difference between a neuron, a nerve and a nerve fibre.
6 a Define 'electrical potential'.
b What is the potential of the membrane of a nerve cell when it is not conducting a nerve impulse?
7 Explain how the potential of a resting nerve cell membrane is maintained.
8 a Define 'action potential'.
b Formation of an action potential is an all-or-none response. Define 'all-or-none response'.
9 What is the 'refractory period' of an action potential?
10 a Explain how a nerve impulse passes along a nerve fibre.
b Explain the difference between the way a nerve impulse is conducted along a myelinated and an unmyelinated nerve fibre.
11 a What is a synapse?
b Explain how a nerve message is carried across a synapse.
c Explain why the message can only cross a synapse in one direction.
12 What is the difference between a synapse and a neuromuscular junction?

Apply your knowledge

1 In what ways do nerve cells differ from most body cells?
2 A nerve impulse is often described as an electrochemical change. Explain why it is described in this way.
3 Hyperkalaemia is a higher than normal level of potassium in the blood and therefore in the extracellular fluid. What effect would hyperkalaemia have on the resting membrane potential of nerve cells?
4 In an examination a student stated that 'an action potential is another name for a nerve impulse'. Is this statement correct? Explain your answer.
5 Lightly press a pencil point onto the skin of your palm. Gradually increase the force with which you are pushing the pencil. How are you able to distinguish different intensities of the same stimulus?
6 The speed of transmission of nerve impulses can vary from 2 m/s to 140 m/s. Explain how there can be such a wide range of speeds of transmission of impulses.
7 Multiple sclerosis is caused by destruction of the myelin sheath. Use references to find out how damage to the sheath results in the jerky body and limb movements, double vision, slurred speech and paralysis that may occur as a result of the disease.



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CHAPTER

04

DIVISIONS OF THE NERVOUS SYSTEM

UNIT 3 CONTENT

SCIENCE UNDERSTANDING

Central and peripheral nervous system

- structure and function of the divisions of the nervous system can be observed and compared at different levels in detecting and responding to the changes in the internal and external environments including:
  - central-peripheral
  - afferent-efferent
  - autonomic-somatic
  - sympathetic-parasympathetic
- the nervous and endocrine systems work together to co-ordinate functions of all body systems, but differ in terms of:
  - speed of action
  - duration of action
  - nature and transmission of the message
  - specificity of message

The nervous system is one of the body's two communication systems. With the endocrine system (see Chapter 2) it coordinates all our voluntary and involuntary actions. The essential purpose of the nervous system is to receive and process information from sense organs, and to bring about responses to the information received.

The nervous system can be divided into parts on the basis of the structure and the functions carried out by each part. These parts of the nervous system are known as divisions but they all work together in a coordinated way.

Divisions of the nervous system

The body's nervous system consists of the brain and spinal cord and all the nerves. To make things confusing, some of the parts of this nervous system are also called nervous systems. The two main parts of the nervous system are the central nervous system (discussed in more detail in Chapter 5) and the peripheral nervous system. The **central nervous system (CNS)**, the control centre, consists of the brain and spinal cord, while the nerves that connect the CNS with the receptors, muscles and glands make up the **peripheral nervous system (PNS)**.

The PNS consists of nerve fibres, which carry information to and from the CNS, and groups of nerve cell bodies, called **ganglia**, which lie outside the brain and spinal cord. The nerve fibres are arranged into nerves, which arise from the brain and the spinal cord. Twelve pairs of nerves arise from the brain. These are the **cranial nerves**. The names of some cranial nerves, such as the optic nerve and the auditory nerve, are probably familiar to you. Most cranial nerves are mixed nerves; that is, they contain fibres that carry impulses into the brain, as well as fibres that carry impulses away from brain. Fibres that carry impulses into the CNS are called **sensory fibres**; those that carry impulses away from the CNS are **motor fibres**. A few cranial nerves carry only sensory impulses or only motor impulses.

Thirty-one pairs of **spinal nerves** arise from the spinal cord. They are all mixed nerves and each is joined to the spinal cord by two roots. The **ventral root** contains the axons of motor neurons that have their cell bodies in the grey matter of the spinal cord. The **dorsal root** contains the axons of sensory neurons that have their cell bodies in a small swelling on the dorsal root known as the **dorsal root ganglion** (Figure 4.1).

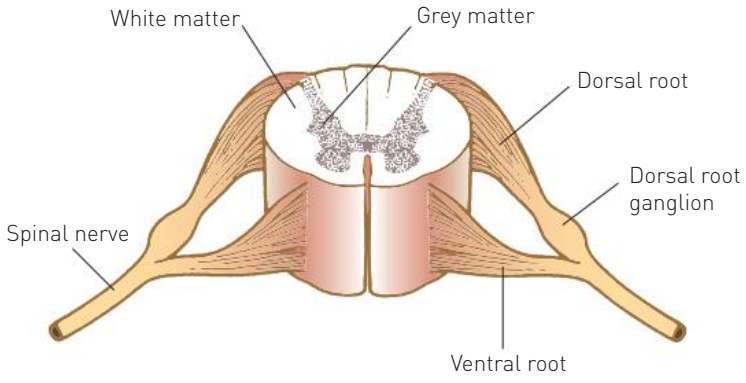


Figure 4.1 Part of the spinal cord, showing a pair of spinal nerves with roots

Names of nerves
This website provides names and descriptions of individual nerves.

The 12 pairs of cranial and 31 pairs of spinal nerves that make up the PNS contain fibres carrying nervous impulses to and from all parts of the body. To make it easier to study the various functions of the PNS, it has been divided and subdivided into parts, each with a particular function.

1 The **afferent** (or **sensory**) **division** of the PNS has fibres that carry impulses *into* the CNS. These impulses are carried into the CNS by sensory nerve cells from receptors in the skin and around the muscles and joints. These nerve cells from the body are called **somatic sensory**

neurons. The afferent division of the PNS also has sensory nerve cells that take impulses from the internal organs into the CNS. These are called **visceral sensory neurons** (Figure 4.2).

2 The **efferent** (or **motor**) **division** has fibres that carry impulses *away* from the CNS. It is subdivided into:

a the **somatic division** (sometimes called the somatic nervous system), which takes impulses from the CNS to the skeletal muscles

b the **autonomic division** (autonomic nervous system), which carries impulses from the CNS to heart muscle, involuntary muscle and glands. The autonomic division is further subdivided into:

i the **sympathetic division** (sympathetic nervous system)

ii the **parasympathetic division** (parasympathetic nervous system).

These parts of the nervous system are summarised in Figure 4.2.

The peripheral nervous system
This website provides more information and images relating to the peripheral nervous system.

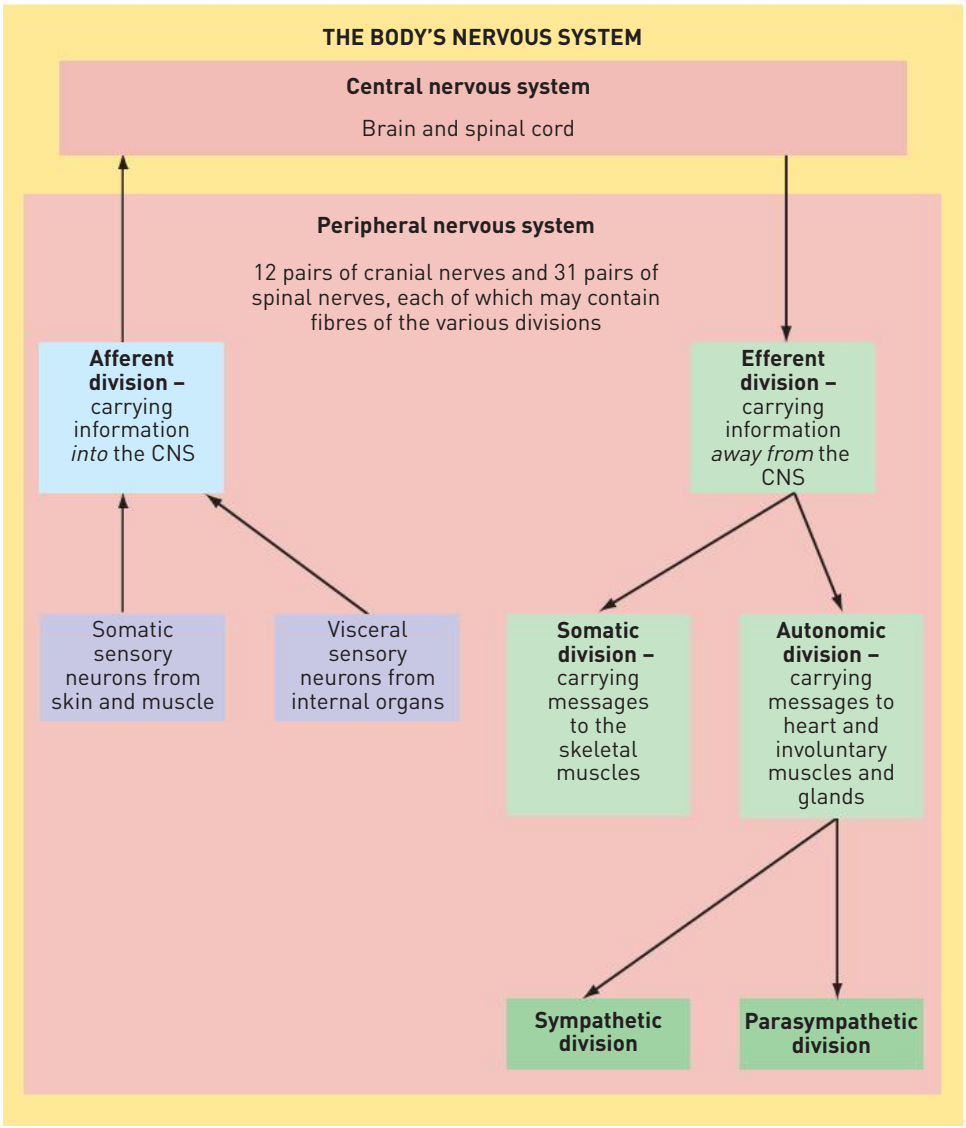


Figure 4.2 The functional organisation of the body's nervous system

The autonomic nervous system

The autonomic nervous system (ANS) is part of the PNS. It is usually studied separately from the rest of the PNS but it is important to remember that structurally and functionally it is part of the body's one nervous system.

The ANS is responsible for the control of the body's internal environment and is involved in many of the mechanisms that keep the internal environment constant. It usually operates without conscious control and is regulated by groups of nerve cells in the medulla oblongata, hypothalamus and cerebral cortex. Some of the body functions regulated by the autonomic division include heart rate, blood pressure, body temperature, digestion, release of energy, pupil diameter, air flow to the lungs, defecation and urination.

The nerve fibres of the ANS make up part of the spinal nerves and part of some of the cranial nerves. They carry impulses to the heart muscle, other muscles of the internal organs and the glands. The pathway travelled by an impulse from the CNS to an organ controlled by the ANS consists of two neurons. One of these has its cell body in the CNS, but the cell body of the other is in a ganglion. A ganglion (plural, 'ganglia') is a group of nerve cell bodies outside the CNS. Most nerve cell bodies are in the grey matter of the brain or spinal cord, but where they occur outside the CNS they are grouped in ganglia.

The pathway from the CNS to heart muscle, involuntary muscle or glands is an important difference between the autonomic division and the somatic division. Where there are two motor neurons involved in the autonomic pathway, the somatic division has just one motor neuron carrying impulses from the CNS to the effector (Figure 4.3).

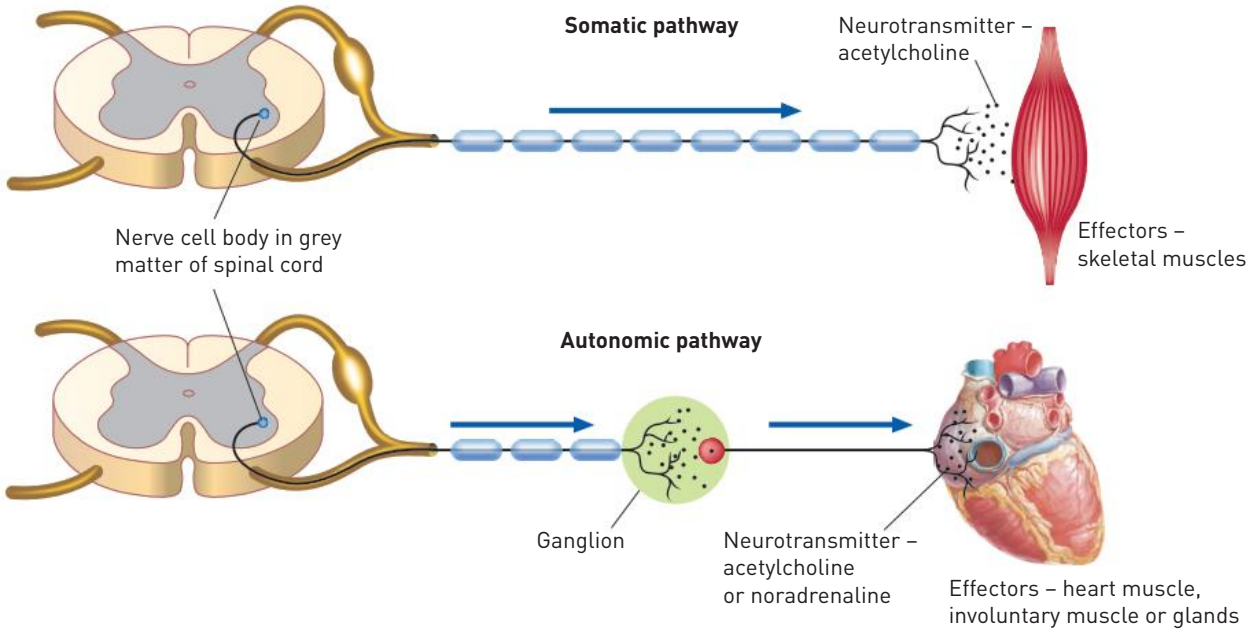


Figure 4.3 The difference in motor pathways between the autonomic and somatic divisions of the peripheral nervous system

There are two other important differences between the autonomic and somatic divisions. First, most organs under autonomic control receive two sets of nerve fibres – sympathetic fibres and parasympathetic fibres. Thus, the ANS is subdivided into sympathetic and parasympathetic divisions. Second, in the somatic nervous system, the neurotransmitter that carries the message from the neuron to the skeletal muscle is acetylcholine; in the ANS either acetylcholine or noradrenaline carries the message to the effector. Table 4.1 summarises these and other differences between the autonomic and somatic divisions.

Table 4.1 A comparison between the autonomic and somatic divisions of the peripheral nervous system

Characteristic	Autonomic division	Somatic division
Effectors	Heart muscle, involuntary muscle, glands	Skeletal (voluntary) muscles
General function	Adjustment of the internal environment (homeostasis)	Response to the external environment
Efferent (outward) pathways	Two nerve fibres from the CNS to the effector with a synapse in a ganglion	One nerve fibre from the CNS to the effector; no synapse and no ganglion
Neurotransmitter at effector	Acetylcholine or noradrenaline	Acetylcholine
Control	Usually involuntary	Usually voluntary
Nerves to target organ	Two sets – sympathetic and parasympathetic	One set
Effect on target organ	Excitation or inhibition	Always excitation

Impulses from the sympathetic and parasympathetic divisions have differing effects on organs or tissues. It is not possible to generalise and say that one set of fibres speeds up organ functioning and the other slows it down. However, it can be said that the parasympathetic division generally produces responses that maintain the body during relatively quiet conditions. The sympathetic division, on the other hand, tends to produce responses that prepare the body for strenuous physical activity. These responses are often called fight-or-flight responses because they prepare the body for situations that may involve aggression or fleeing from a threat (Figure 4.4).

Table 4.2 on page 54 summarises the effects of the sympathetic and parasympathetic fibres of the ANS. The message from the autonomic nerves to the muscles and glands under their control is carried by a neurotransmitter at the nerve endings. Parasympathetic nerve endings release acetylcholine and sympathetic nerve endings release noradrenaline.

Science Photo Library/Oscar Burriel

Figure 4.4 The sympathetic division of the autonomic nervous system brings about many of the body's responses to fear

Table 4.2 A summary of the effects of the autonomic nervous system

Structure	Effect of sympathetic stimulation	Effect of parasympathetic stimulation
Heart	Increases rate and strength of contraction	Decreases rate and strength of contraction
Lungs	Dilates bronchioles (fine air passages in the lungs)	Constricts bronchioles
Stomach, intestines	Decreases movement	Increases movement
Liver	Increases breakdown of glycogen and release of glucose	Increases uptake of glucose and synthesis of glycogen
Iris of the eye	Dilates pupil	Constricts pupil
Sweat glands	Increases sweat secretion	No effect
Salivary glands	Decreases secretion of saliva	Increases secretion of saliva
Blood vessels of:		
skin	Constricts vessels	Little effect
skeletal muscle	Dilates vessels	No effect
internal organs	Constricts vessels (except in heart and lung)	Little effect
Urinary bladder	Relaxes muscles of wall	Constricts muscles of wall
Adrenal medulla	Stimulates hormone secretion	No effect

Note: This is only a summary of the most important effects of sympathetic and parasympathetic stimulation. There are many other effects of these divisions.

Autonomic nervous system
This website provides another look at the autonomic nervous system.

EXTENSION

Lie detectors measure ANS activity. Their use is based on the idea that when a person lies there are involuntary changes in their body functions.

Find out:

- what kinds of things lie detectors measure and how they are measured
- whether it is activity of the sympathetic or parasympathetic divisions that produces the responses measured
- how reliable lie detectors are, and reasons for their reliability or unreliability.

Fight-or-flight responses

Under normal circumstances we are not aware of the activities of the ANS. This does not mean that it is in a resting state. When you are sitting quietly reading a human biology textbook, your sympathetic and parasympathetic nerves are sending out impulses to the internal organs to maintain the stability of the body's functions. For example, the heart has an inbuilt rate of contraction of about 100 beats per minute. While at rest, parasympathetic stimulation keeps this down to around 70 to 80 beats per minute.

In threatening situations the balance between sympathetic and parasympathetic stimulation is upset and the sympathetic becomes dominant. Situations that involve fear, anger, stress, danger or competition provoke what is called a **fight-or-flight response** or **alarm reaction**. These responses prepare the body for increased activity (in other animals, to fight or to flee). Activation of the sympathetic division results in the following responses.

- The rate and force of contraction of the heart increase, with a consequent increase in blood pressure.

- Blood vessels in organs involved in strenuous activity – such as the skeletal muscles, heart and liver – dilate.
- Blood vessels of organs not involved in activity – such as the kidney, stomach, intestines and skin – constrict.
- Airways in the lungs dilate and the rate and depth of breathing increases.
- Blood glucose level rises, because the liver converts more glycogen into glucose.
- Secretion from sweat glands increases.
- The adrenal medullae release the hormones adrenaline and noradrenaline, which intensify and prolong the above responses.

Think of a situation in which you have been fearful or angry; for example, addressing the school at an assembly, poised on the blocks at the start of a race, about to sit for an important exam, being confronted by a snarling dog or being accused of something that was not your fault. As a result, you were probably aware of your heart racing, you may have begun to sweat and your skin may have become pale (see Figure 4.4). These are typical fight-or-flight responses.

EXTENSION

As people get older, changes occur in the nervous system. Some changes are serious enough to be called a disease; an example is Alzheimer's disease. Other changes are just a natural part of ageing.

Find out:

- the changes to the nervous system that occur in everyone as they get older
- the reasons for those changes
- what can be done to reduce or delay the changes to the nervous system.

Autonomic disorders
This website provides a discussion of autonomic disorders and their treatment.

Comparison of hormonal and nervous coordination

Both the endocrine system and the nervous system are involved in communication within the body. However, they do not duplicate each other's roles; rather, they complement and reinforce each other.

The differences between the actions of nerves and hormones are as follows.

- Nervous responses are more rapid than hormonal ones, because nerve impulses travel rapidly along nerve fibres, while hormones are transported in the bloodstream. The nervous system responds to a stimulus in milliseconds, while the release of hormones may take from several seconds to several days.
- When a stimulus ceases, the nervous system stops generating nerve impulses and the response ceases almost immediately. Thus, nerve impulses bring about an immediate response, which lasts for only a short time. Hormones are typically slower-acting and responses can last a considerable time, even years.
- Nervous messages are an electrochemical change that travels along the membrane of a neuron. Endocrine messages are chemicals (hormones) that are usually transported by the blood.
- Nerve impulses travel along a nerve fibre to a specific part of the body and often influence just one effector; hormones travel to all parts of the body, are carried by the blood and often affect a number of different organs.

It should be stressed that these differences are only generalisations. There are exceptions to each of them. If you read carefully through Chapters 2 to 5 you will be able to find some of these. For example, response to the hormone adrenaline can be quite rapid, and some chemical messengers are not carried by the blood because their site of action is adjacent to the cells in which they are produced.

Despite these differences there are important similarities between the two systems.

- Some substances function as both hormones and neurotransmitters. Examples are noradrenaline, antidiuretic hormone and dopamine.
- Some hormones such as oxytocin and adrenaline are secreted by neurons into the extracellular fluid.
- Some hormones and neurotransmitters have the same effect on the same target cells. For example, noradrenaline and the hormone glucagon both act on liver cells to cause glycogen to be broken down into glucose.

A comparison of the nervous and endocrine systems is summarised in Table 4.3.

Table 4.3 A comparison of the nervous and endocrine systems

Characteristic	Nervous system	Endocrine system
Nature of message	Electrical impulses and neurotransmitters	Hormones
Transport of message	Along the membrane of neurons	By the bloodstream
Cells affected	Muscle and gland cells; other neurons	All body cells
Type of response	Usually local and specific	May be very general and widespread
Time taken to respond	Rapid – within milliseconds	Slower – from seconds to days
Duration of response	Brief – stops quickly when the stimulus stops	Longer lasting – may continue long after the stimulus has stopped

Science inquiry

ACTIVITY 4.1 An autonomic reflex

Work in pairs for this activity, with one person acting as the subject and the other as observer.

The subject should close his or her eyes for at least one minute. While facing a window, or other bright light, the subject then opens their eyes while the observer looks closely to see what happens.

Swap roles and repeat the activity.

1. What change was observed in the subject's pupils when the eyes were opened?
2. What change was observed in the subject's iris when the eyes were opened?
3. Why is the response that you observed described as a reflex?
4. Many reflexes are described as protective. Is the reflex that you observed a protective reflex? Explain.
5. Would it be possible to consciously prevent the response that you observed from occurring?
6. Which division of the autonomic nervous system caused the response that you observed?
7. Optometrists place drops of a drug in the eyes to dilate the pupils so that the eyes can be examined. The drug blocks receptors for acetylcholine. Suggest why such a drug placed in the eyes could cause the pupil to dilate.

Review questions

1. How many pairs of nerves arise from each of the brain and spinal cord?
2. What is a mixed nerve?
3. On what sort of nerve would you find a ventral root and a dorsal root? Explain where these roots are located.
4. If the ventral root of a spinal nerve were damaged, would it affect the sensory functions or the motor functions of that nerve? Explain.
5. **a** What is the difference between the afferent and efferent divisions of the peripheral nervous system?
   b What is the difference between the somatic and autonomic divisions of the efferent division of the peripheral nervous system?
6. Explain the relationship between the autonomic nervous system, the efferent division and the peripheral nervous system.
7. Describe four differences between the somatic and autonomic divisions of the peripheral nervous system.
8. In general terms, what is the difference between responses brought about by the sympathetic and parasympathetic divisions of the autonomic nervous system?
9. **a** List four stimuli that could lead to a fight-or-flight response.
   b List four responses that would prepare the body for fight or flight.
10. What is a ganglion?
11. Describe three differences between the action of nerves and that of hormones.
12. Describe some of the similarities between the nervous and endocrine systems.

Apply your knowledge

1. It is sometimes said that the sympathetic division of the autonomic nervous system produces fight-or-flight responses, while the parasympathetic division is concerned with 'rest and digest'. Do you think these are appropriate descriptions for the two divisions? Explain your answer.
2. Urinary retention (inability to empty the bladder or incomplete emptying of the bladder) and incontinence (uncontrollable, involuntary leaking of urine) are both possible symptoms of disease of the autonomic nervous system. Which part of the autonomic division would be affected in each case? Explain your answer.
3. If the dorsal root of a spinal nerve were damaged, would there be any impairment of the autonomic functions controlled by that nerve?
4. If a drug stimulated acetylcholine receptors, would it affect the autonomic division, the somatic division or both? Give reasons for your answer.
5. The drug atropine occupies acetylcholine receptors at the synapse. Ophthalmologists once used atropine when they needed to dilate a patient's pupils. Explain why atropine would have this effect.
6. Figure 4.4 shows a person's reaction to extreme fear. Describe the nervous and hormonal changes that would be taking place in the woman's body at the time the photograph was taken (you may need to refer to Chapter 2).

CHAPTER 05

THE CENTRAL NERVOUS SYSTEM

UNIT 3 CONTENT

SCIENCE UNDERSTANDING

Central and peripheral nervous system

- structure and function of the divisions of the nervous system can be observed and compared at different levels in detecting and responding to the changes in the internal and external environments including:
  - central-peripheral
  - afferent-efferent
  - autonomic-somatic
  - sympathetic-parasympathetic
- the parts of the central nervous system, including the brain (cerebrum, cerebellum, medulla oblongata, hypothalamus, corpus callosum) and spinal cord, have specific roles in the co-ordination of body functions and are protected by the meninges and cerebro-spinal fluid

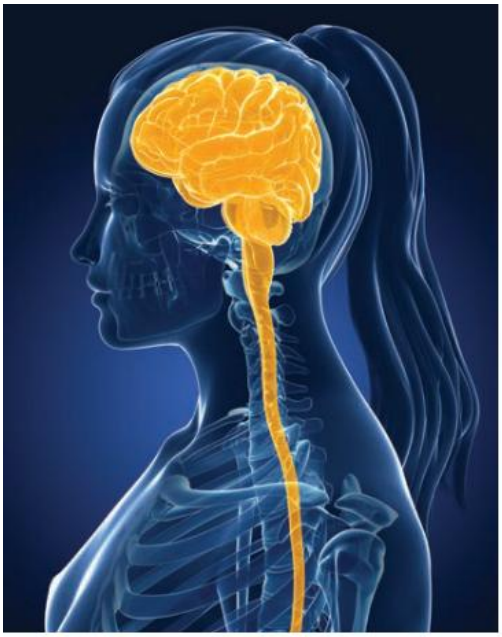


Figure 5.1 The central nervous system – brain and spinal cord

The brain and spinal cord make up the **central nervous system (CNS)**, the place where incoming messages are processed and where outgoing messages are initiated. Nerves carry the messages in and out of the CNS. These nerves make up the **peripheral nervous system (PNS)**. Both the central and peripheral nervous systems are made up of the nerve cells that were described in Chapter 3.

Protection of the central nervous system

The brain and the spinal cord are very delicate and vital parts of the body, and are therefore heavily protected (Figures 5.2 and 5.3). Three structures protect the CNS:

- bone
- membranes called meninges
- a fluid called cerebrospinal fluid (CSF).

The outermost protective layer is bone. The brain is protected by the **cranium**, the part of the skull that houses the brain; the spinal cord runs through an opening in the vertebrae called the **vertebral canal**.

Inside the bones, and covering the surface of the brain and spinal cord, are three layers of connective tissue forming membranes called the **meninges**. They cover the entire CNS. The outer meningeal layer is tough and fibrous. It sticks closely to the bones of the skull, but on the inside of the vertebral canal it is not so close fitting. This outer membrane has been described as having a texture and thickness similar to a household rubber glove. The middle meningeal layer is a loose mesh of fibres, while the inner layer is far more delicate. It contains many blood vessels and sticks closely to the surface of the brain and spinal cord.

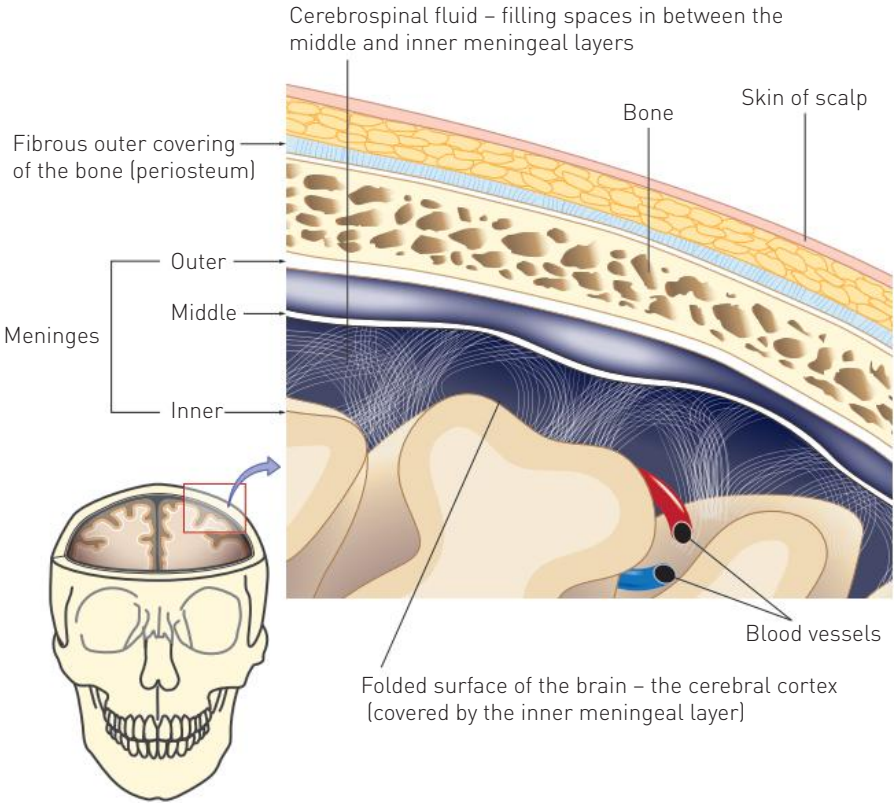


Figure 5.2 Structures that protect the brain

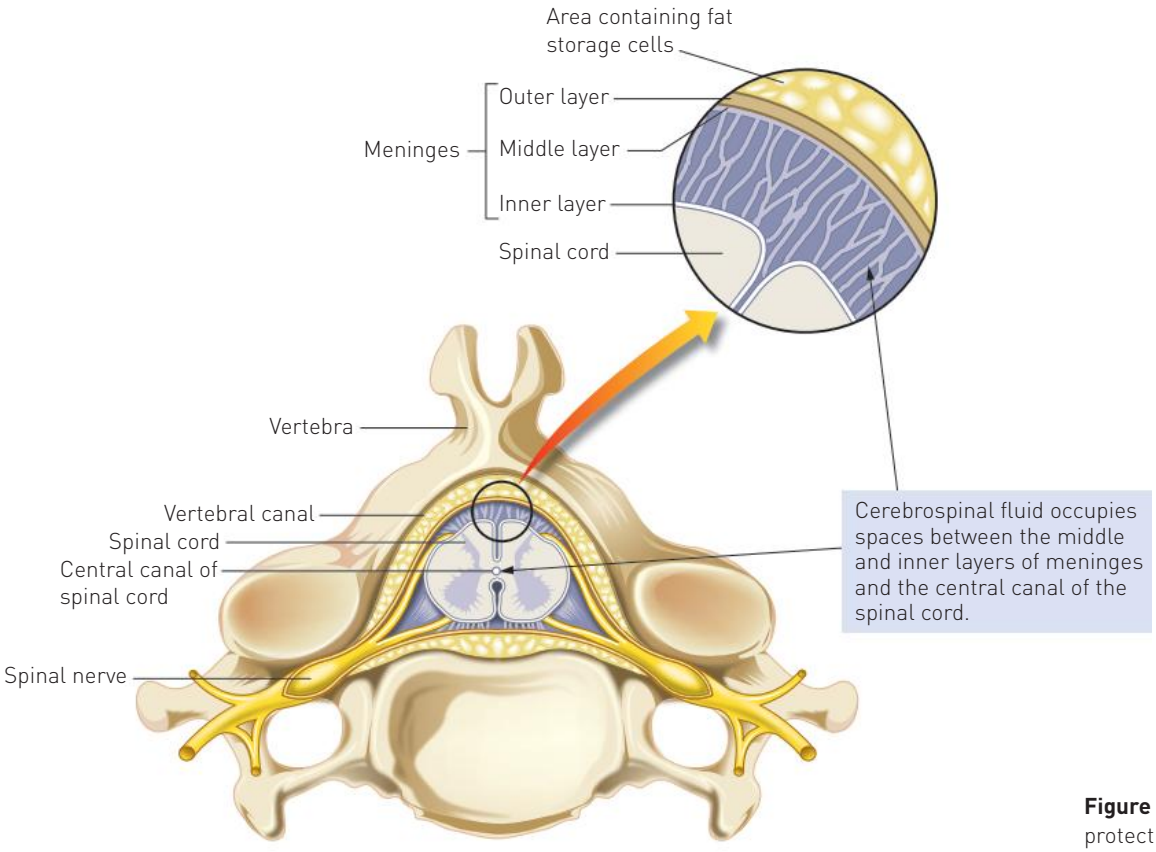


Figure 5.3 Structures that protect the spinal cord

The third protective structure is **cerebrospinal fluid (CSF)**, which occupies a space between the middle and inner layers of meninges. It also circulates through cavities in the brain and through a canal in the centre of the spinal cord. The CSF is a clear, watery fluid containing a few cells and some glucose, protein, urea and salts. The protective role of the CSF is to act as a shock absorber, cushioning any blows or shocks the CNS may sustain.

The CSF also supports the brain. The brain is suspended inside the cranium and floats in the fluid that surrounds it. The CSF is formed from the blood and it circulates around and through the CNS, eventually re-entering the blood capillaries. During its circulation it takes nutrients to the cells of the brain and spinal cord and carries away their wastes.

Therefore, the CSF has three functions: protection, support and transport.

The brain

The brain is a very complex organ, both in structure and in its functions. Much of the brain's workings are still a mystery and new discoveries are constantly being made. In this section we will deal only with those parts of the brain that have major functions, but it is important to remember that the brain works as an integrated whole. Damage to any part can profoundly affect its functions. We will confine our discussion of the brain to the cerebrum, cerebellum, hypothalamus, medulla oblongata and corpus callosum (Figure 5.4, page 62).

The cerebrum

Structure of the cerebrum

The **cerebrum** is by far the biggest part of the brain. It consists of an outer surface of grey matter, about 2–4 mm thick, known as the **cerebral cortex**. Below the cortex is white matter, and deep inside the cerebrum is additional grey matter called the **basal ganglia**.

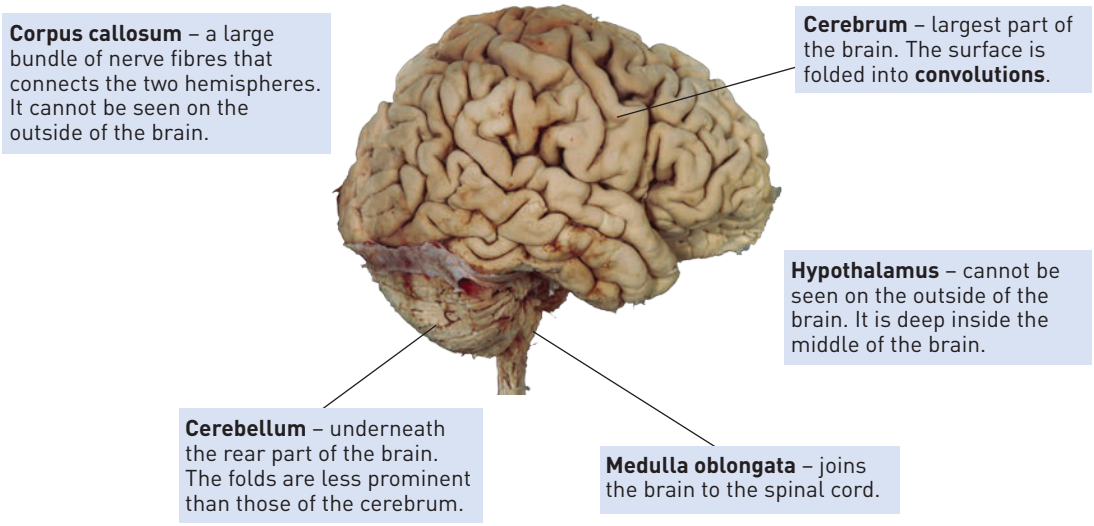


Figure 5.4 External view of the brain

The cerebral cortex is folded in patterns that greatly increase its surface area. In this way the cortex contains 70% of all the neurons in the CNS. Folding produces rounded ridges called **convolutions** (or gyri; singular **gyrus**). The convolutions are separated either by shallow downfolds called **sulci** (singular 'sulcus') or deep downfolds called **fissures** (Figure 5.5).

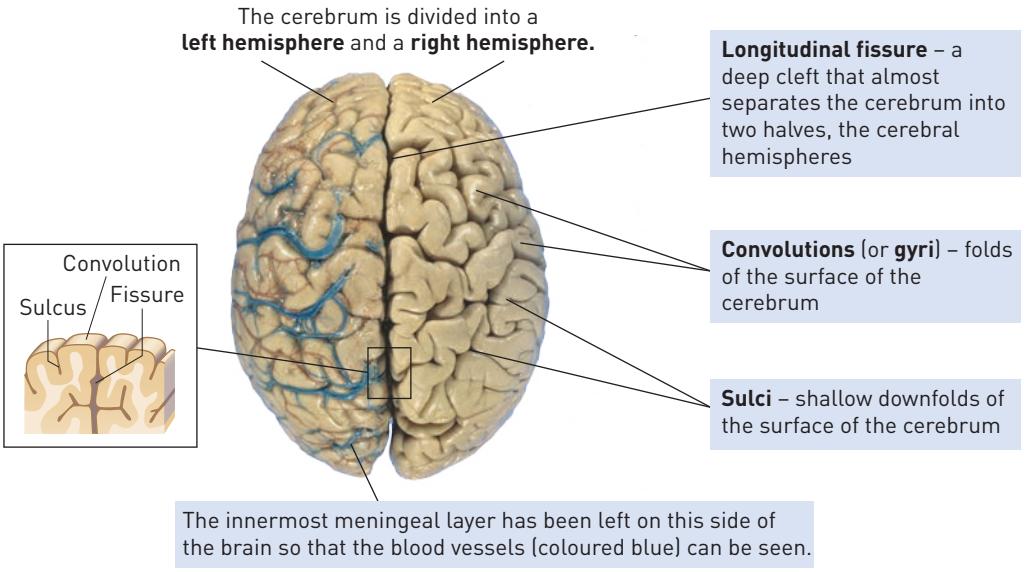


Figure 5.5 Convolutions and fissures of the cerebrum as seen from above

The deepest fissure, the **longitudinal fissure**, almost separates the cerebrum into two halves – the left and right **cerebral hemispheres**. Joining the two hemispheres, at the base of the longitudinal fissure, is an area of white matter consisting of a large bundle of transverse fibres. This is the **corpus callosum**. The patterns of folding of the cerebral cortex vary from person to person. However, certain fissures and sulci are fairly constant and are used to further subdivide each cerebral hemisphere into four lobes – the **frontal**, **temporal**, **occipital** and **parietal lobes** (Figure 5.6). Another part of the cerebrum, the **insula**, is deep inside the brain and is regarded as a fifth lobe.

Between the cerebral cortex (the grey matter at the surface of the cerebrum) and the basal ganglia (the grey matter deep inside) is white matter composed of bundles of nerve fibres that have a sheath of white fatty material called **myelin** around them. Within the CNS, bundles of nerve fibres are called **tracts**. (Outside the CNS they are called nerves.)

Three types of tracts occur in the white matter:

1. tracts that connect various areas of the cortex within the same hemisphere
2. tracts that carry impulses between the left and right hemispheres
3. tracts that connect the cortex to other parts of the brain or to the spinal cord.

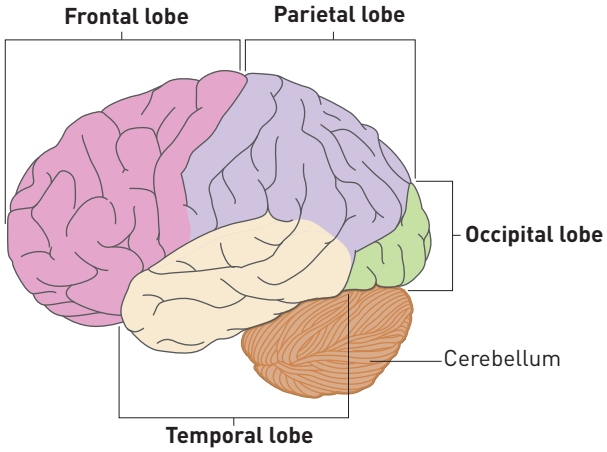


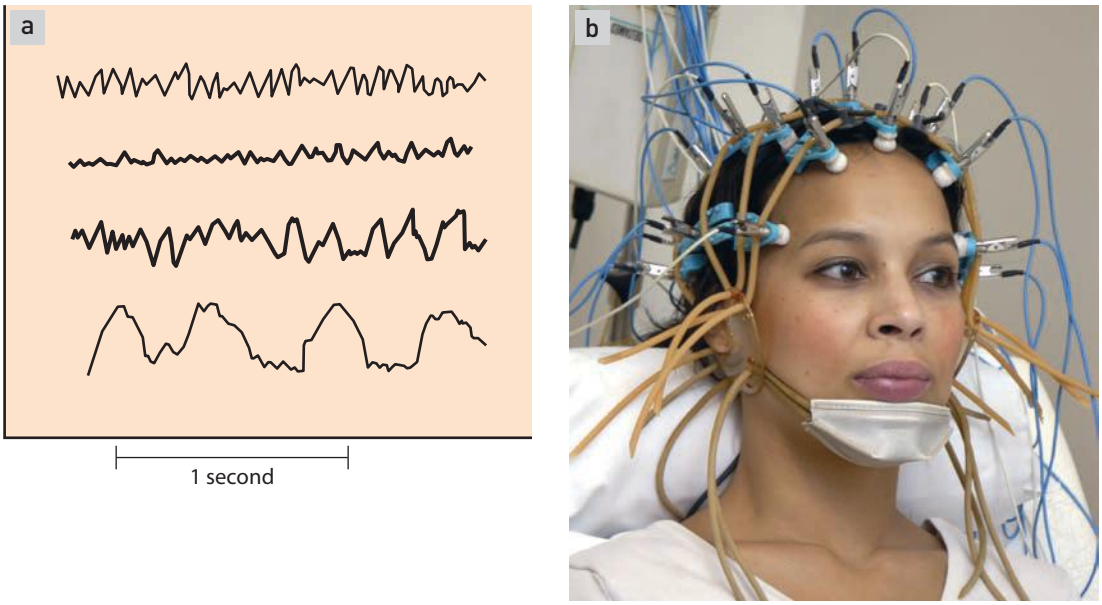
Figure 5.6 The lobes of the cerebrum. The fifth lobe, the insula, is not visible from the outside of the brain.

Functions of the cerebrum

The cerebral cortex is involved in mental activities such as thinking, reasoning, learning, memory, intelligence and sense of responsibility. It is also concerned with perception of the senses and the initiation and control of voluntary muscle contraction.

To find out what various parts of the cerebral cortex do, scientists have:

- studied brain waves – changes in voltage that occur in the cerebral cortex – which are detected by electrodes attached to the scalp and recorded as an **electroencephalogram (EEG)** (Figure 5.7)
- electrically stimulated specific areas and observed the responses
- examined changes in cerebral blood flow during different forms of physical or mental activity
- observed the effects on people of brain damage and/or disease
- experimented on other mammals.



Getty Images/Science Photo Library

Figure 5.7a An electroencephalogram is a record of electrical changes in the cerebral cortex. **b** The changes are detected by electrodes attached to the forehead and the scalp.

From such investigations it has been possible to determine and map the functional areas of the cortex. Figure 5.8 shows the general location of the functional areas, but the situation is more complex than this because no area of the brain functions alone. Also, the boundaries between areas are indistinct and there is considerable overlap, so that one region may have several different functions.

There are basically three types of functional area in the cortex:

- **sensory areas**, which interpret impulses from receptors
- **motor areas**, which control muscular movements
- **association areas**, which are concerned with intellectual and emotional processes.

Sensory areas receive and process nerve impulses from the senses.

Motor areas send impulses to muscles, especially for voluntary movement.

Association areas interpret information from the senses and make it useful.

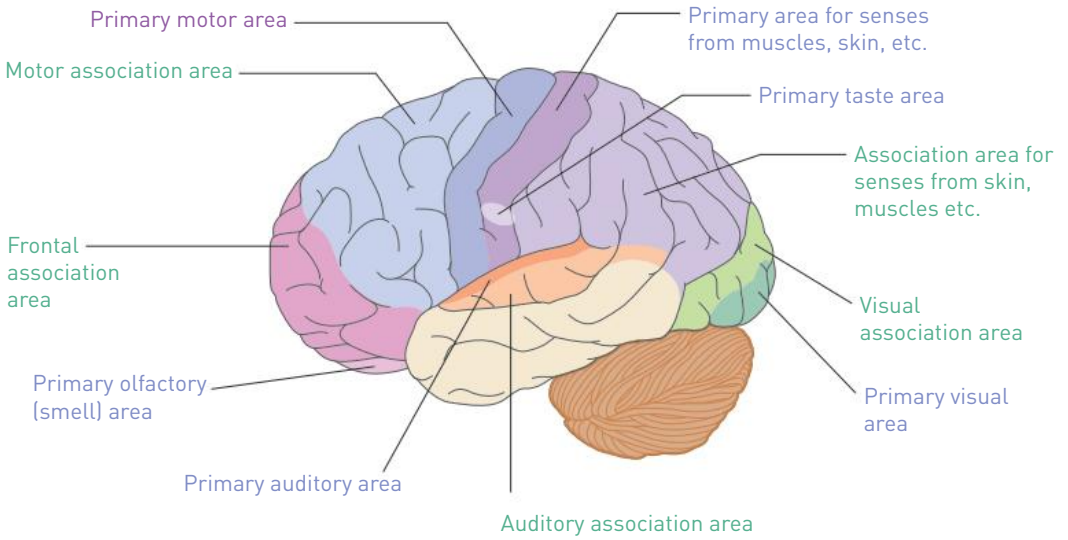


Figure 5.8 Some functional areas of the cerebral cortex

The basal ganglia, the masses of grey matter inside each hemisphere, consist of groups of nerve cell bodies associated with control of skeletal muscles. Nearly all the impulses from our sense organs are carried to the cerebral cortex, which then has all the relevant information about the environment and can initiate responses accordingly.

Although the two sides of the cerebrum appear to be very similar, close inspection shows that the two hemispheres are not identical. For example, in right-handed people the right frontal lobe is wider than the left and the left occipital and parietal lobes are wider than the right ones. Many specialised functions occur in only one hemisphere. Language ability, for example, is normally controlled by the left hemisphere; musical and artistic abilities are a function of the right hemisphere.

Cerebral hemispheres
This website provides further information on the different functions of the two cerebral hemispheres.

One of the important functions of the cerebrum is memory. The association areas of the cerebral cortex are involved in memory (Figure 5.8). Memories are not stored in individual memory cells in the brain: they are pathways of nerve cells. When a memory is stored, new links are made between neurons or existing links are modified.

EXTENSION

We all need a certain amount of sleep to continue to function normally.

Find out:

- what happens to the brain during sleep
- the difference between deep sleep and rapid eye movement (REM) sleep
- the difference between sleep and a coma.

The corpus callosum

The **corpus callosum** is a wide band of nerve fibres that lies underneath the cerebrum at the base of the longitudinal fissure (Figure 5.9). Nerve fibres in the corpus callosum cross from one cerebral hemisphere to the other and allow the two sides of the cerebrum to communicate with each other.

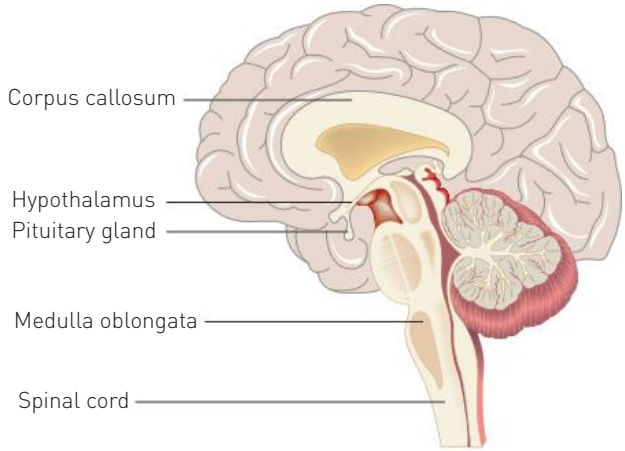


Figure 5.9 Longitudinal section of the brain showing the location of the corpus callosum, hypothalamus and medulla oblongata

The cerebellum

The **cerebellum** lies under the rear part of the cerebrum. It is the second-largest part of the brain and its surface is folded into a series of parallel ridges (Figure 5.4 on page 62). The outer folded part of the cerebellum is grey matter. Inside is white matter that branches to all parts of the cerebellum, rather like the branches of a tree (Figure 5.10).

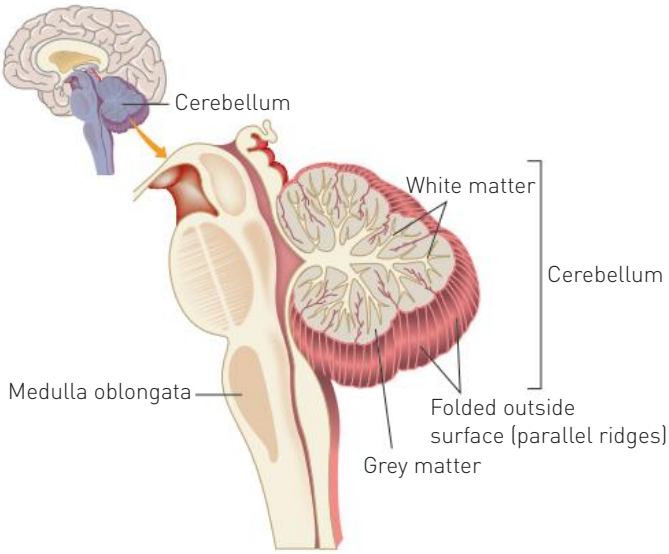


Figure 5.10 The location and interior structure of the cerebellum

The cerebellum exercises control over posture, balance and the fine coordination of voluntary muscle movement. To carry out these functions the cerebellum has to receive sensory information from the inner ear (for posture and balance) and from stretch receptors in the skeletal muscles. All the functions of the cerebellum take place below the conscious level. Impulses do not originate in the cerebellum and so without it we could still move, but our movements would be spasmodic, jerky and uncontrolled. Smooth, coordinated movements such as those required for writing, playing a musical instrument or keying into a computer would be impossible.

The hypothalamus

The **hypothalamus** lies in the middle of the brain and cannot be seen from the outside (Figure 5.9; see also Figure 2.3 on page 24). Although small, the hypothalamus controls many body activities, but it is mostly concerned with homeostasis (that is, maintaining a constant environment for the cells).

Functions of the hypothalamus include the regulation of:

- the autonomic nervous system (see Chapter 4), including the regulation of heart rate, blood pressure, the secretion of digestive juices, movements of the alimentary canal and the diameter of the pupil of the eye
- body temperature
- food and water intake
- patterns of waking and sleeping
- the contraction of the urinary bladder
- emotional responses such as fear, anger, aggression, pleasure and contentment
- the secretion of hormones and coordination of parts of the endocrine system (see Chapter 2); acting through the pituitary gland, the hypothalamus regulates metabolism, growth, reproduction and responses to stress.

The medulla oblongata

The **medulla oblongata** is a continuation of the spinal cord (Figure 5.9). It is about 3 cm long and extends from just above the point where the spinal cord enters the skull. Many nerve fibres simply pass through the medulla going to or from the other parts of the brain, but the medulla does have an important role in automatically adjusting body functions.

The medulla oblongata contains:

- the **cardiac centre**, which regulates the rate and force of heartbeat
- **respiratory centres**, which control rate and depth of breathing
- the **vasomotor centre**, which regulates the diameter of blood vessels.

The ways in which these centres work will be discussed further in Chapter 8.

In addition to the centres listed above, there are others that regulate the reflexes of swallowing, sneezing, coughing and vomiting. All the centres in the medulla oblongata are influenced and controlled by higher centres in the brain, particularly the hypothalamus.

The spinal cord

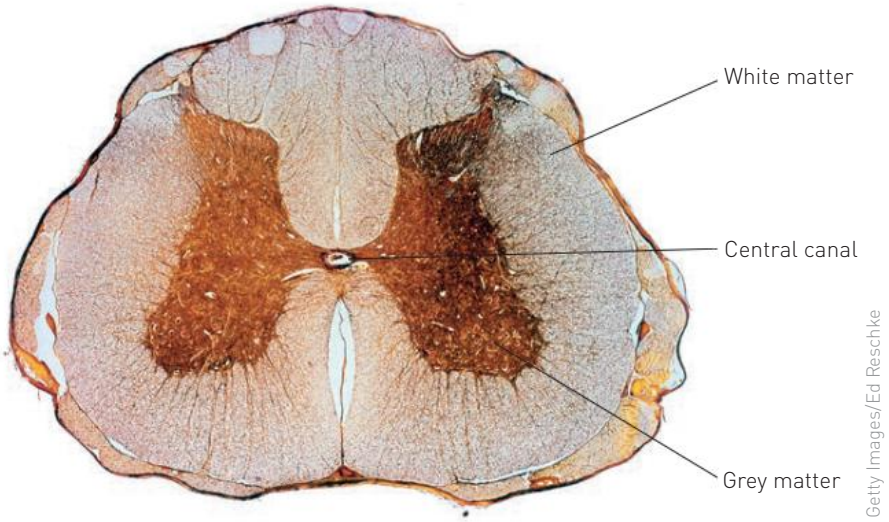
The **spinal cord** is a roughly cylindrical structure that extends from the foramen magnum, the large opening at the base of the skull, to the second lumbar vertebra, which is at about waist level. It is about 44 cm in length.

As we have seen, the spinal cord, like the brain, is heavily protected. The cord is enclosed in the vertebral canal, and inside the ring of bone are the three meningeal layers (see Figure 5.3 on page 61). However, the outermost meningeal layer is not joined to the bone as it is in the skull. Instead, there is a space containing fat, connective tissue and blood vessels. These serve as padding around the spinal cord and allow the cord to bend when the spine is bent.

If a cross-section of the spinal cord is examined, it is seen to consist of areas of grey matter and areas of white matter. The composition of these two areas is the same as in the brain – the grey matter is composed of nerve cell bodies and unmyelinated nerve fibres, and the white matter is composed of myelinated fibres. Unlike the cerebrum and cerebellum of the brain, where the grey matter is at the surface, the grey matter of the spinal cord is at the centre, surrounded by the white matter.

The grey matter is roughly in the shape of a letter H. In the cross-bar of the H is a small space called the **central canal** (Figure 5.11). This runs the length of the spinal cord and contains cerebrospinal fluid. The myelinated nerve fibres of the white matter are arranged in bundles known as ascending and descending tracts. **Ascending tracts** are sensory axons that carry impulses upwards, towards the brain. **Descending tracts** contain motor axons that conduct impulses downwards, away from the brain. Thus, one of the functions of the spinal cord is to carry sensory impulses up to the brain and motor impulses down from the brain. The second function of the spinal cord is to integrate certain reflexes (fast, automatic responses). The mechanism involved in spinal reflexes will be discussed in Chapter 6.

Spinal cord
This website provides more information about the spinal cord.



Getty Images/Ed Reschke

Figure 5.11 A cross-section of the spinal cord as seen under the low power of a microscope. The grey matter is coloured brown in this photo.

Table 5.1 A summary of the functions of the main functional areas of the CNS

Structure	Function
Cerebral cortex	Higher-order functions such as thinking, reasoning, memory, learning, conscious awareness of surroundings
Corpus callosum	Communication between the two cerebral hemispheres
Cerebellum	Coordination of fine contractions of muscles resulting in smooth movements and the maintenance of posture and balance
Hypothalamus	Homeostasis; regulation of the heart, digestive system, appetite, thirst, metabolism, body temperature, response to fear or anger
Medulla oblongata	Under the influence of the hypothalamus, regulates the heart, breathing and diameter of blood vessels
Spinal cord	Provides a pathway for communication between muscles and glands and the brain. Integration of automatic, protective reflexes

WS

The central nervous system

Science inquiry

ACTIVITY 5.1 The brain

A sheep's brain is similar to that of a human, so examining a sheep's brain can help you to understand what a human brain is like.

YOU WILL NEED

Sheep's brain; dissecting instruments; dissecting board or tray; gloves; safety glasses

WHAT TO DO

1. Place the brain on the dissecting board and locate the cerebrum, cerebellum and medulla oblongata (refer to Figure 5.4 on page 62). There will probably also be some of the spinal cord attached to the brain.
2. Notice the folding of the cerebrum. These are called convolutions. A human brain has many more convolutions than a sheep. What is the significance of the larger number of convolutions in a human compared with a sheep?
3. Shallow downfolds on the surface of the cerebrum are called sulci; deep downfolds are called fissures. Locate a sulcus and a fissure. Describe the difference between them.
4. Using Figure 5.6 (on page 63) locate the four lobes that can be seen on the outside of the cerebrum.
5. Locate the deep cleft that divides the cerebrum into two halves, or hemispheres.
6. Using forceps, peel off a little of the membrane that covers the surface of the cerebrum. This membrane is the inside layer of the meninges. What is the function of this inner meningeal layer?
7. Using a scalpel in the cleft between the two hemispheres of the cerebrum, cut the brain lengthwise into two halves. Notice that the inside of the brain is moist. What is the fluid that fills spaces inside the brain? Where does the fluid come from and what is its function?
8. Describe the appearance of the corpus callosum at the base of the cerebral hemispheres.
9. Draw a diagram of one side of the brain looking at the cut surface. Label the meninges, cerebrum, corpus callosum, cerebellum, medulla oblongata, spinal cord, the four lobes, convolutions, a fissure and a sulcus.
10. Using a scalpel, slice into the cerebrum and look at the cut surface. Which is at the surface of the cerebrum, grey matter or white matter?
11. Cut open the cerebellum. Are the grey and white matter arranged in the same way as in the cerebrum?

ACTIVITY 5.2 Phineas Gage

In 1848 Phineas Gage was foreman of a gang of workers building a railway in the American state of Vermont. His gang's job was to blast rock with explosives. On 13 September of that year, after placing gunpowder in a hole they had drilled in a rock, Gage began to compact the charge by pushing an iron rod into the hole. The rod was 3 cm in diameter and more than 1 m long. The charge exploded and drove the rod through Gage's skull. It entered the side of his face, passed behind his left eye and went out through the top of his cranium (Figure 5.12). Reports claimed that the iron rod landed 25 m away. Remarkably Gage survived the horrendous injury to his brain. He was able to work again (but not with explosives!) and he died 12 years after the accident.

After the accident, changes were reported in Gage's behaviour, but his bodily functions such as heartbeat, breathing, digestion, metabolism and regulation of body temperature were unaffected.

Phineas Gage
A good place to begin your search for answers to these questions

Go to the weblink for help in answering the following questions.

1. How is it possible that, with damage to such a large and vital part of the brain, Gage was able to function relatively normally?

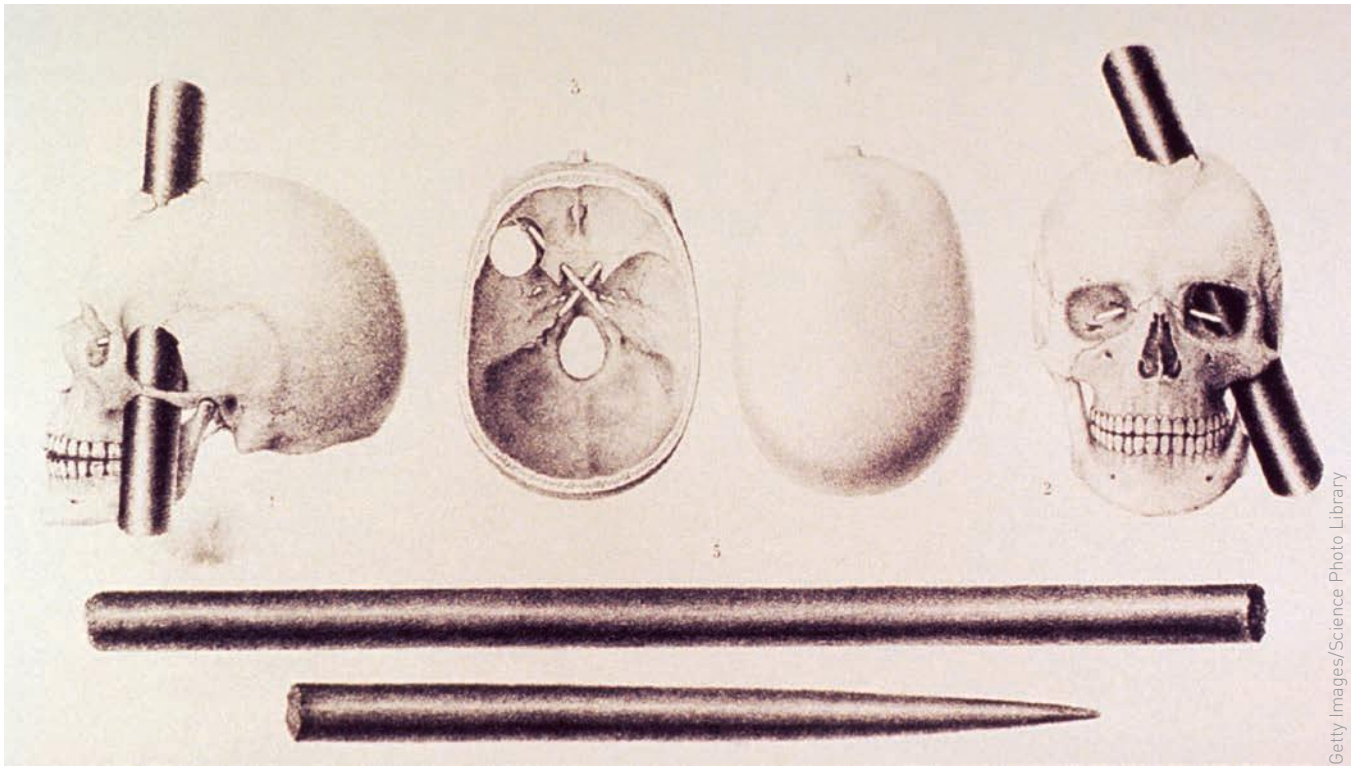


Figure 5.12 The head injury to Phineas Gage

2 Changes in a person's functioning or behaviour as a result of injury to the brain were used by scientists to determine the functions of the affected parts of the brain. Were scientists able to learn anything about the brain from Gage's injury?

3 Did Gage's injury have any positive benefits for medical science?

Review questions

1 Describe the three structures that protect the central nervous system.
2 What is cerebrospinal fluid? Where does it come from, where does it go to and what does it do?
3 **a** What is the cerebral cortex?
b List the advantages of having the cerebral cortex folded.
c What is the difference between a sulcus and a fissure?
4 **a** What are the functions of the cerebral cortex?
b Name the three types of area in the cerebral cortex and give the function of each type.
5 **a** Describe the location of the corpus callosum.
b Why is the corpus callosum white?
c What is the function of the corpus callosum?
6 **a** Describe the location of the cerebellum.
b What is the main function of the cerebellum?
7 **a** Describe the location of the hypothalamus.
b List some of the functions of the hypothalamus.
8 **a** Describe the location of the medulla oblongata.
b What are the three important centres within the medulla oblongata?
9 Describe the location of grey matter in the spinal cord. How does its location differ from that in the cerebrum and the cerebellum?

Apply your knowledge

1 If a person receives a heavy blow to the back of the head, the sensation experienced is often described as 'seeing stars'. Can you suggest a reason why a person would see stars as a result of such a blow?
2 After sustaining a head injury in a car accident, a person had difficulty chewing and swallowing. What part of the brain could have been damaged?
3 Paraplegia, inability to move the legs, may be caused by an injury to the spinal cord. Explain why such an injury could result in paraplegia.
4 Some of the functions of the hypothalamus are achieved through the pituitary gland. How does the hypothalamus influence the pituitary?
5 A person could survive complete destruction of one of the cerebral hemispheres, which make up nearly 40% of the volume of the brain. By contrast, destruction of the hypothalamus, which is only about the size of an almond, would result in certain death. Explain the reasons for this difference.
6 In severe cases of epilepsy, as a last resort, the corpus callosum may be severed so that the two cerebral hemispheres can no longer communicate with each other. Patients who have had this procedure are commonly referred to as having a 'split brain'. As each of the two cerebral hemispheres has separate functions, a split brain has a significant impact on the performance of simple tasks. Use references to find out the effects that a split brain would have on a person's functioning.

DJ Taylor / Shutterstock.com

CHAPTER

06

DETECTING AND REGULATING CHANGE

UNIT 3 CONTENT

SCIENCE INQUIRY SKILLS

- select, use and/or construct appropriate representations, including diagrams, models and flow charts, to communicate conceptual understanding, solve problems and make predictions

SCIENCE UNDERSTANDING

Central and peripheral nervous system

- different receptors detect changes in the internal and external environments including thermoreceptors, osmoreceptors, chemoreceptors and receptors for touch and pain
- the reflex arc comprises of specially structured neurons including sensory, interneuron and motor neurons, to transmit information from the receptor to the effector to respond rapidly to stimuli

Homeostasis

- homeostatic processes involve nerves and hormones in maintaining the body's internal environment within tolerance limits through the control of metabolism and physiological and behavioural activities

As you read this chapter are you sitting, standing or reclining, are you listening to music, is the room too hot or too cold, are you hungry or thirsty, do any of your muscles ache, or are you perfectly comfortable?

We are aware of our surroundings, our position and the internal state of our bodies because receptors detect changes and send the information to the central nervous system. This chapter discusses the ways in which different receptors detect changes in our external and internal environments and the mechanisms by which our bodies respond to such changes.

Receptors

A **receptor** is a structure that is able to detect a change in the body's internal or external environment. Sometimes receptor cells of a particular type are grouped together in a **sense organ**, such as the light receptors in the eye or the receptors sensitive to sound vibrations in the ear. Other receptors are simple nerve endings and may be spread through parts of the body or even the whole body, such as pain receptors or the temperature receptors in the skin.

In this section we will discuss some of the various types of receptors.

Thermoreceptors

Thermoreceptors are able to respond to heat and cold. In the skin are thermoreceptors that inform the brain of changes in the temperature outside the body. The information is received by the hypothalamus and also by the cerebrum so that we are consciously aware of the temperature of our surroundings. Skin thermoreceptors are nerve endings that are sensitive to either heat or cold but not both. If the skin is tested with hot and cold probes it is found that there are definite hot spots and cold spots, depending on the thermoreceptors present.

The temperature inside the body, the core temperature, is monitored by thermoreceptors in the hypothalamus. These detect the temperature of the blood that is flowing through the brain. Using information received from the skin and from its own thermoreceptors, the hypothalamus is able to regulate body temperature (see Chapter 7).

Osmoreceptors

Osmotic pressure is determined by the concentration of substances dissolved in the water of the blood plasma. **Osmoreceptors** are located in the hypothalamus and are sensitive to osmotic pressure. They respond to very small changes in osmotic pressure and are able to stimulate the hypothalamus so that the body's water content is maintained within very narrow limits (see Chapter 7).

Chemoreceptors

Chemoreceptors are stimulated by particular chemicals. They are present in the nose, making us sensitive to odours, and in the mouth, giving us sensitivity to tastes. There are also internal chemoreceptors that are sensitive to the composition of the body fluids. Of particular importance are chemoreceptors in certain blood vessels that are sensitive to the pH of the blood and to the concentrations of oxygen and carbon dioxide. These are involved in the regulation of the heartbeat and of breathing (see Chapter 8).

Touch receptors

Touch receptors are found mainly in the skin and there are a number of different types. Some are close to the surface of the skin and are sensitive to very light touches. These occur in greater concentrations in areas of skin that are more sensitive, such as the lips, fingertips, eyelids and external genital organs.

Nerve endings are also associated with the base of each hair follicle. These respond to any light touch that bends the hair. Touch receptors close to the skin surface and those attached to the hairs adapt rapidly, and so after a short time we are no longer aware of the touch. For example, when first putting on clothing we are aware of it touching the skin, but that sensation disappears very quickly.

Other receptors are located deeper in the skin and are sensitive to pressure and vibrations (see Figure 6.1).

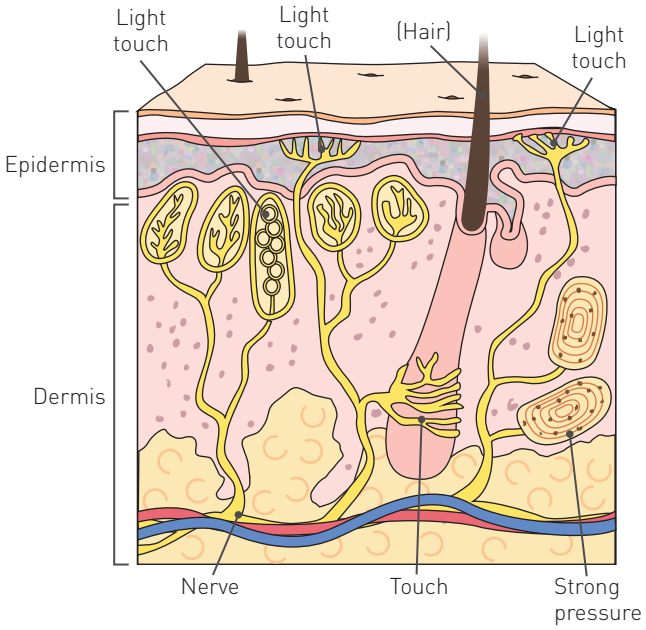


Figure 6.1 Section of the skin showing touch receptors

Pain receptors

Pain receptors (also called nociceptors) are stimulated by damage to the tissues, such as from a cut or a heavy bump, by poor blood flow to a tissue, or by excessive stimulation from stimuli such as heat or chemicals. The receptors for pain are especially concentrated in the skin and the mucous membranes. They occur in most organs, but not in the brain.

Pain is uncomfortable but it is essential for our wellbeing. Pain warns us that damage to tissues is occurring, and we can therefore take evasive action or seek medical help so that damage is minimised.

Unlike many other receptors, pain receptors adapt little or not at all, so that pain continues as long as the stimulus is present. In some cases prolonged stimulation of pain receptors makes the pain worse. The failure of pain receptors to adapt keeps the person aware that a tissue-damaging situation exists.

Reflexes

A **reflex** is a rapid, automatic response to a change in the external or internal environment. All reflexes have four important properties.

- A **stimulus** is required to trigger a reflex – the reflex is not spontaneous.
- A reflex is **involuntary** – it occurs without any conscious thought.
- A reflex response is **rapid** – only a small number of neurons are involved.
- A reflex response is **stereotyped** – it occurs in the same way each time it happens.

Some reflexes involve the unconscious parts of the brain, but most are coordinated by the spinal cord. When a nerve impulse comes into the spinal cord from a receptor, the message is not necessarily carried up to the brain. The impulse may be passed to motor neurons at the same level in the cord, or may travel a few segments up or down the cord before travelling out through a motor neuron. In these cases the reflex is carried out by the spinal cord alone and is known as a **spinal reflex**. The pathway a nerve impulse follows in travelling from a receptor to an effector is known as a **reflex arc** or, in the case of a spinal reflex, a **spinal reflex arc**.

Because a spinal reflex does not involve the brain, it is involuntary, even though contraction of skeletal muscles may occur. Impulses may be sent to the brain and so we become aware of what is happening, but this awareness does not occur until after the response has been initiated. For example, if you step on something sharp with bare feet, the reflex response is to withdraw your foot from the painful stimulus. By the time your brain becomes consciously aware of the painful stimulus, your foot has already been withdrawn.

A reflex arc has the following basic components.

1. A **receptor** is either the ending of a sensory neuron or a specialised cell associated with the end of a sensory neuron. The receptor reacts to a change in the internal or external environment by initiating a nerve impulse in the sensory neuron.
2. A **sensory neuron** carries impulses from the receptor to the CNS.

3 There is at least one **synapse**. The nerve impulse may be passed directly to a motor neuron or there may be one or more interneurons, which direct the impulse to the correct motor neuron.
4 A **motor neuron** carries the nerve impulse to an effector.
5 An **effector** receives the nerve impulse and carries out the appropriate response. Effectors are muscle cells or secretory cells.

Figure 6.2 shows the components in a simple spinal reflex involving three neurons. The response would occur in a fraction of a second and while it was occurring, impulses would travel up the spinal cord to the brain. Only after the response had been made would the person become consciously aware of the situation. Many reflexes, such as the one shown in Figure 6.2, protect the body from injury. Blinking when something touches the cornea of the eye, sneezing or coughing when something irritates the nose or trachea, and constriction of the pupil in response to intense light are other protective reflexes.

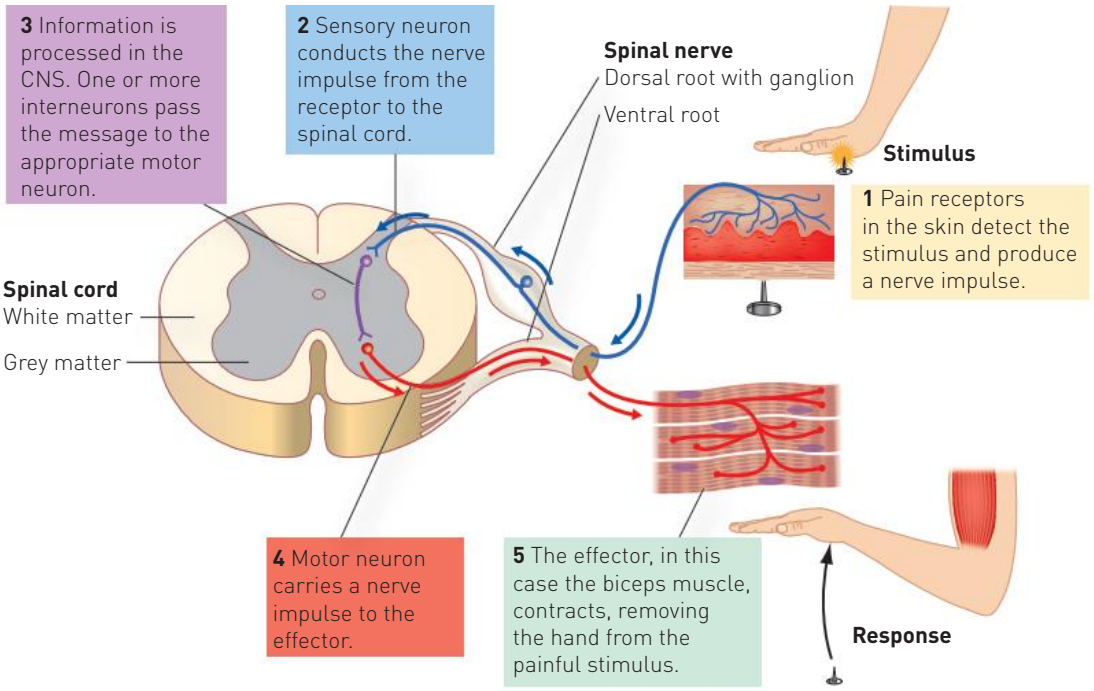


Figure 6.2 The neurons involved and the pathway followed by the nerve impulses in a spinal reflex. In this example the impulses enter and leave the spinal cord by the same spinal nerve. This is not always the case.

Simple reflexes and reflex arcs
This website provides more information about simple reflexes and reflex arcs and an animation of the latter.

Reflex arc
This website has an animation of a reflex arc.

Other reflexes include secretion of saliva in response to the sight, smell or taste of food, the ejaculation of semen during sexual intercourse and the responses brought about by the autonomic nervous system (see Table 4.2 on page 54).

EXTENSION

Doctors may use reflexes to find out whether a patient has an impairment of the nervous system. Absence or exaggeration of a particular reflex may indicate damage to nerves or to the spinal cord through injury or disease.

Find out about the following reflexes and what absence or exaggeration of the reflex could indicate:

- patellar reflex (knee jerk)
- Achilles reflex (ankle jerk)
- abdominal reflex
- plantar reflex and Babinski sign.

Learned reflexes

The protective reflexes mentioned above are present from birth. More complex motor patterns appear during a baby's development – including reflexes such as suckling, chewing or following movements with the eyes. These innate reflexes are determined genetically.

Some complex motor patterns are learned and are called **acquired reflexes**. Muscular adjustments required to maintain balance while riding a bike, jamming on the brakes of a car to avoid a dangerous situation or catching a ball are all acquired reflexes. They are learned through constant repetition.

Homeostasis

Have you ever run to catch a bus or a train, or perhaps run up several flights of stairs? After such vigorous activity you may have been sweating, your face may have been red, you would have been breathing heavily, and you would have been able to feel your heart beating forcefully and rapidly. All these responses would have occurred automatically, without any conscious thought on your part. Such responses are a part of homeostasis. **Homeostasis** is the process of keeping the environment inside the body fairly constant.

Our body cells work best at a particular temperature, when surrounded by fluid with a particular pH, when given a constant supply of oxygen and glucose, and when wastes are constantly removed. Maintaining these, and other optimum conditions for cell functioning, is all part of homeostasis.

Homeostatic mechanisms help us to be independent of our external environment. For example, if you suddenly plunge into a cold swimming pool, the cells of your brain, liver, stomach, heart and other internal organs will continue to function normally despite the sudden change in external temperature (Figure 6.3).

Figure 6.3 Homeostasis makes us relatively independent of the external environment.

The body's cells are surrounded by fluid, and it is the composition and temperature of this fluid that must be maintained within very fine limits. The important aspects of the internal environment that the body needs to regulate include:

- core body temperature
- pH and concentrations of dissolved substances in the body fluids
- concentration of glucose in the blood
- concentration of oxygen and carbon dioxide in the blood and other body fluids
- blood pressure
- concentration of metabolic wastes.

The maintenance of this **steady state** does not mean that nothing changes. Instead, there is a dynamic equilibrium in which the input and output of materials and energy are balanced. All the systems of the body contribute to homeostasis, not only to supply the cells' needs, but also to maintain a constant cellular environment.

To maintain homeostasis the body must be able to both sense changes in the internal and external environment and compensate for those changes. The nervous and endocrine systems are the main sensory and controlling body systems and, in the case of homeostasis, they operate through feedback systems, many of which involve negative feedback. Homeostasis of specific aspects of the body's internal environment will be considered in Chapters 7 and 8.

Tolerance limits

Many factors can vary in the human body. For example, oxygen concentration in the tissues, salt concentration, temperature and glucose concentration all rise and fall a little. If there is too big a rise or too big a fall then things start to go wrong with the way the body works.

Tolerance limits are the upper and lower limits to a range of factors. Within these limits the body functions normally. A rise above, or a fall below, the normal range means that the individual's tolerance limits have been exceeded and dysfunctions will occur.

Feedback systems

A **feedback system** is a circular situation in which the body responds to a change, or **stimulus**, with the response altering the original stimulus. In the case of a **negative feedback system**, the response causes the stimulus, or variable, to change in a direction opposite to that of the original change.

Take, for example, a variable such as the concentration of glucose in the blood. When we exercise, our muscles use up glucose to release the energy required for muscle contraction. The muscles absorb glucose from the blood and consequently the blood glucose level tends to fall. This is the stimulus. The liver responds by releasing more glucose into the blood (Figure 6.4). Thus, the response has caused the blood glucose level to go up, which is the *opposite* of the fall in glucose that initiated the response. In this way the blood glucose level is maintained within a range that is acceptable for efficient cellular functioning.

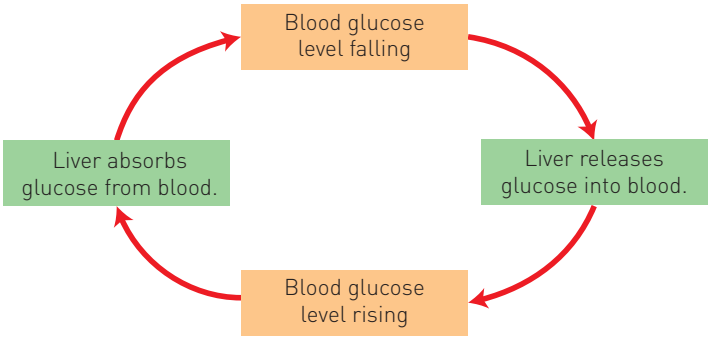


Figure 6.4 An example of a feedback system. In this case the feedback loop is controlling the body's blood glucose level

Negative feedback systems, or **steady state control systems**, that maintain homeostasis involve cycles that have a number of common features.

- The **stimulus** is the change in the environment that causes the system to operate.
- The **receptor** detects the change.
- The **modulator** is a control centre responsible for processing information received from the receptor and for sending information to the effector.
- The **effector** carries out a response counteracting the effect of the stimulus.
- **Feedback** is achieved because the original stimulus has been changed by the response.

Homeostatic mechanisms are controlled by both the nervous system and the endocrine system. Both systems detect when the body is beginning to deviate from its normal balanced state: the **nervous system** sends electrical messages to the appropriate organs so that the change is counteracted; the glands of the **endocrine system** secrete chemical messengers, or hormones, into the blood. Hormones, however, generally work more slowly than nerve impulses in coordinating homeostasis.

Stimulus-response and feedback

In science a **model** is a simplified representation of something that is fairly complex. The stimulus-response-feedback model is a simple way of explaining how homeostatic mechanisms work. The components of the model are described above and Figure 6.5 summarises these components and explains how the regulatory mechanism works.

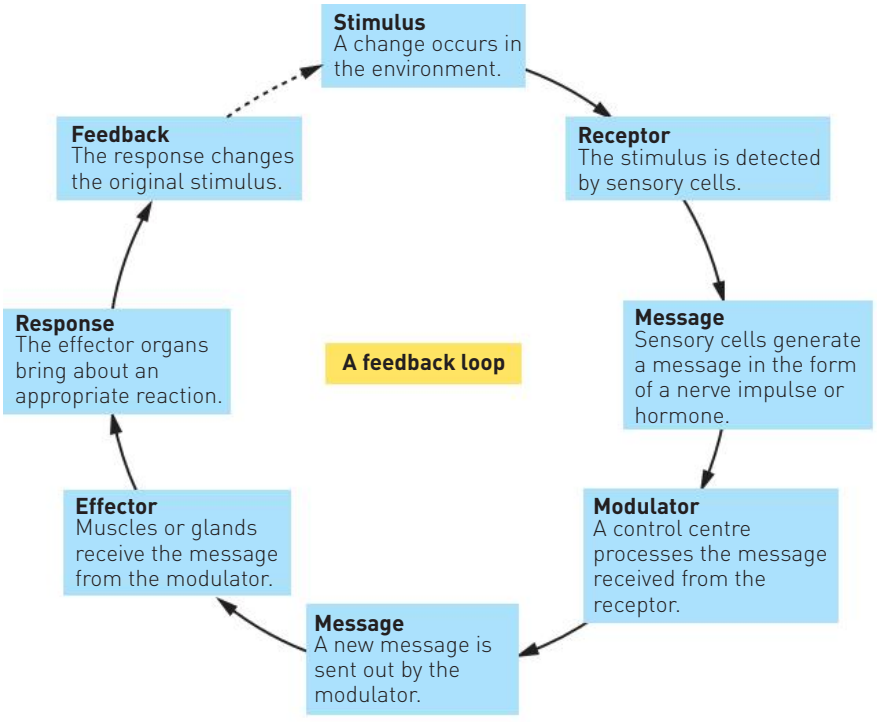


Figure 6.5 The stimulus-response-feedback model

Negative feedback

In homeostatic mechanisms the response has the effect of reducing or eliminating the stimulus that caused it. This is called **negative feedback**. For example, suppose you feel cold. In response to the stimulus of feeling cold you put on a jumper and no longer feel cold. Your response has reduced or eliminated the original stimulus of feeling cold.

Negative feedback
This website has a simple quiz on negative feedback. Test yourself!

An analogy that is often used to explain a negative feedback loop is that of an air conditioning system in a room or building. Suppose that the thermostat is set to a comfortable 22°C. On a warm day, when the temperature rises above 22°C, the thermostat automatically switches the air conditioner on so that cool air is brought into the room. The air in the room becomes cooler and the thermostat then switches the air conditioner off when it reaches its target temperature. This process repeats itself so that the air temperature remains relatively constant.

Figure 6.6 shows how the components of the air conditioning system correspond to the components of a negative feedback loop. Note that the temperature fluctuates above and below the temperature set on the thermostat. It is the same with the human body. Things such as the concentration of blood glucose and body temperature fluctuate around a normal level. This fluctuation is called a **dynamic equilibrium**. The point around which conditions fluctuate is called the **set point**. For the air conditioner in our scenario, the set point is 22°C; for human body temperature, the set point is 37°C.

Negative feedback keeps the internal environment in a fairly steady state.

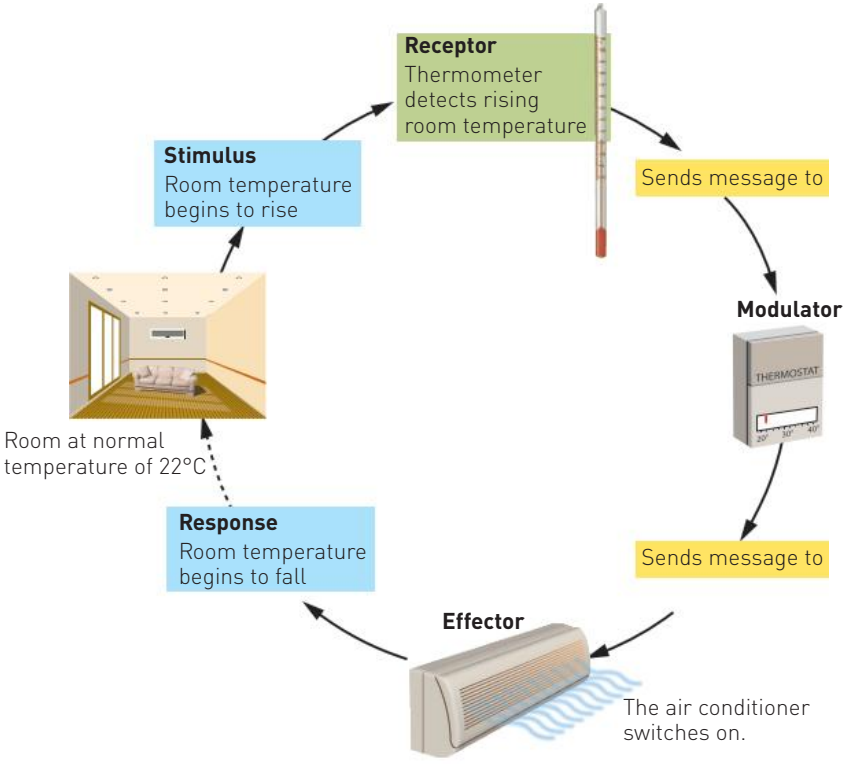


Figure 6.6a An air conditioning system uses negative feedback to keep room temperature fairly constant.

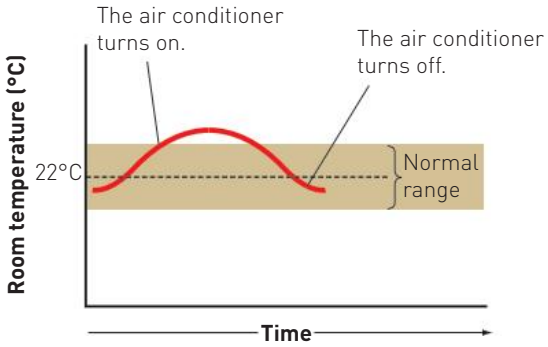


Figure 6.6b Room temperature fluctuates around the temperature determined by the thermostat.

Positive feedback

Positive feedback has no role in homeostasis but it is included here so that you can understand the difference between positive and negative feedback. When **positive feedback** occurs, the response to a stimulus reinforces and intensifies the stimulus. The intensified stimulus results in an even greater response, and so on. Obviously, this could not result in homeostasis, but there are a few situations in which it does occur in the human body. It is important in controlling processes that must be completed quickly.

A good example of positive feedback occurs during childbirth, a process that must be completed as rapidly as possible to avoid stress and injury to mother and baby. Labour is initiated by the secretion of the hormone oxytocin from the posterior lobe of the pituitary gland (see page 25). Oxytocin causes contractions of the uterus. The contractions push the baby's head against the mother's cervix. Stimulation of the cervix causes it to send nerve impulses to the brain, which responds by instructing the pituitary to secrete more oxytocin. The increased oxytocin makes the uterus contract more strongly. These contractions push the baby's head more forcibly against the cervix, which sends even more impulses to the brain, and so the uterine contractions are increasingly intensified (Figure 6.7). Once the baby is delivered, the cervix is no longer stretched; it ceases sending nerve impulses to the brain and the positive feedback cycle stops.

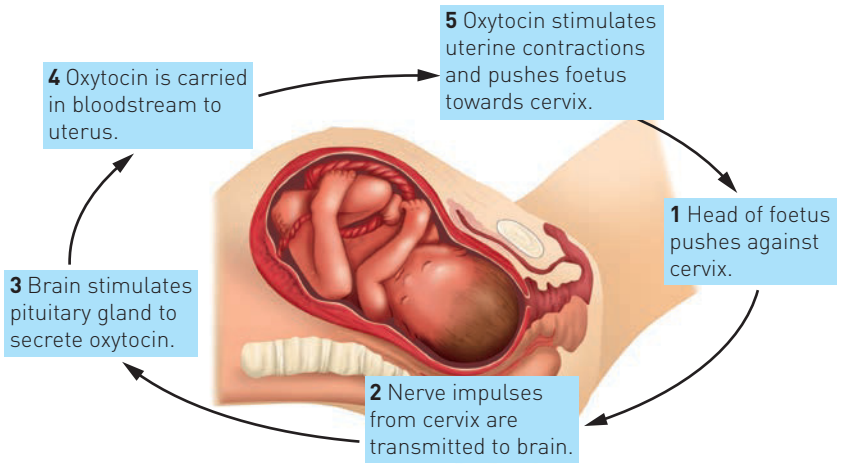


Figure 6.7 Childbirth is regulated by a positive feedback system.

Another example of positive feedback is blood clotting. This process must be completed quickly to minimise blood loss. However, sometimes positive feedback can be harmful. An example is a high fever. A small rise in body temperature can be beneficial in fighting infection; however, if body temperature rises above 42°C, a dangerous positive feedback loop can occur. The raised body temperature causes a higher metabolic rate that produces more heat, which raises the temperature still further. This increases the metabolic rate and so the temperature spirals upwards. Unless medical treatment is given, death will result when body temperature reaches about 45°C. (Fever is discussed further in Chapter 10.)

Science inquiry

ACTIVITY 6.1 Reflexes

In this activity you will examine some simple reflex responses.

YOU WILL NEED (FOR EACH PAIR)

Rule; glass rod; antiseptic solution; beaker; stethoscope

WHAT TO DO

For each of the following tests, one member of the pair should act as the subject; the other as the investigator.

I THE KNEE REFLEX

The subject should sit on a stool or a bench-top with one leg crossed over the other. Using a rule, the investigator should lightly strike the subject's crossed leg just below the knee cap.

1 Describe the response that occurs.

The stimulus for the response is the stretching of the patellar tendon just below the knee cap.

2 Describe the location of the muscle or muscles that produce the response.

3 Describe, in words, the reflex arc that is involved in the response.

Try to get a response with the knee straight and bent at different angles.

4 Does the response seem to be stronger at any particular angle of flexion? If so, can you suggest an explanation?

II THE HEEL REFLEX

Stand the subject beside a stool or chair with one leg kneeling on the seat of the chair. Use a rule to strike the back of the subject's ankle.

5 Describe the response.

6 What is the stimulus in this case?

7 In what ways is the heel reflex similar to the knee reflex?

8 Doctors often test reflexes such as the knee and heel reflex. What do you think testing such reflexes would tell a doctor?

III THE EYE REFLEX

With the subject seated directly in front, the investigator should suddenly clap their hands in front of the subject's face.

9 Describe any response observed.

10 Is the response a natural or a learned response?

11 Does the response have a purpose? Explain.

IV THE SWALLOWING REFLEX

The uvula is a piece of tissue that hangs down at the back of the throat. When the mouth is wide open, it can be seen as an inverted V shape.

With the subject's mouth open as widely as possible, the investigator should lightly touch the uvula with a glass rod that has been dipped in antiseptic solution.

12 Describe the response that occurs.

13 How does this reflex aid swallowing?

14 Draw and label a diagram showing the reflex arc that is involved in the swallowing reflex.

V CARDIAC SPHINCTER REFLEX

Where the oesophagus enters the stomach there is a circular band of muscle, the cardiac sphincter. This muscle controls the entry of food and liquids to the stomach.

Place a stethoscope against the left side of your partner's abdominal wall and listen while some water is swallowed.

15 Describe the sound you hear a few seconds after the water is swallowed.

The sound is caused by water entering the stomach after the relaxation of the sphincter muscle.

16 What stimulus causes the cardiac sphincter to relax?

CONCLUSIONS

17 Do all the reflexes that you have investigated have the four important properties that were described in this chapter?

18 Write a brief statement summarising the importance of reflexes to the normal functioning of the human body.

ACTIVITY 6.2 Reaction time

Responses do not occur instantaneously; even reflex responses require time for perception of the stimulus, for conduction of impulses to and from the brain or spinal cord, and for the effector to carry out the response. Reaction time, the time it takes to respond to a stimulus, depends on many factors, including the type and intensity of the stimulus and whether conscious thought is involved in the response.

Design and carry out an investigation into reaction time. Some ideas are presented below but you may decide to do something quite different. (Reaction timers are available on the Internet. Use a search engine to search for 'reaction timer'. Some sites time reactions directly, some allow you to download freeware and some give directions for making reaction timers. Sites that time reactions will not be suitable for many of the suggestions below.)

1 If you have access to an electronic timing device that will measure time in fractions of a second, you could try:
- **a** a visual stimulus such as a light coming on or going off, and a single finger movement response such as depressing a switch
- **b** a visual stimulus with a response involving many muscles, such as moving the whole hand or arm to depress a switch
- **c** an auditory stimulus with either a single finger or a multiple movement response
- **d** a stimulus with a response by the foot
- **e** comparing response time by the left and right hand/foot
- **f** changes in response time with practice
- **g** the effect of distracting the subject while waiting for the stimulus.

Record your results in a suitable way.

2 If no electronic timer is available, it is possible to estimate reaction time using a falling object. The investigator holds a metre or half-metre rule by one end so that it hangs vertically. The subject places the thumb and forefinger on opposite sides of, but not touching, the bottom end of the rule. When the investigator releases the rule, the subject grasps it between thumb and forefinger as soon as it falls. From the scale on the rule the distance of the fall can be measured. Use Figure 6.8 on page 82 to determine the reaction time.

Discuss with other students the sources of error in these investigations and try to minimise them as far as possible.

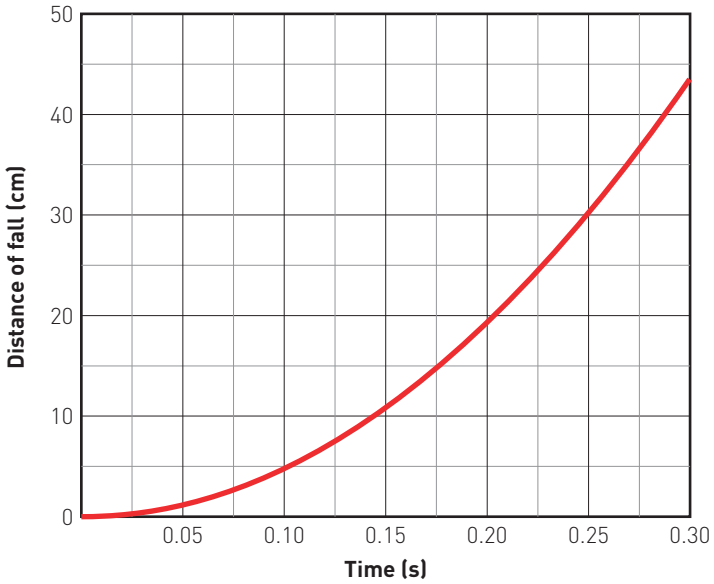


Figure 6.8 Graph showing time taken for an object to fall a given vertical distance

FURTHER INVESTIGATIONS

There are many other factors that may, or may not, influence reaction time. For example, you could investigate whether any of the following have an effect on reaction time:

- gender
- age
- caffeine consumption (in the form of tea or coffee)
- physical fatigue
- consumption of a meal
- use of the dominant hand compared with the non-preferred hand.

ACTIVITY 6.3 More reaction times

Reaction times

Reaction time is the time that elapses between a stimulus and the response to the stimulus. You can test your reaction time at the weblink. (You can access all weblinks directly via http://hp3and4.nelsonnet.com.au.)

1. Describe the pathway taken by the nerve impulses involved in detecting the stimulus and making the response.
2. Is the response an innate or an acquired response?
3. Draw a column graph showing your reaction time for five trials.
4. Does your reaction time decrease with practice? If so, suggest why.
5. Do five trials with your left hand and then five trials with your right. Describe and explain any difference between the two sets of trials.

Review questions

1 In what parts of the body are thermoreceptors found?
2 What does it mean when we say that receptors adapt to a stimulus?
3 What are the characteristics of a reflex?
4 Draw a diagram showing the components of a reflex arc. Fully label your diagram.
5 **a** What is homeostasis?
b What are the aspects of the internal environment that need to be regulated?
6 Define 'tolerance limits'.
7 Explain what the following terms mean:
a dynamic equilibrium
b set point.
8 Why is the stimulus-response-feedback mechanism referred to as a model?
9 **a** Using examples, explain the difference between positive and negative feedback.
b Why would a positive feedback loop be unable to achieve homeostasis?

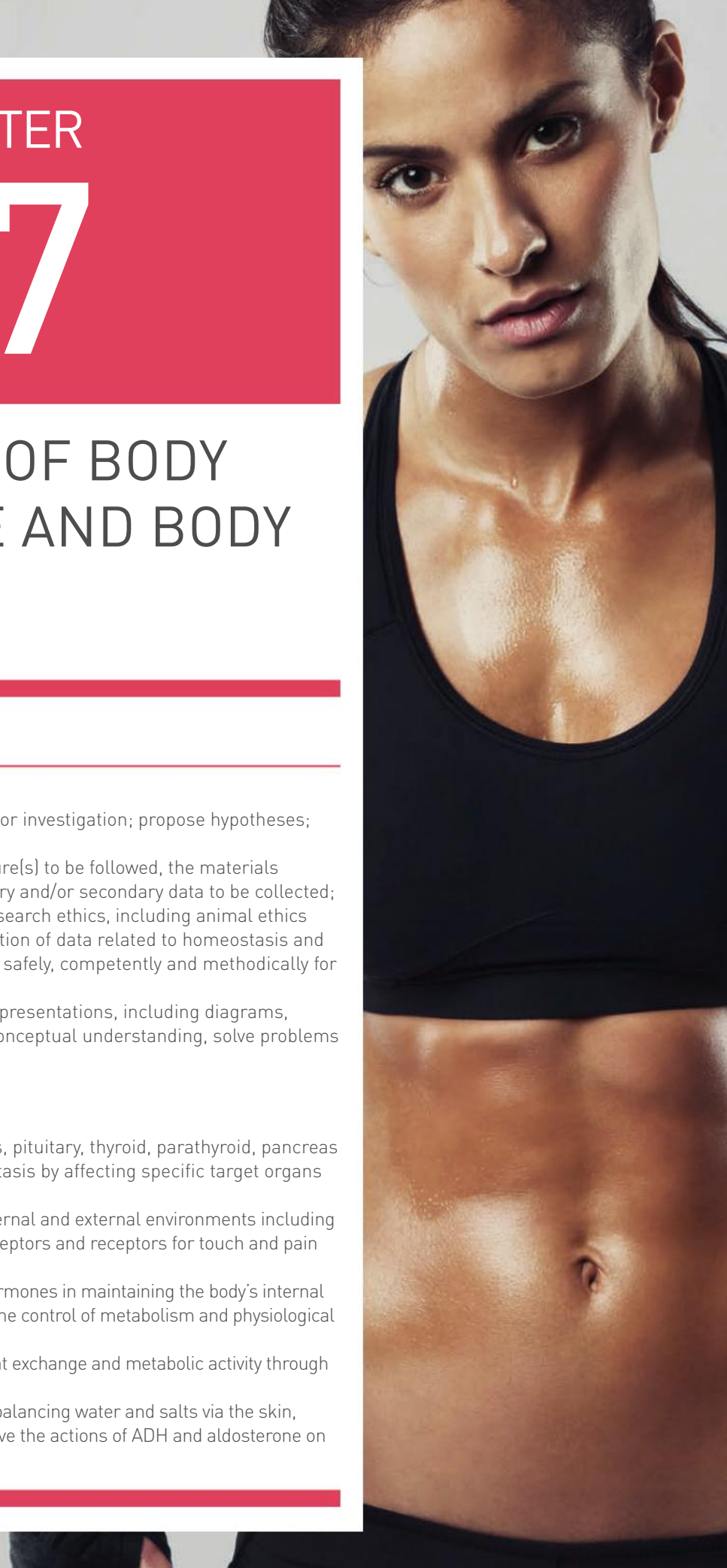
Apply your knowledge

1 Many reflexes are protective. List five protective reflexes.
2 Explain how we are able to distinguish between a light touch and heavy pressure on the skin.
3 A driver approaching traffic lights saw the lights change from green to amber. She transferred her foot from the accelerator to the brake in order to stop. Describe the pathways of the nerve impulses that would be involved in this response.
4 A person stepped on a broken bottle and by a reflex response withdrew their foot from the painful stimulus. Assume that the distance from the person's foot to the spinal cord was 1.2 m. Using the figures for speed of transmission of nerve impulses quoted in Chapter 3 (on page 40), what is the shortest time (in milliseconds) that could have elapsed between the stimulus and the response (1000 ms = 1 s)?
5 Is the situation described in Question 4 an example of a feedback system? Explain your answer.
6 When you withdraw your hand from a painful stimulus, the response occurs before you become consciously aware that you have hurt yourself. Explain how this is possible.
7 Why would it be unwise to continually take pain killers for a particular pain without seeking medical help?

CHAPTER

07

HOMEOSTASIS OF BODY TEMPERATURE AND BODY FLUIDS



UNIT 3 CONTENT

SCIENCE INQUIRY SKILLS

- identify, research and construct questions for investigation; propose hypotheses; and predict possible outcomes
- design investigations, including the procedure(s) to be followed, the materials required, and the type and amount of primary and/or secondary data to be collected; conduct risk assessments; and consider research ethics, including animal ethics
- conduct investigations, including the collection of data related to homeostasis and the use of models of disease transmission, safely, competently and methodically for the collection of valid and reliable data
- select, use and/or construct appropriate representations, including diagrams, models and flow charts, to communicate conceptual understanding, solve problems and make predictions

SCIENCE UNDERSTANDING

Endocrine system

- hormones secreted from the hypothalamus, pituitary, thyroid, parathyroid, pancreas and adrenal glands are involved in homeostasis by affecting specific target organs

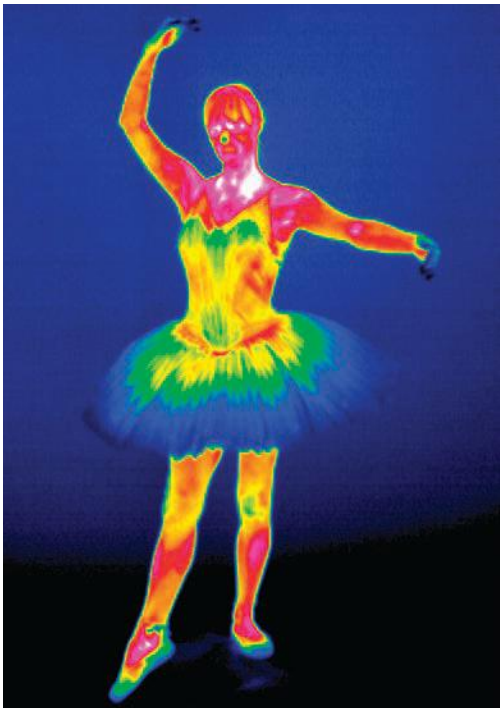
Central and peripheral nervous system

- different receptors detect changes in the internal and external environments including thermoreceptors, osmoreceptors, chemoreceptors and receptors for touch and pain

Homeostasis

- homeostatic processes involve nerves and hormones in maintaining the body's internal environment within tolerance limits through the control of metabolism and physiological and behavioural activities
- thermoregulation occurs by the control of heat exchange and metabolic activity through physiological and behavioural mechanisms
- body fluid concentrations are maintained by balancing water and salts via the skin, digestive system and the kidneys, which involve the actions of ADH and aldosterone on the nephron, and the thirst reflex

On a hot day you would probably respond by getting out of the sun, removing some of your outer clothing and turning on a fan or air conditioner. These are behavioural responses to the high temperature, but at the same time changes will be occurring inside your body that you are not consciously aware of. All these responses, conscious and unconscious, are working together to keep the body's core temperature within its tolerance limits. This regulation of body temperature – thermoregulation – makes us relatively independent of the environmental temperature.



Tony Mcconnell/Science Photo Library

Figure 7.1 A thermogram of a ballerina showing relative temperatures at the surface of the body. The warmest areas are white followed by red, yellow, green and blue with purple being the coldest.

Thermoregulation

Human body temperature remains remarkably constant at about 36.8°C. To achieve this, the heat gained by the body must exactly equal the heat lost from the body (Figure 7.2). Both the production of heat by body activities and the loss of heat from the body must be subject to precise physiological control. Maintaining the balance between heat production and heat loss is called **thermoregulation**.

Constancy of body temperature is an important aspect of homeostasis because the chemical reactions occurring in cells are very heat-sensitive. A temperature around 37°C is the optimum for cellular reactions and so cells maintained at this temperature function in a stable manner. Under most conditions, internal body temperature is higher than the surrounding environmental temperature. The heat produced from metabolic activity helps to maintain this higher level. However, during exercise and other strenuous activity, the increase in metabolic rate generates more heat than the body needs to keep its temperature constant. The excess heat needs to be removed or body temperature will rise. Increased body temperature can cause nerve malfunction, change in the structure of proteins, and death. It is therefore extremely important for the body to be able to regulate its internal temperature and maintain it within fairly precise limits.

Regulation of body temperature is an excellent example of a homeostatic control system, with a dynamic equilibrium being maintained between factors that contribute to heat gain and factors that contribute to heat loss.

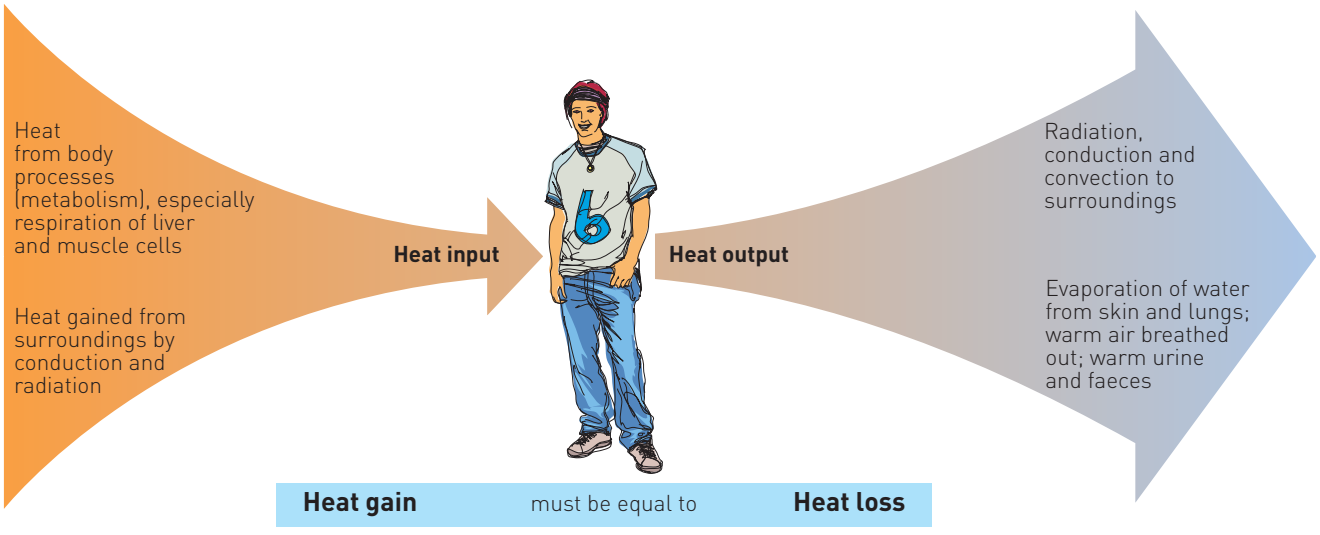


Figure 7.2 A constant human body temperature is achieved by a balance between heat gain and heat loss.

Although body temperature remains fairly constant, variation does occur as a matter of course. This variation may result from activity or changes in external temperature. In addition, there is a characteristic daily body temperature cycle, with the lowest temperature generally occurring in the morning and the highest in the evening. Women have higher temperatures during the second half of the menstrual cycle as a result of the effects of the hormone progesterone.

Heat production

The carbohydrates, proteins and lipids that we eat contain energy in chemical bonds that hold the various parts of the molecule together. In the process of cellular respiration, in which food is oxidised in the cells, this energy is released.

Some of the energy is used for muscle contraction, for active transport of substances across the cell membrane, for building up new complex molecules, and so on. Most of the energy, however, is released in the form of heat.

The rate at which energy is released by the breakdown of food is called the **metabolic rate**. Many factors, such as exercise, stress and body temperature, affect the metabolic rate of an individual. The one with the greatest effect is exercise. During exercise, muscular activity can increase metabolic rate by up to 40 times so that very large quantities of heat are released.

Metabolic rate also increases in times of stress because of the activities of the autonomic division of the nervous system. Stimulation of sympathetic nerves releases noradrenaline from the nerve endings; noradrenaline increases the metabolic activity of cells. Strong sympathetic stimulation may cause dramatic increases in the metabolic rate, but usually for only a few minutes.

Rising body temperature is another factor that increases metabolic activity. For each 1°C rise in temperature, the rate of biochemical reactions increases by about 10%. When an individual is suffering from a high fever, the metabolic rate may be up to double the normal rate.

Temperature receptors

The body has temperature receptors, or thermoreceptors. Those in the skin and in some mucous membranes are called **peripheral thermoreceptors**. Others are located in the hypothalamus and are called **central thermoreceptors**.

Peripheral thermoreceptors provide the hypothalamus with information about the external environment. There are two types of peripheral thermoreceptors: **cold receptors** are stimulated by environmental temperatures lower than normal, and **heat receptors** detect temperatures higher than normal. When cold receptors are stimulated, the hypothalamus receives the information and initiates heat conservation and heat production mechanisms. If heat receptors are stimulated, mechanisms operate to reduce heat production and increase heat loss.

Peripheral thermoreceptors alone would not be efficient in the regulation of body temperature as it is the core temperature that must be regulated. In addition to the central thermoreceptors located in the hypothalamus, there are others at various internal locations such as the spinal cord and the abdominal organs. All are connected to the hypothalamus, which is the body's main temperature-regulating centre. Nerve impulses sent out by the hypothalamus control activities that help to either increase or decrease body temperature.

The skin and temperature regulation

The skin is a very important organ in regulating body temperature. Changes in the skin can speed up or slow down the rate at which heat is lost from the body. Blood vessels carry heat to the skin from the core of the body. Heat can then be lost from the skin by conduction, convection, radiation and evaporation.

The diameter of blood vessels to the skin is controlled by autonomic nerves, which can act to increase or decrease the flow of blood near the surface, thereby increasing or decreasing the rate of heat loss. These automatic adjustments to skin blood flow keep core body temperature constant in moderate conditions.

When large amounts of body heat must be lost and skin blood vessels are already at maximum dilation, sweating must occur. **Sweating** is the active secretion of fluid by the **sweat glands** (Figure 7.3) and the periodic contraction of cells surrounding the ducts to pump the **sweat** to the skin surface. The production and transport of sweat to the skin surface is stimulated by sympathetic nerves. Sweat is water containing dissolved substances, primarily sodium chloride, along with small amounts of urea, lactic acid and potassium ions. Evaporation of sweat from the skin has a cooling effect: heat is removed from the skin when liquid sweat changes into vapour. Cooling of the skin results in cooling of the blood flowing through the skin.

Even in the absence of sweating there is continual loss of water by evaporation from external body surfaces. This evaporation, along with water that is evaporated from the lungs and respiratory passages, accounts for a considerable proportion of the daily heat loss from the body.

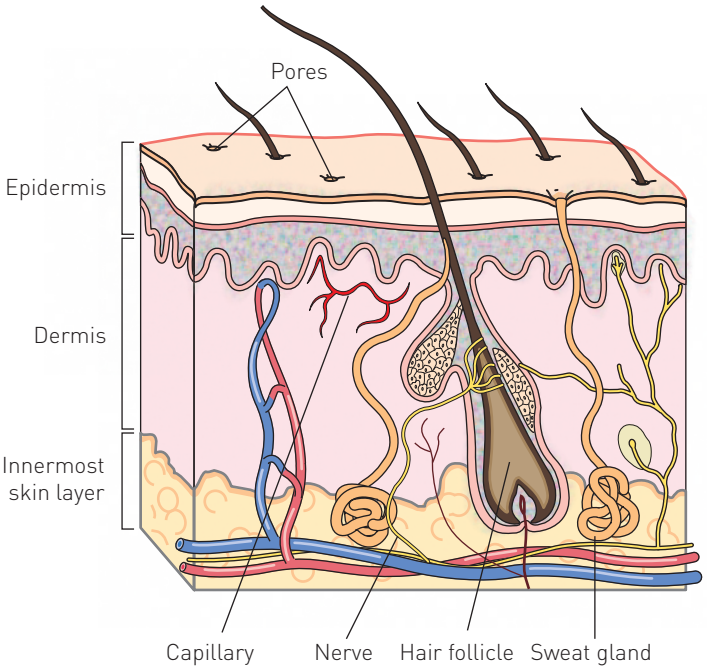


Figure 7.3 A section of skin showing sweat glands

Preventing body temperature from falling

If the environmental temperature falls, or if a person goes from a warm room into a cold environment outside, the cold receptors in the skin send messages to the hypothalamus. The hypothalamus then sends out impulses aimed at reducing heat loss and increasing heat production so that body temperature is maintained. The body can respond by physiological changes (changes in body functioning) and behavioural changes.

- One physiological response is **vasoconstriction** in the skin. Impulses from the hypothalamus stimulate sympathetic nerves that cause blood vessels in the skin to constrict. This vasoconstriction decreases the flow of warm blood to the skin from the internal organs, thus decreasing the transfer of heat from the internal body organs to the skin. The skin becomes cooler because there is less warm blood flowing through it. Less heat will then be lost from the body surface. In this way, vasoconstriction of skin blood vessels helps maintain body temperature in cold conditions (Figure 7.4).

Heat transfer
This website gives more information about the different methods of heat transfer: conduction, convection and radiation.

More on heat transfer
This website provides an animation of the various methods of heat transfer.

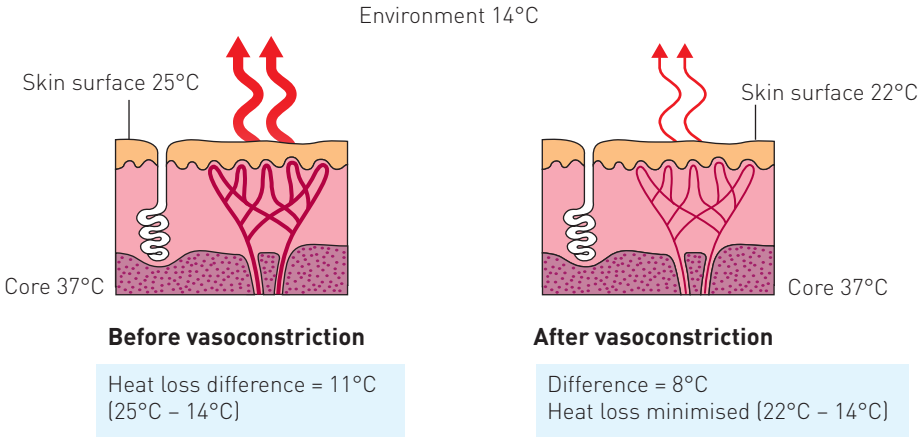


Figure 7.4 The effect of vasoconstriction in the skin

- A second response initiated by the hypothalamus is the stimulation of the adrenal medulla by sympathetic nerves. This stimulation results in the medulla secreting adrenaline and noradrenaline into the blood. These hormones bring about an increase in cellular metabolism that leads to an increase in heat production. This helps to maintain internal body temperature in conditions where there is rapid heat loss.
- In cold conditions, heat may be produced by a third response – shivering. A fall in body temperature causes the hypothalamus to send stimuli to the parts of the brain that increase skeletal muscle tone. This increase in muscle tone leads to oscillating, rhythmic muscle tremors occurring at a rate of around 10 to 20 per second. These tremors are known as shivering and can increase body heat production several-fold within minutes. As no external work is done, all the energy liberated by the metabolic activity goes towards internal heat. Shivering is under the primary control of the hypothalamus, but conscious input from the cerebral cortex can suppress the urge to shiver.
- The fourth response to a fall in body temperature is an increase in the production of thyroxine. The hypothalamus is able to cause the anterior lobe of the pituitary to secrete thyroid-stimulating hormone (TSH), which causes the thyroid gland to release thyroxine into the blood. The increased levels of thyroxine increase metabolic rate, resulting in an increase in body temperature. This response is slower to have an effect, but it is longer-lasting than other responses. The small change in metabolic rate that occurs between the warm summer months and cool winter ones is a result of this response.
- A behavioural response may occur if we become consciously aware of cold conditions. If we feel cold we can behave in a way that reduces heat loss, such as by putting on an extra jumper or sheltering from a cold wind. Another behavioural response that helps to reduce heat loss is reducing the surface area of the body from which heat can be lost. You may have noticed that when you are cold in bed you tend to curl up into a ball.

Preventing body temperature from rising

When the weather is warm, or when we exercise, the heat produced by metabolism is greater than that needed to maintain a constant body temperature. This excess heat needs to be lost from the body, otherwise core temperature will rise. Most heat loss occurs through the skin, although smaller amounts of heat are lost with the gases breathed out from the lungs, and with the faeces and urine.

The following responses ensure that body temperature does not rise.

- **Vasodilation** of skin blood vessels increases blood flow through the skin. The skin becomes reddish in colour, surface temperature rises, and there is greater heat loss through radiation and convection (Figure 7.5).

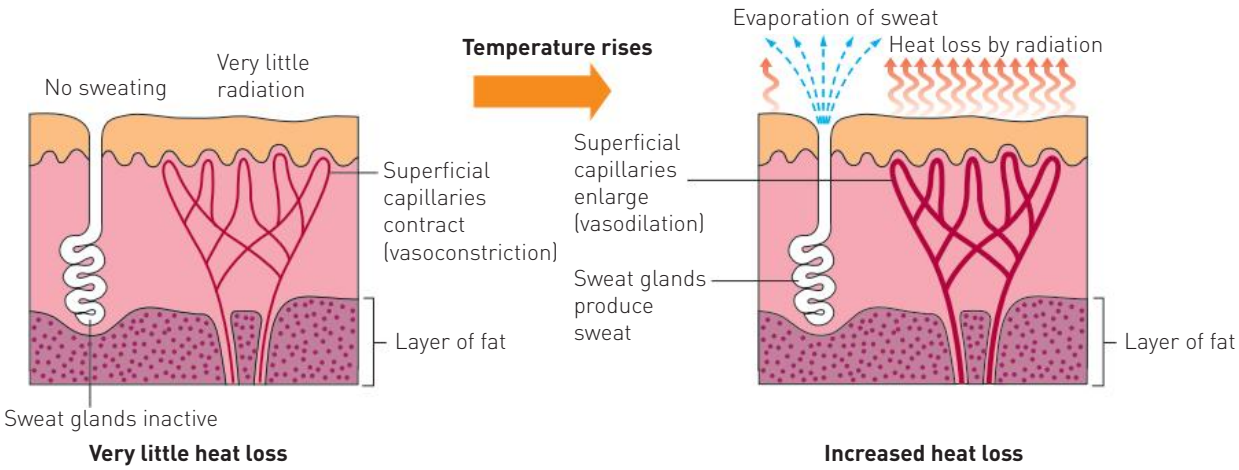


Figure 7.5 Heat loss from the skin can be increased by vasodilation of skin blood vessels and by sweating.

- Above environmental temperatures of about 28°C, sweating is needed to increase heat loss from the body (Figure 7.5). The cooling effect of sweating is effective only in environments that are fairly dry. If the air is very humid, sweat cannot evaporate. If both humidity (the water vapour concentration of the air) and temperature are high, individuals often suffer considerable discomfort as the sweat remains on the skin or simply drips off. It is only in a low-humidity environment that sweating is a really effective means of preventing body temperature from rising. If environmental temperatures are greater than 37°C, heat is gained from the environment and the evaporation of sweat is then the only avenue for heat loss.
- In the long term there can be a decrease in metabolic rate, which means less heat is produced in the body. Such a decrease is brought about by reduction in the secretion of thyroxine, a response that occurs in summer when there is much less heat loss than in winter.
- Behavioural responses can also help to prevent body temperature from rising. Actions such as turning on a fan or air conditioner, removing external clothing and reducing physical activity can all help to keep temperature constant.

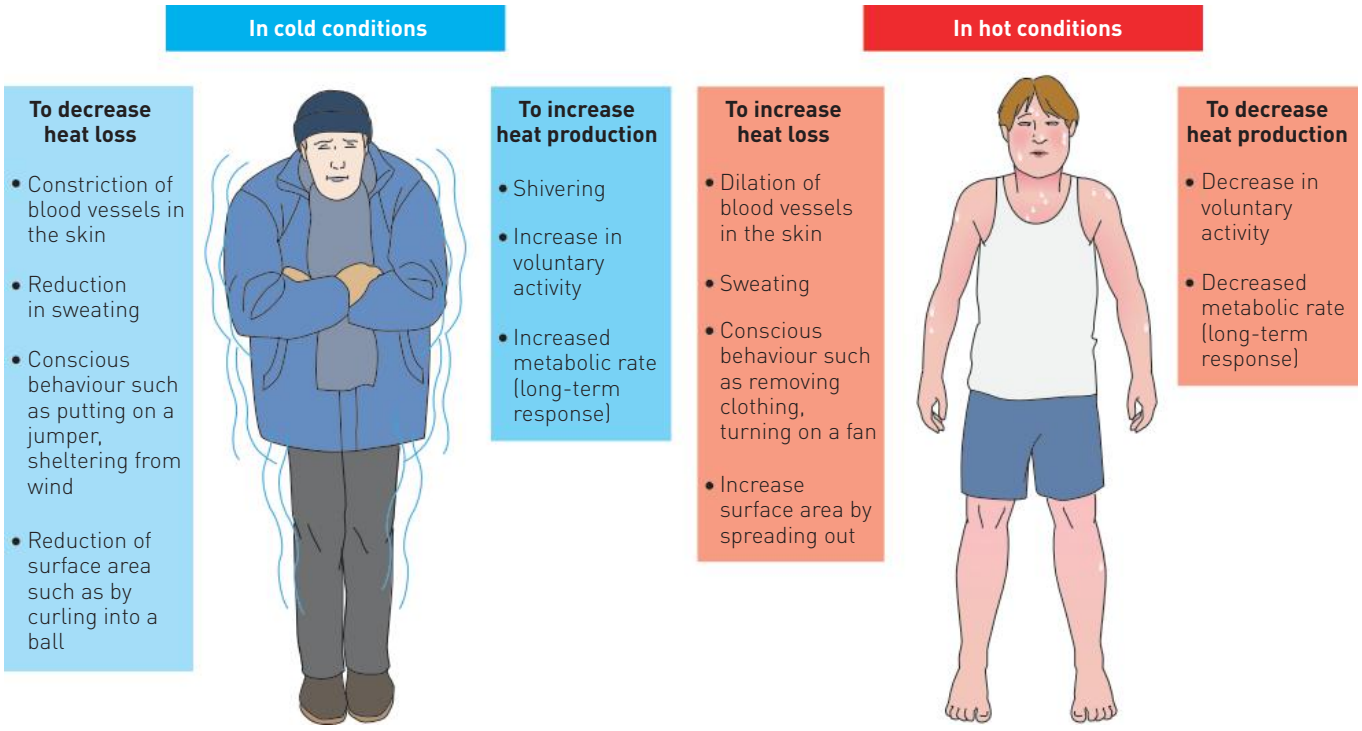


Figure 7.6 Mechanisms for regulating temperature

Control of thermoregulation

As we have seen, it is the hypothalamus that exercises control over the various mechanisms involved in maintaining body temperature. The hypothalamus monitors the temperature of the blood and receives impulses from the peripheral thermoreceptors. Through negative feedback loops involving the autonomic division of the nervous system, it controls the diameter of skin blood vessels, sweating, shivering and other mechanisms for maintaining temperature. Figure 7.7 on page 90 summarises the role of the hypothalamus in thermoregulation.

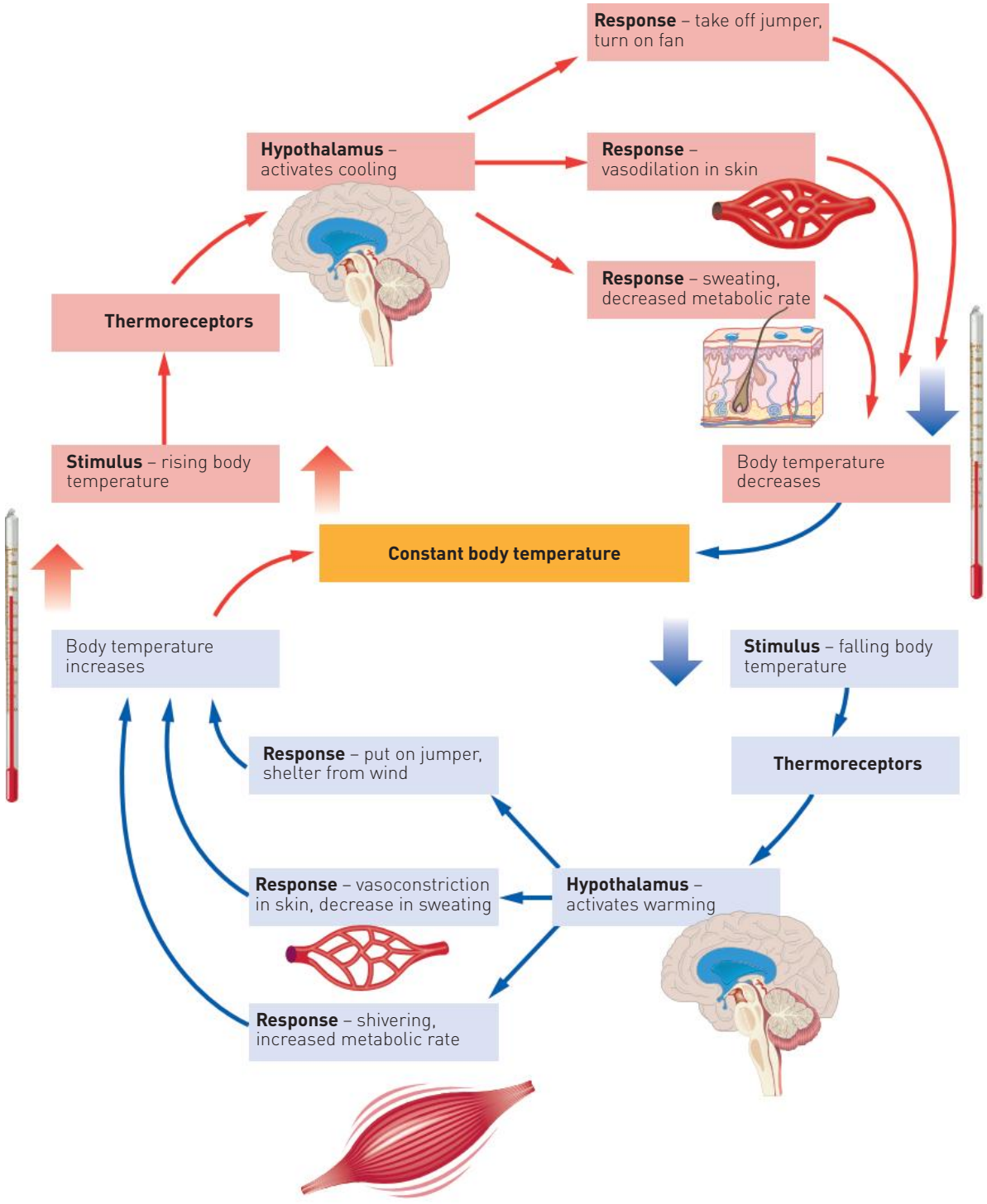


Figure 7.7 The role of the hypothalamus and mechanisms involved in maintaining a constant body temperature

EXTENSION

In the arms and legs there is exchange of heat between the arteries carrying blood to the limbs and the veins taking blood away from the limbs. This is called a countercurrent heat exchange.

Find out how countercurrent heat exchange operates and its significance in maintaining core body temperature.

Temperature tolerance

A core body temperature over 42°C is dangerous and death usually occurs if it rises above about 45°C. High body temperature can result from a fever, but it can also occur in certain environmental conditions. When the temperature and relative humidity are high, it is difficult for the body to lose heat by radiation or evaporation. In this case body temperature rises and the regulatory mechanisms cease. This is called **heat stroke** and it can be very serious, or even fatal, if brain cells are affected. Treatment consists of cooling the body as quickly as possible by immersing the patient in cold water.

A condition that occurs more frequently than heat stroke is **heat exhaustion**. This occurs as a result of extreme sweating and vasodilation to lose heat. The loss of water in sweating reduces the volume of blood plasma and the vasodilation reduces resistance to blood flow. Blood pressure is thus reduced and output of blood from the heart decreases. The person may, therefore, collapse. Unlike heat stroke, the body temperature is almost normal.

Extreme cold can also cause death. If a person's core temperature falls below 33°C, the metabolic rate is so low that heat production is unable to replace the heat lost and body temperature continues to fall. This condition is called **hypothermia**. Death can occur at core temperatures below 32°C, but people have been known to survive even lower temperatures.

Hyperthermia
This website provides more information about hyperthermia.

Hypothermia
This website provides more information about hypothermia.

WS

Homeostasis of body temperature

Regulation of the composition of body fluids

Body fluids

The human body is approximately 60% water, but this proportion varies considerably between individuals and can be as low as 45% or as high as 75%. Males, with an average of 65%, have a higher percentage of water in their bodies than females, with an average of 55%. Thus, the body of a male weighing 70 kg, with a water content of 65%, would contain 45.5 L of water. This large amount of water is contained in the various body fluids. The fluid inside the cells is called the **intracellular fluid** or **cytosol**. Fluid outside the cells is the **extracellular fluid**. Extracellular fluid includes the blood plasma and the fluid between the cells, which is called **intercellular fluid** (Figure 7.8). Alternative names for intercellular fluid are **interstitial fluid** and **tissue fluid**. Table 7.1 summarises the types of body fluid.

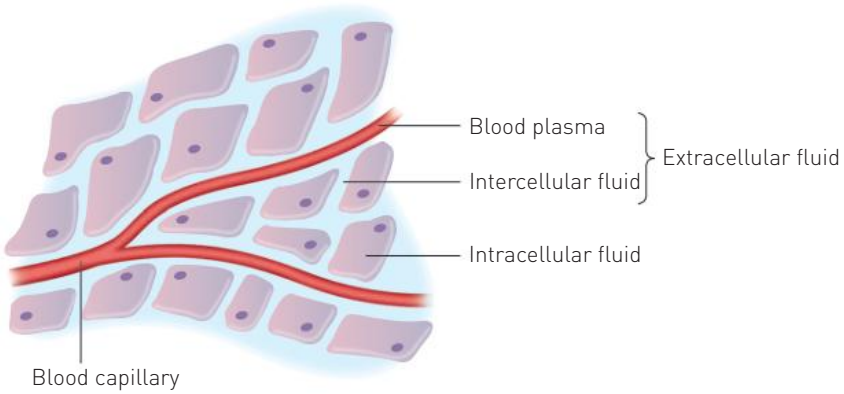


Figure 7.8 The body fluids

Table 7.1 Body fluids

Type of body fluid	Proportion of total body fluid	Components of the body fluid
Intracellular fluid	2/3 of total body water	Fluid inside the cell – the cytosol
Extracellular fluid	1/3 of total body water	Fluid that is outside the cells
Plasma	1/4 of extracellular fluid	The fluid part of the blood
Intercellular fluid	3/4 of extracellular fluid	Lymph, cerebrospinal fluid, synovial fluid in joints, fluids of eyes and ears, fluid in the chest and abdominal cavities and around the heart, fluids of the alimentary canal, kidney filtrate

The different body fluids are not isolated from one another – there is a continuous exchange of materials between them. Plasma is separated from the intercellular fluid by the thin walls of the capillaries, and there is a relatively free exchange of materials between the two. However, dissolved materials that are large molecules, such as the proteins of the plasma, tend to remain within the blood vessels as they are too large to move through the capillary walls.

Water moves easily through plasma membranes and so any difference in osmotic concentration between the intracellular fluid and the extracellular fluid does not last very long. If an imbalance in osmotic concentration does occur in any tissue, osmosis normally restores the balance within seconds. The exchange of materials across cell membranes was discussed in *Human Perspectives Units 1 & 2 ATAR*.

Fluid balance

In the same way that heat gain must be equal to heat loss in order to maintain a constant body temperature, fluid gain must equal fluid loss if the composition of body fluids is to be kept fairly constant.

Most of the body fluid is obtained from water that is either taken in as a liquid or contained in food that is eaten. A small amount is obtained as a by-product of chemical processes occurring within the cells. This water is referred to as **metabolic water**. Over a period of a day or so, the quantity of water taken in must balance the quantity of water lost. Fluids are lost from the body via the kidneys, through the skin, from the surface of the lungs and from the alimentary canal. Typically, about 2.5 L of fluid are lost each day. Figure 7.9 summarises the sources of fluid intake and the avenues of output.

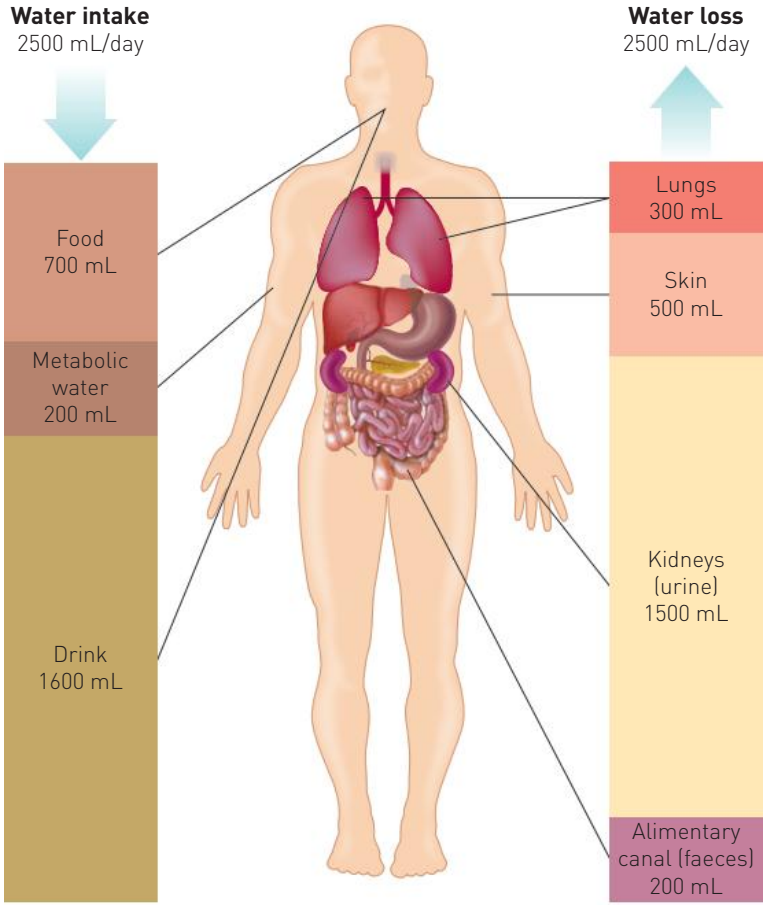


Figure 7.9 Daily fluid intake and output

Excretion

Excretion is the removal from the body of the waste products of metabolism. Many wastes are toxic and would be harmful to health if allowed to accumulate in the body fluids. Every cell produces waste products, so their removal before they reach harmful concentrations is extremely important.

Several organs in the body take part in excretion.

- The **lungs** are involved in the excretion of carbon dioxide. Carbon dioxide and water are produced by all body cells during cellular respiration. The body cannot use carbon dioxide and it is carried in the blood until it reaches the lungs, where it is excreted. Some water is also lost from the lungs, in the form of water vapour, as we exhale. (See Chapter 8 for more detail.)
- **Sweat glands** in the skin secrete water containing by-products of metabolism such as salts, urea and lactic acid.
- The **alimentary canal** passes out bile pigments that entered the small intestine with the bile. These pigments are the breakdown products of haemoglobin from red blood cells. They leave the body with the faeces. The bulk of the faeces is composed of undigested food materials. These are not considered to be excretory products as they have not been produced by the cells.
- The **kidneys** are the principal excretory organs. They are responsible for maintaining a constant concentration of materials in the body fluids. One of the important wastes removed by the kidneys is urea, and this is produced in the liver during the breakdown of proteins.

The kidneys

As you can see from Figure 7.9, about 60% of the water lost from the body each day is excreted by the kidneys as urine. Water loss from the lungs and from the alimentary canal cannot be regulated. Water loss from the skin (sweat) is directly linked to temperature regulation. This means that only water loss from the kidneys can be regulated to achieve a constant concentration of dissolved substances in the body fluids. Thus, the kidneys are not just excretory organs; they play a major role in regulating the composition of body fluids.

The kidneys are a pair of reddish-brown organs located in the abdomen. They are on either side of the vertebral column, at about the level of the lowest ribs, and are attached to the rear wall of the abdominal cavity. Each kidney is about 11 cm long, and due to the presence of the liver, the right kidney is usually slightly lower than the left. The kidneys are embedded in, and held in position by, a mass of fatty tissue.

A tube, the **ureter**, leaves each kidney and drains into a muscular reservoir, the **urinary bladder** (Figure 7.10). This empties to the outside through a tube, the **urethra**.

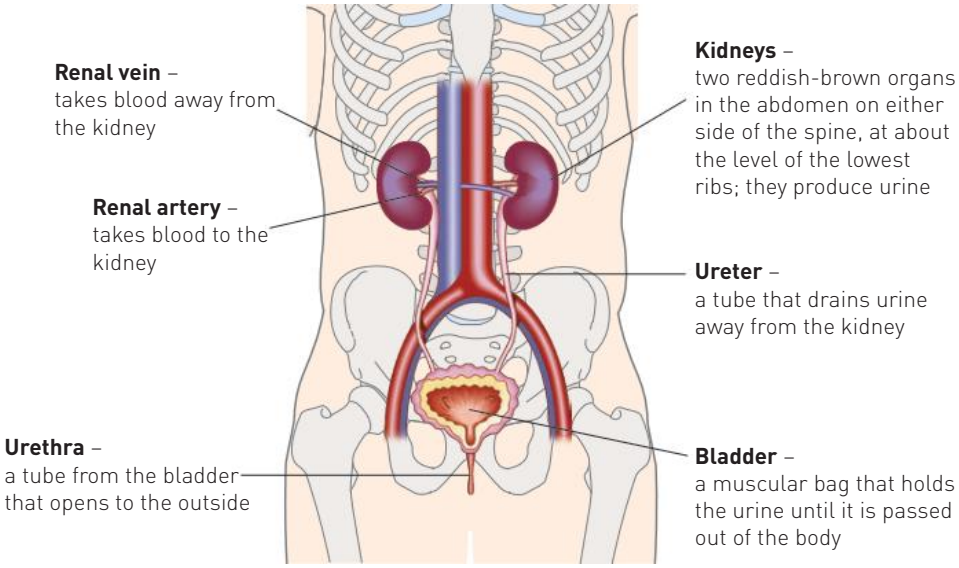


Figure 7.10 The kidneys and associated organs

Each kidney contains about 1.2 million microscopic units called nephrons. The **nephron** is the functional unit of the kidney; that is, it is the nephrons that carry out the kidney's role in excretion and water regulation. Figure 7.11 shows a nephron and explains how it functions. Detailed information about the structure and function of the nephron was covered in *Human Perspectives Units 1 & 2 ATAR*.

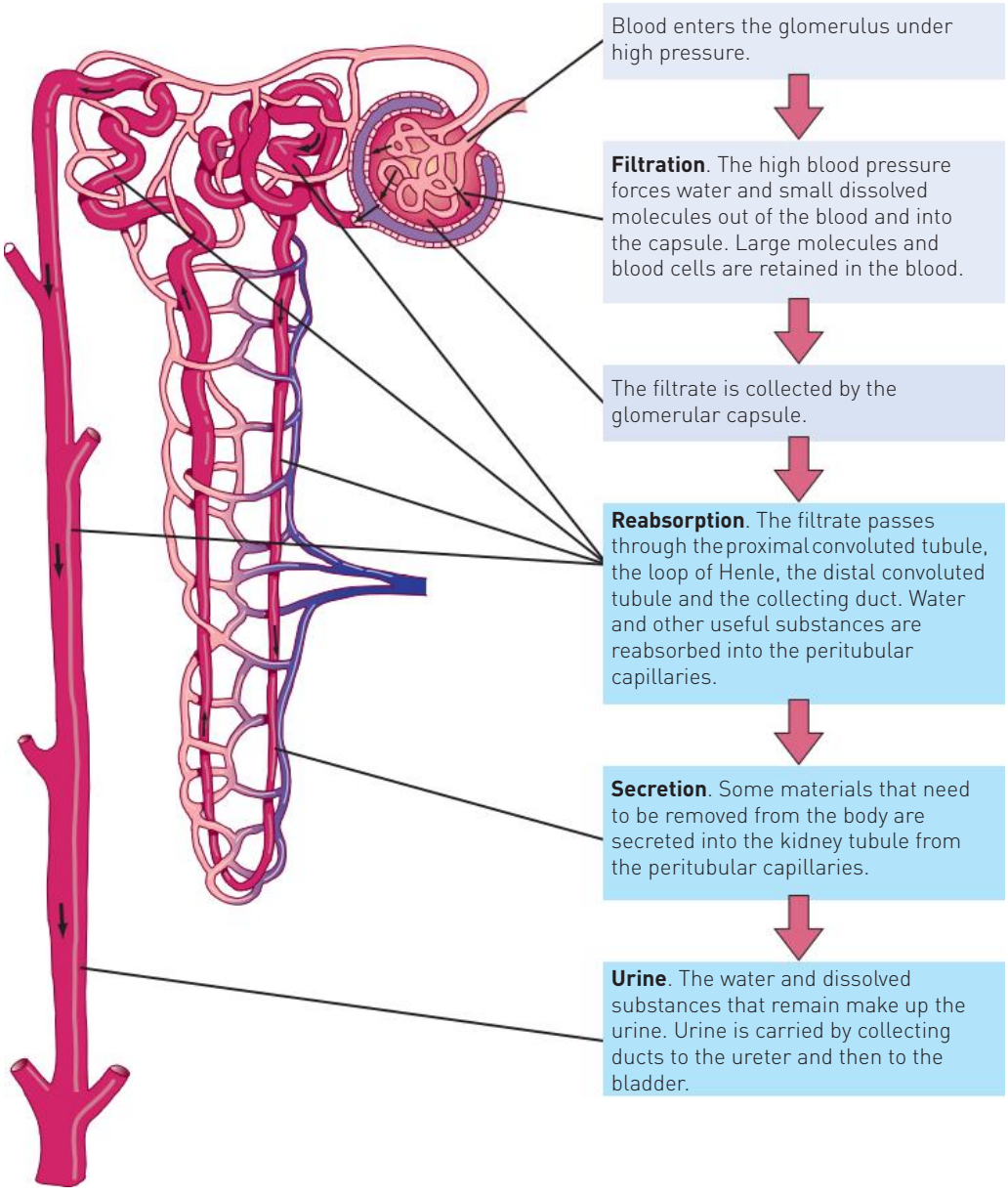


Figure 7.11 The functional unit of the kidney is the nephron.

Control of water loss by the kidneys

The volume and composition of urine produced by the kidneys depends on how much water there is in the body fluids. If you drink a large volume of water, you will quite soon produce a large volume of dilute urine. If you become dehydrated, through not drinking enough water, you will produce a smaller volume of concentrated urine.

Approximately 99% of the water filtered through the glomeruli of the kidneys is reabsorbed. This reabsorption occurs through the walls of the kidney tubules along their entire length. However, the reabsorption occurring at the proximal convoluted tubule and loop of Henle

(nephron loop) is by osmosis, while reabsorption at the distal convoluted tubule and collecting tubule is active reabsorption. The level of active reabsorption is controlled by a hormone known as **antidiuretic hormone (ADH)**.

ADH is produced by the hypothalamus and released from the posterior lobe of the pituitary (see page 26). The permeability of the walls of the distal convoluted tubule and collecting duct is controlled by ADH. When the concentration of ADH in the blood plasma is high, the tubules are very permeable to water, and thus water is able to leave the tubule and enter the surrounding capillary network. This outward flow of water from the fluid within the tubules reduces its volume and hence increases the concentration of the materials remaining. On the other hand, when the concentration of ADH in the plasma is low, the tubules are not very permeable to water, and little water is reabsorbed into the plasma of the blood. In this situation, the fluid within the tubules remains fairly dilute, as its volume is not reduced to any significant extent.

The action of ADH in controlling water balance is another example of a feedback process maintaining the internal environment of the body. The mechanism for the process is described below and illustrated in Figure 7.12.

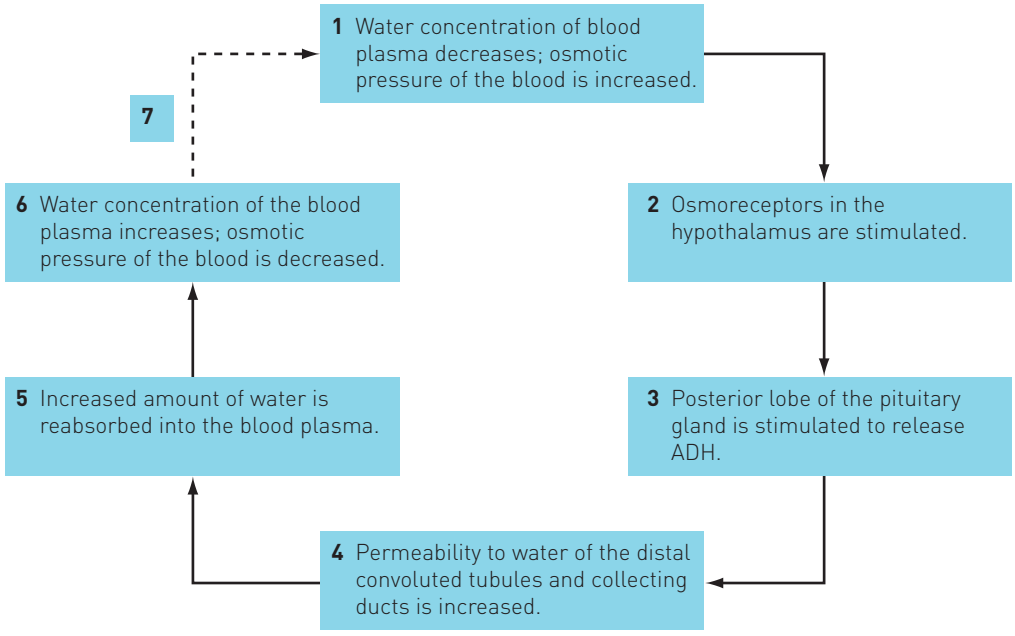


Figure 7.12 The regulation of water output by antidiuretic hormone (the numbers refer to the points listed in the text)

1. If a decreased amount of water is in the blood, such as would result from increased loss of water through sweat, the water concentration of the blood plasma would decrease. This means the osmotic pressure of the blood is raised.
2. Osmoreceptors in the hypothalamus detect the increased osmotic pressure of the blood.
3. The hypothalamus stimulates the posterior lobe of the pituitary gland to release ADH into the bloodstream.
4. ADH is carried all over the body by the blood but it affects its target organs, which are the nephron tubules in the kidney. The permeability to water of the distal convoluted tubules and the collecting ducts is increased.
5. More water is then reabsorbed into the blood plasma from the tubules and ducts.
6. The reabsorption of water increases the water concentration in the plasma and so the osmotic pressure of the blood is decreased.
7. The response is decreased osmotic pressure of the blood. This has eliminated or reduced the original stimulus that was increasing osmotic pressure of the plasma. Negative feedback has occurred.

In addition to ADH, **aldosterone** is another hormone that plays a part in the regulation of water output. Aldosterone, sometimes called the salt-retaining hormone, is secreted by the adrenal cortex. It acts on the kidney tubules to increase the amount of sodium (salt) reabsorbed into the bloodstream and to increase the amount of potassium excreted in the urine. Because water is also reabsorbed along with the sodium, aldosterone has a role in regulating water content of the body. Increasing water reabsorption increases blood volume, which in turn increases blood pressure. Thus, increased aldosterone secretion has the indirect effect of increasing blood pressure.

Regulating water intake

Water is continually lost from the body in sweat, urine, faeces and exhaled breath (see Figure 7.9 on page 92). At times of strenuous activity this water loss can be quite high. As water is lost from the blood, the plasma becomes more concentrated, and has a lower water content and hence a higher osmotic pressure. As a result, water moves from the intercellular fluid into the plasma by osmosis. Now the intercellular fluid is more concentrated, and water diffuses out of the cells, so the cells start to shrink from dehydration.

The events that take place to bring about intake of water and restoration of the water balance are listed below.

1. As water is lost from the various body fluids, there is a reduction in plasma volume and an increase in osmotic concentration of the extracellular fluid.
2. Osmoreceptors in a thirst centre in the hypothalamus detect the rising osmotic concentration of the blood. Other stimuli such as a dry mouth are also involved.
3. Stimulation of the thirst centre makes the person feel thirsty.
4. The conscious feeling of thirst stimulates the person to drink.
5. The fluid consumed is absorbed into the plasma from the alimentary canal.
6. As the blood circulates through the body, it enables the intercellular fluid and intracellular fluid to return to the proper osmotic concentration. Figure 7.13 shows how water moves between the various parts of the body.

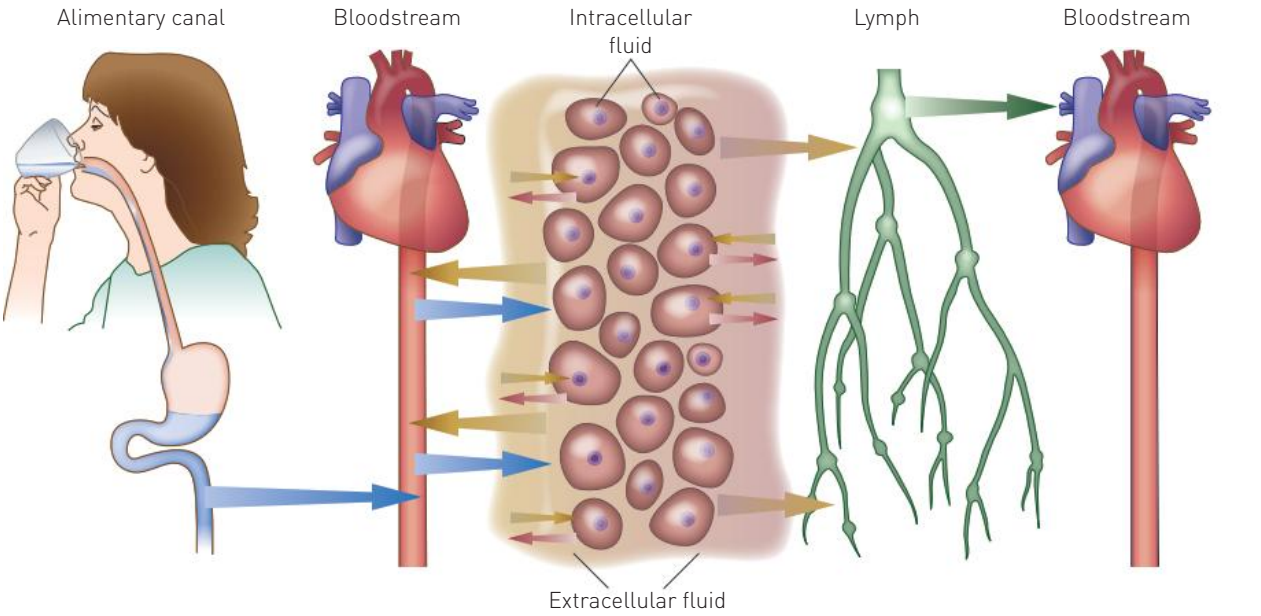


Figure 7.13 Movement of water between the various parts of the body

7 After drinking, the thirst centre is no longer stimulated and the desire to take in water ceases. This is another negative feedback loop. In this case it is involved in the regulation of the water content of the body (see Figure 7.14).

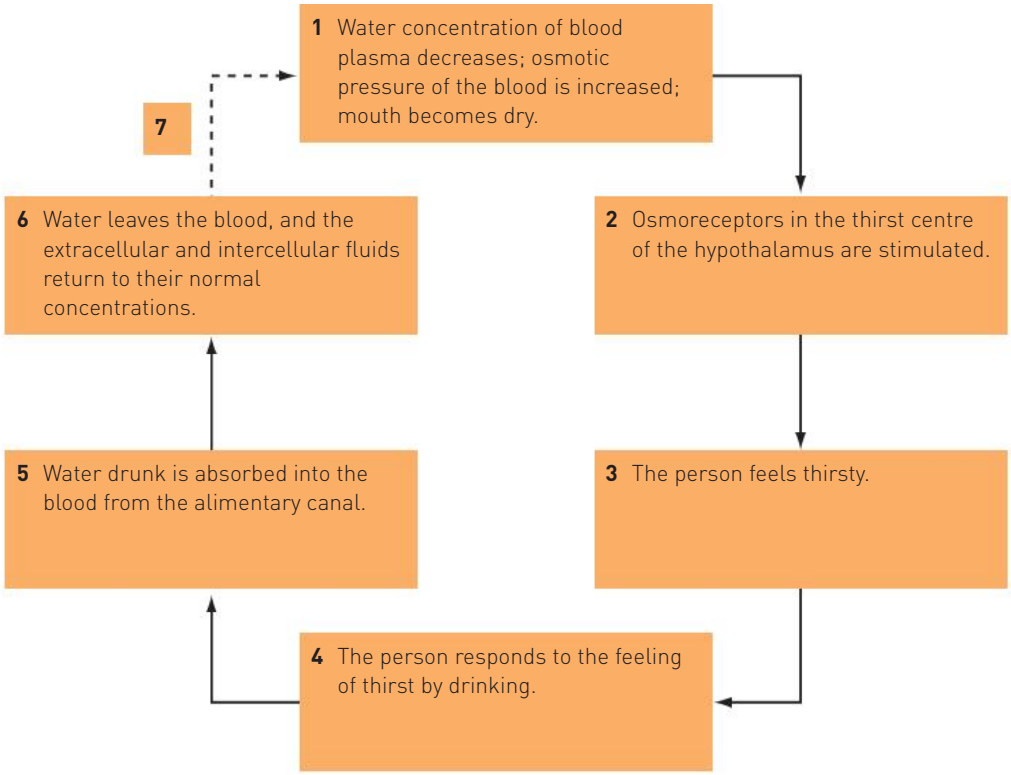


Figure 7.14 Regulation of water balance by the thirst mechanism (the numbers refer to the points listed in the text)

Too much and too little

We are all aware of the ultimate consequences of **dehydration** – when water loss exceeds water intake. You have probably read stories or news reports about people dying in the desert through lack of water. Symptoms of dehydration become noticeable when a person has lost about 2% of their normal body water. The loss may be through sweating, vomiting or diarrhoea. Elderly people can suffer from dehydration because the thirst reflex becomes less effective as we grow older. Symptoms of dehydration include severe thirst, low blood pressure, dizziness and headache. If the condition remains untreated the patient becomes delirious, loses consciousness and dies.

It is possible to have too much water in the body. This is called **water intoxication**, or sometimes water poisoning. It occurs when body fluids become diluted and cells take in extra water by osmosis. This may happen if a person loses a lot of water and salts through sweating and replaces the loss with plain water. In such cases, the water consumed should contain dissolved substances to replace the lost salts and the water. The first sign of water intoxication is usually lightheadedness. Headache, vomiting and collapse may follow.

Dehydration and water intoxication
This website provides more information on water as a vital nutrient and includes discussion of dehydration and water intoxication.

WS

Homeostasis of body fluids

EXTENSION

Elderly people are much more likely to suffer from water regulation problems than the young. The gradual decline in the effectiveness of the thirst reflex has already been mentioned, but there is also a decline in the effectiveness of the kidneys.

Find out the changes in kidney function that occur with age, and describe some of the conditions that can occur in elderly people due to poor kidney function.

Science inquiry

ACTIVITY 7.1 Investigating thermoregulation

Working with a partner or in a small group, design an investigation to answer a question, or questions, about thermoregulation.

You could try making the subject as hot as possible, such as by seating them in front of a heater, covering them with blankets and soaking their feet in buckets of warm water. Or you could make the subject as cold as possible by removing some clothing, wrapping their body in a wet towel and turning on a fan, soaking their feet in iced water and sitting them in the cool room of the school canteen.

Questions that you could try to answer are:

1. What changes occur in core body temperature when the skin temperature is changed?
2. What changes are evident at the surface of the body when the environment is very hot or very cold?
3. Do changes in environmental temperature affect breathing rate, heart rate or blood pressure?

ACTIVITY 7.2 Experiments in a heated room

Sir Charles Blagden (1748–1820) was an English doctor and scientist. In a report to the Royal Society in 1775, he was the first person to describe the link between sweating and regulation of body temperature. He carried out many experiments on thermoregulation and in 1775 published his results in a paper titled 'Experiments and observations in an heated room'. In one of his experiments he spent 45 minutes in a chamber that was heated to more than 120°C. With him in the chamber were some research assistants, a dog and a piece of beef. They all emerged from the chamber unharmed, but the beef was cooked.

1. Beef is muscle from a cow or a bull. Explain how the men's muscles were unharmed after 45 minutes in the hot chamber, while the muscle in the beef was cooked.
2. Would you expect to see any changes in the appearance of the men after they had been in the hot chamber? Explain your answer.
3. The men were in the hot chamber for 45 minutes. Do you think they would be able to survive for a much longer period? Explain.
4. Do you think the men (and the dog) would have had anything to drink while in the chamber? Explain.
5. A sauna is a small room where people can experience heating in dry or humid conditions. The temperature in the room can vary from 60°C to 120°C. High humidity is used at lower temperatures but at higher temperatures only dry heat is used. Explain why a high-humidity sauna should not be set to a high temperature.
6. Suggest some precautions that should be taken when using a sauna.

ACTIVITY 7.3 Effect of drinking on urine production

This is an activity that you can do at home.

YOU WILL NEED

Measuring cylinder or some other container for measuring volume of liquid; several jars, beakers or test tubes; clock or watch; graph paper.

WHAT TO DO

1. Empty your bladder by urinating as completely as possible.
2. After 15 minutes urinate again, this time collecting the urine in a measuring cylinder. Record the volume of urine. Keep a small sample for observation later. Label the sample.

3 Drink a litre of water.
4 Fifteen minutes after drinking the water, urinate again, measure the volume of urine and record the result. Keep a small sample for observation later. Label the sample.
5 Repeat step 4 every 15 minutes for 90 minutes.
6 Plot a graph showing the volume of urine produced each 15 minutes for the duration of the experiment.

STUDYING YOUR RESULTS

1 What was your rate of urine production (in mL per hour) before drinking the litre of water?
2 What was your rate of urine production (in mL per hour) after drinking the litre of water?
3 What proportion of the litre of water that you drank was excreted in 90 minutes?
4 Was there any difference in the colour of the urine before and after you drank the litre of water? If so, how can you explain the difference in colour?
5 Was there any change in the colour of the urine as the investigation progressed? If so, how can you explain the change in colour?
6 Draw a flow chart to show the sequence of events that would have occurred from the time you drank the water to the time your kidneys began to increase water excretion.
7 Explain why the changes in urine production were necessary to maintain a constant level of water in the body.

Review questions

1 Why must heat loss equal heat gain?
2 Describe the ways in which the body can gain heat.
3 What are the two types of thermoreceptors and in what parts of the body are they located?
4 Describe the role of the skin in regulating body temperature.
5 **a** What responses are likely to occur if core body temperature begins to fall?
b What responses are likely to occur if core body temperature begins to rise?
6 Explain the difference between heat stroke and heat exhaustion.
7 Describe the different types of body fluid.
8 Define 'metabolic water'.
9 **a** What are nephrons?
b Draw a diagram of a nephron and label the places where filtration, reabsorption and secretion occur.
10 Describe the role of antidiuretic hormone (ADH) in regulating water output.
11 How does the thirst reflex regulate water intake?
12 How much water would a person lose before symptoms of dehydration became evident?
13 Aldosterone regulates the amount of sodium in the blood. Explain why:
a aldosterone influences the amount of water excreted from the body
b aldosterone affects blood pressure.

Apply your knowledge

1 Using shivering as an example, draw a stimulus–response model to show the processes involved. Make sure you include the effect of the feedback on the original stimulus.
2 In very cold weather it is our fingers and toes that often feel coldest.
a Why are fingers and toes affected by cold more than other parts of the body?
b The fingers and toes may appear white when very cold. Explain why.
c When very cold, people sometimes appear to be 'blue with cold'. What makes the skin appear blue?
3 Alcohol increases blood flow through the skin. What advice would you give to a person who recommended 'a stiff drink to warm you up'? Explain.
4 Vasoconstriction in the skin occurs when a person's body temperature is low, or when a person is very scared or very angry (we say someone is 'white with fear' or 'white with anger').
a Apply the feedback model shown in Figure 6.5 on page 77 to each of these responses. Do they both fit the model? Explain your answer.
b What is the advantage to a person of vasoconstriction in the skin:
i when body temperature is tending to fall?
ii when the person is scared or angry?
5 A thermograph shows the temperature at the surface of an object or body. Examine the thermograph of the ballerina shown in Figure 7.1 (page 85).
a What parts of the ballerina's skin are the hottest? What parts are the coolest?
b Explain the reasons for the differences in skin temperature that you have described in your answer to part **a** of this question.
6 Explain why excretion is closely related to maintaining fluid balance.
7 Examine Figure 7.12 on page 95 and identify the stimulus, receptor, modulator, effector, response and feedback.
8 A person lost in the desert would suffer extreme dehydration. Although the thirst receptors would try to initiate drinking behaviour, the lack of available water would not allow this requirement to be met. Describe the mechanisms the body would employ to conserve water while getting rid of metabolic wastes.

9 A student made the following observations. On a very hot day, little urine was produced and it was dark in colour. On a cold day, urination occurred more frequently and the urine was pale in colour. Explain these observations.

10 An athlete had blood samples taken before and after a vigorous training session on a hot, dry day. The sample taken after training had a much higher concentration of ADH than the sample taken before training. Explain why there would be a difference in concentrations.

11 For the regulation of the following, draw up a table listing the body systems that are involved in the regulation in one column and a brief statement of the role of each system in a second column.

a Body temperature

b Body fluid balance

12 Table 7.2 shows the water loss from a person's skin and kidneys under different conditions. Use the data in the table to explain the relationship between regulation of body temperature and regulation of fluid content of the body.

Table 7.2 Water loss in differing conditions

Organ	Water lost (mL/hour)		
	At room temperature	In hot weather	With lengthy vigorous exercise
Skin	19	73	225
Kidneys	58	50	20

CHAPTER

08

HOMEOSTASIS OF BLOOD SUGAR AND GAS CONCENTRATIONS

UNIT 3 CONTENT

SCIENCE INQUIRY SKILLS

- identify, research and construct questions for investigation; propose hypotheses; and predict possible outcomes
- design investigations, including the procedure(s) to be followed, the materials required, and the type and amount of primary and/or secondary data to be collected; conduct risk assessments; and consider research ethics, including animal ethics
- conduct investigations, including the collection of data related to homeostasis and the use of models of disease transmission, safely, competently and methodically for the collection of valid and reliable data
- communicate to specific audiences and for specific purposes using appropriate language, nomenclature, genres and modes, including scientific reports

SCIENCE UNDERSTANDING

Endocrine system

- the hypothalamus, pituitary, thyroid, parathyroid, pancreas, thymus, gonads, pineal and adrenal glands are endocrine glands found in the human body
- hormones secreted from the hypothalamus, pituitary, thyroid, parathyroid, pancreas and adrenal glands are involved in homeostasis by affecting specific target organs

Central and peripheral nervous system

- the parts of the central nervous system including the brain (cerebrum, cerebellum, medulla oblongata, hypothalamus, corpus callosum) and spinal cord have specific roles in the co-ordination of body functions and are protected by the meninges and cerebro-spinal fluid

Homeostasis

- homeostatic processes involve nerves and hormones in maintaining the body's internal environment within tolerance limits through the control of metabolism and physiological and behavioural activities
- blood sugar levels are maintained by controlling of sugar uptake, its storage and release by cells and use in metabolism; these processes involve the hormones of the pancreas and adrenal glands
- gas concentrations are controlled by balancing the intake of oxygen and the removal of carbon dioxide via the lungs, through the actions of the medulla oblongata and the autonomic nervous system

Glucose in the bloodstream

Maintaining a stable internal environment involves the coordinated activities of many of the body's systems. The nervous, endocrine, respiratory, circulatory, digestive and excretory systems all work together to maintain homeostasis.

In the previous chapter we saw how body temperature and the composition of body fluids are regulated. In this chapter we focus on how the body maintains a constant supply of oxygen and glucose to the tissues, how carbon dioxide is removed and the role of the circulation in these regulatory processes.

Regulation of blood sugar

Sugar in the blood is in the form of glucose. When doctors (and human biology textbooks) talk about blood sugar they are really talking about the amount of glucose in the blood. All cells need a constant supply of glucose because it is the source of energy for all the cells' activities, such as movement, reproduction, synthesising molecules, active transport and many others. Energy is released from glucose molecules by cellular respiration.

$$\text{Glucose} + \text{oxygen} \longrightarrow \text{carbon dioxide} + \text{water} + \text{energy}$$

The body's source of glucose is the food we eat. Carbohydrates in our food are broken down into glucose during digestion and then absorbed into the blood through the walls of the small intestine. After a meal, blood glucose concentration can rise sharply. Homeostatic mechanisms then begin to operate to reduce the blood glucose concentration and maintain it at the normal level (Figures 8.1 and 8.2). Any excess glucose in the blood must be removed and stored ready for use in cellular activities between meals.

Glucose is stored as **glycogen**, a molecule made of long chains of glucose molecules. Glycogen is the form in which carbohydrate is stored in the body. Storage is mainly in the liver and muscle cells.

The pancreas and adrenal glands secrete hormones that affect the level of glucose in the blood (Figure 8.3). The liver stores glycogen, from which glucose can be made and added to the blood; or glucose can be removed from the blood and stored as glycogen (Figure 8.4, page 104).

Jim Varney/Science Photo Library

Figure 8.1 A glucometer (blood glucose meter) being used to measure the level of glucose in the blood. A small sample of blood is taken from a prick in the patient's finger, and placed on the white strip of the glucometer. This patient's reading of 9.9 millimoles/litre is equivalent to 178 mg of glucose/100 mL of blood.

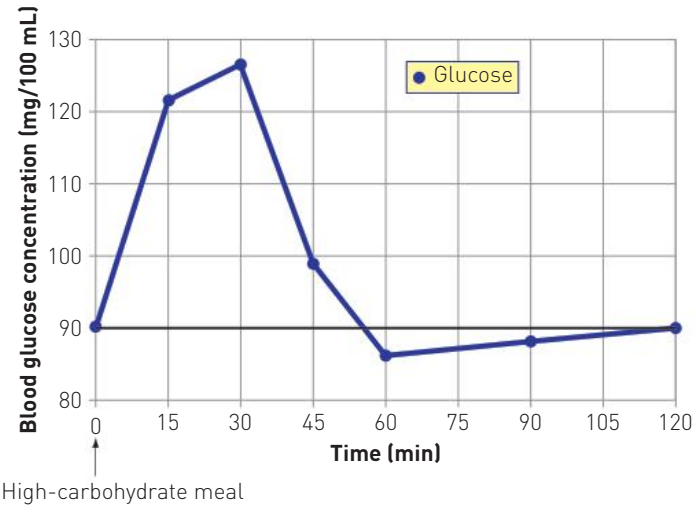


Figure 8.2 Change in blood glucose concentration over time following a high-carbohydrate meal

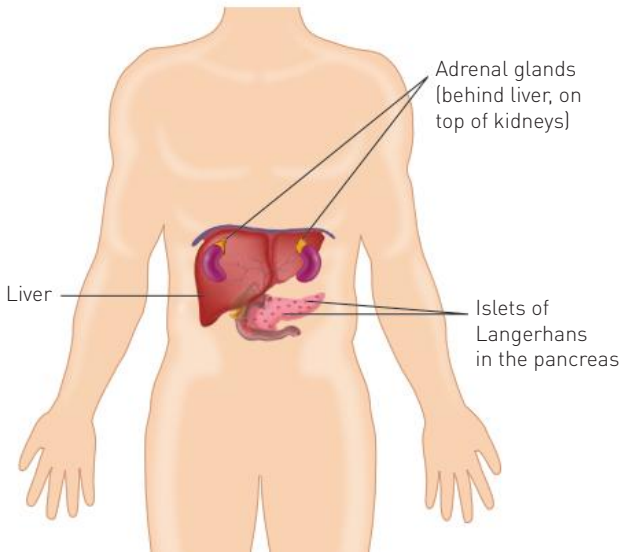


Figure 8.3 Main organs involved in the regulation of blood sugar

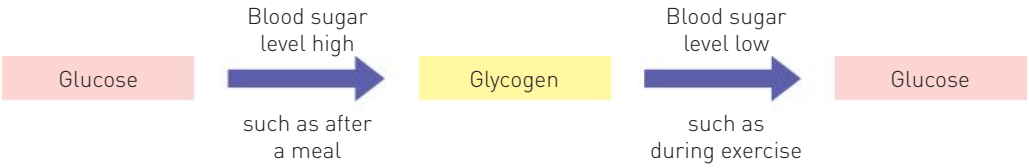


Figure 8.4 A summary of glucose–glycogen conversions

Role of the liver

The liver is in the upper part of the abdominal cavity just below the diaphragm. It is the largest gland in the body and has a very important role in the control of blood sugar concentration. The liver is able to convert glucose into glycogen for storage, or glycogen to glucose for release into the blood.

Most of the liver's blood supply comes through the hepatic portal vein, which brings blood directly from the stomach, spleen, pancreas and small and large intestines. Thus, the liver has the first chance to absorb the nutrients from digested food.

After a typical meal containing a high proportion of carbohydrates is consumed, the breakdown products, mainly glucose, are absorbed into the blood capillaries of the villi of the small intestine. The hepatic portal vein carries the glucose to the liver, where a number of things may occur.

- Glucose may be removed from the blood by the liver to provide energy for liver functioning.
- It may be removed by the liver and/or muscles and converted into glycogen for storage.
- It may continue to circulate in the blood, available for body cells to absorb and use as a source of energy.
- Glucose in excess of that required to maintain both normal blood sugar level and tissue glycogen level is converted into fat for long-term storage (Figure 8.5).

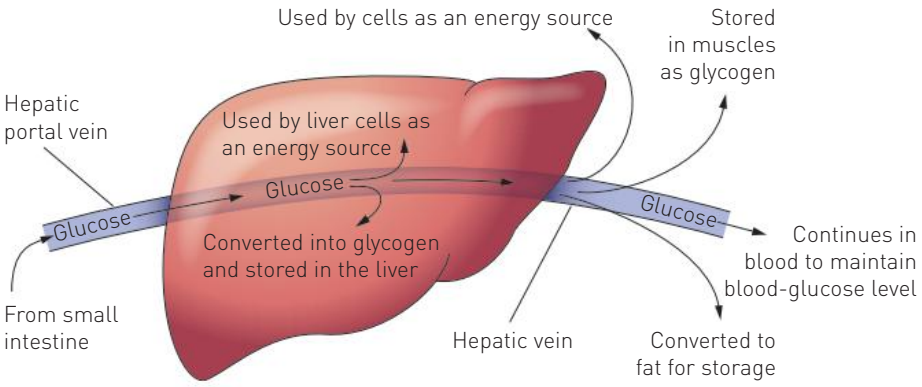


Figure 8.5 The fate of glucose absorbed in the small intestine

The body is able to store about 500 g of glycogen: about 100 g is stored in the liver and the remainder in skeletal muscle cells. Glucose molecules are chemically combined in long chains to form glycogen molecules. This process, known as **glycogenesis**, is stimulated by the pancreatic hormone **insulin**. Glycogen itself cannot be used by cells – it must be converted back into glucose or to other simple sugars. Glycogen stored in the liver is available for conversion into glucose to maintain blood sugar levels and supply energy for liver activity. Glycogen in muscle cells provides the glucose required for muscle activity.

If the level of glucose in the blood drops below normal because of glucose consumption by the muscle cells during exercise or by the body tissues between meals, the glycogen stored in the liver and muscle cells can be broken down into glucose. This process of converting glycogen back into glucose is called **glycogenolysis**. Most frequently, it occurs between meals and is stimulated by another pancreatic hormone, **glucagon** (see Figure 8.6).

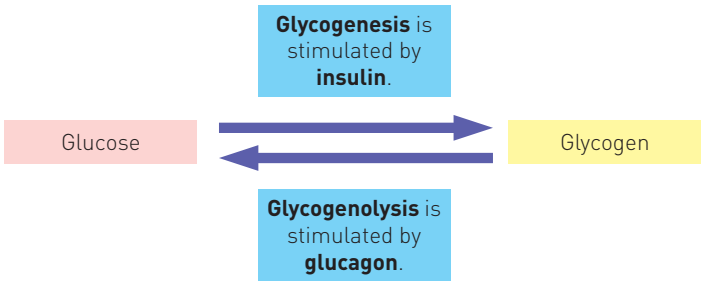


Figure 8.6 Glucose–glycogen conversions stimulated by pancreatic hormones

Glycogen stored in the liver is a short-term energy supply. It can provide glucose for body cell use for only about six hours if no other supply is available. If more energy is required, the body uses the energy reserves in stored fat.

Role of the pancreas

The pancreas is a pale grey gland, 12–15 cm long, lying partly in the curve of the duodenum. Within the pancreas are clusters of hormone-secreting cells called the **islets of Langerhans** (Figure 2.11, page 30). The cells in the islets are of two types. The **alpha cells** secrete glucagon, and the **beta cells** secrete insulin. Both hormones are secreted into the bloodstream and are concerned with the control of blood sugar levels.

Insulin from the beta cells causes a *decrease* in blood sugar levels. It does so in two main ways: first, it accelerates the transport of glucose from the blood into the cells, especially those of the skeletal muscles; and second, it accelerates the conversion of glucose into glycogen. In addition, insulin stimulates the conversion of glucose into fat in adipose tissue (fat storage tissue) and causes an increase in protein synthesis in some cells. All these activities decrease blood sugar levels (Figure 8.7). The level of blood sugar regulates the secretion of insulin via a negative feedback system. When blood sugar levels rise above normal, chemical sensors in the beta cells of the islets of Langerhans stimulate those cells to secrete insulin (Figure 8.9 on page 106). As the level of blood sugar decreases, the cells are no longer stimulated and production is reduced.

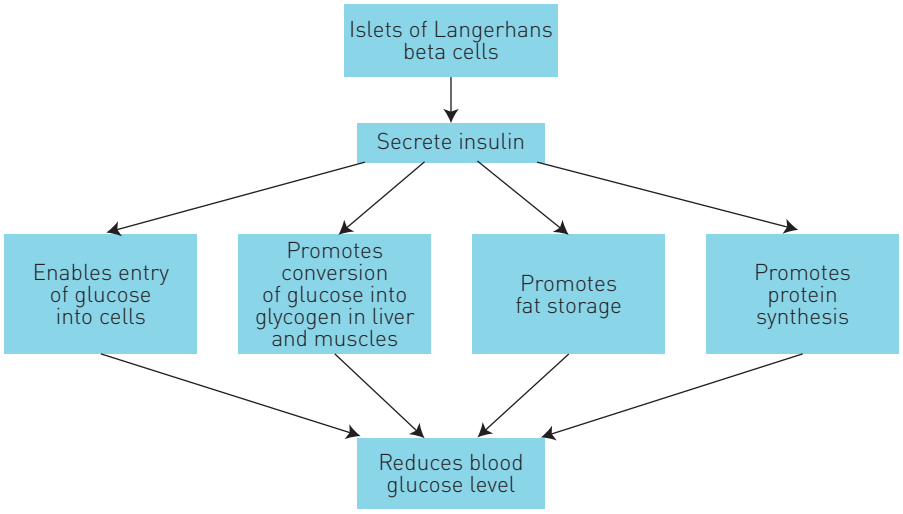


Figure 8.7 Effects of insulin on blood glucose levels

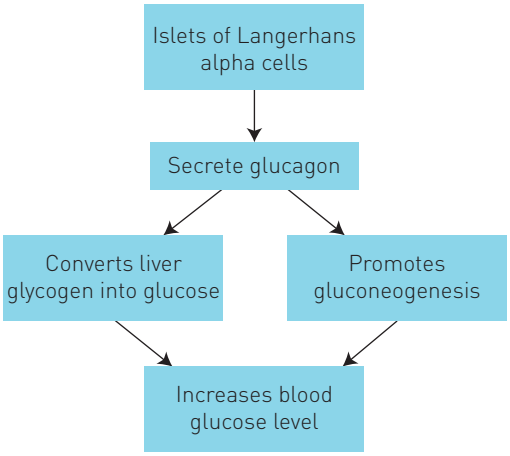


Figure 8.8 Effect of glucagon on blood glucose levels

Glucagon from the alpha cells causes an *increase* in blood sugar levels. It does this by stimulating glycogenolysis – the conversion of glycogen into glucose – in the liver. The glucose formed is then released into the blood, and the blood sugar level rises. Glucagon also stimulates the liver to produce new sugar molecules from fats and amino acids, a process called **gluconeogenesis**. In addition, it may have a mild stimulating effect on protein breakdown (Figure 8.8). The regulation of the secretion of glucagon, like that of insulin secretion, is directly determined by the level of sugar in the blood and is again based on a negative feedback system. When the blood sugar falls below normal, chemical sensors in the alpha cells of the islets of Langerhans stimulate those cells to secrete glucagon. As the blood sugar level increases, the cells are no longer stimulated and production is reduced (Figure 8.9).

Insulin and diabetes
This website provides more information on the role of insulin and glucagons in blood sugar regulation.

Blood sugar regulation
This website provides more information on the regulation of blood sugar.

Homeostasis of blood sugar

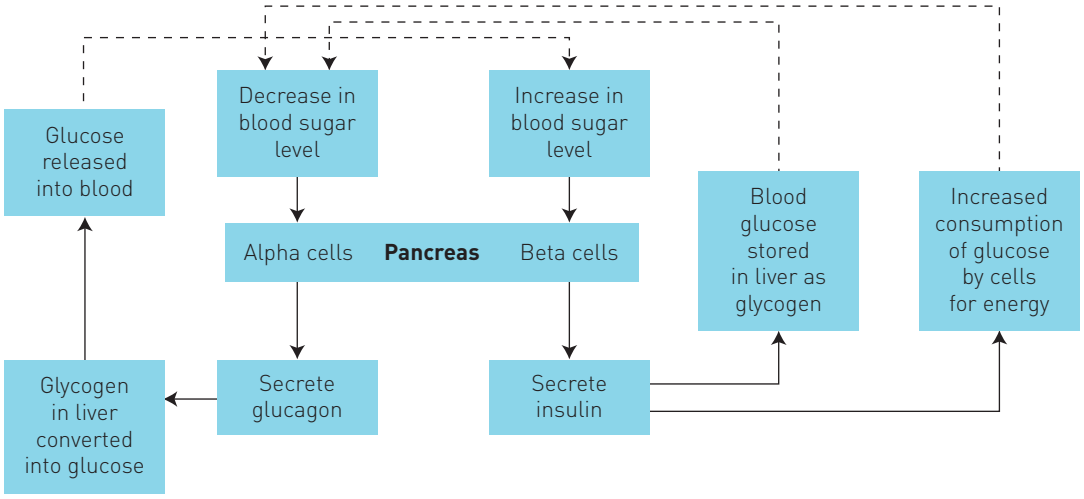


Figure 8.9 Regulation of blood sugar by insulin and glucagon

Role of the adrenal glands

The adrenal glands are situated just above the kidneys, one gland above each (Figure 2.10, page 29). Each gland is composed of two distinct parts: the outer part is called the **cortex** and the inner part is the **medulla**. The adrenal glands produce a number of hormones, but in discussing the control of blood sugar, we are interested only in the secretion of glucocorticoids by the adrenal cortex, and the secretion of adrenaline (epinephrine) and noradrenaline (norepinephrine) by the adrenal medulla.

The adrenal cortex is stimulated to secrete its hormones by adrenocorticotropic hormone (ACTH) from the anterior lobe of the pituitary. The hormones secreted are glucocorticoids, the best known of which is **cortisol**. They regulate carbohydrate metabolism by making sure enough energy is provided to the cells. In doing so, they stimulate the conversion of glycogen into glucose (Figures 8.10 and 8.11). They also increase the rate at which amino acids are removed from cells (mainly muscle cells) and transported to the liver. Some of these amino acids may be converted into glucose by the liver if glycogen and fat levels are low. This process of converting a substance other than carbohydrate into glucose is called gluconeogenesis (see Table 8.1). Glucocorticoids also promote the mobilisation of fatty acids from adipose tissue, allowing muscle cells to shift from glucose to fatty acids for much of their metabolic energy.

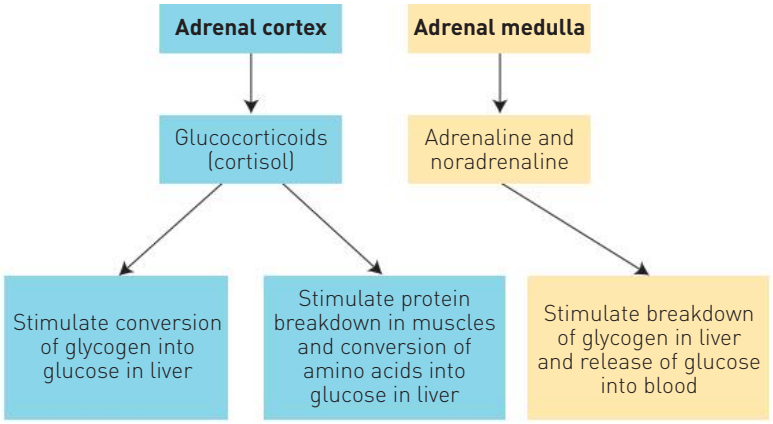


Figure 8.10 Effect of adrenal hormones on blood glucose levels

The adrenal medulla synthesises adrenaline and noradrenaline, hormones that produce the same effects as those brought about by sympathetic nerves of the autonomic nervous system. One such effect is the increase of blood sugar levels (Figures 8.10 and 8.11). In particular, adrenaline elevates blood glucose levels and in doing so counteracts the effects of insulin. It stimulates the production of lactic acid from glycogen in muscle cells, and the lactic acid can then be used by the liver to manufacture glucose.

Table 8.1 Terms relating to glucose metabolism

Term	Meaning
Glycogenesis	Formation of glycogen from other carbohydrates, especially glucose (in Greek, *genesis* means 'origin' or 'creation')
Glycogenolysis	Breakdown of glycogen to glucose (in Greek, *lysis* means 'to separate or break down')
Gluconeogenesis	Conversion of fats or proteins into glucose (in Greek, *neo* means 'new')

Blood sugar homeostasis

The normal level of glucose in the blood is between 4 and 6 millimoles per litre (5 mmol/L = 90 mg/100 mL). Many activities take place to maintain the level within these narrow limits. Our discussion has covered the involvement of the liver, pancreas and adrenal glands. For homeostasis it is the contribution of all three, working in an integrated manner, that enables blood sugar concentration to remain fairly constant. Figure 8.11 summarises the major influences on these processes.

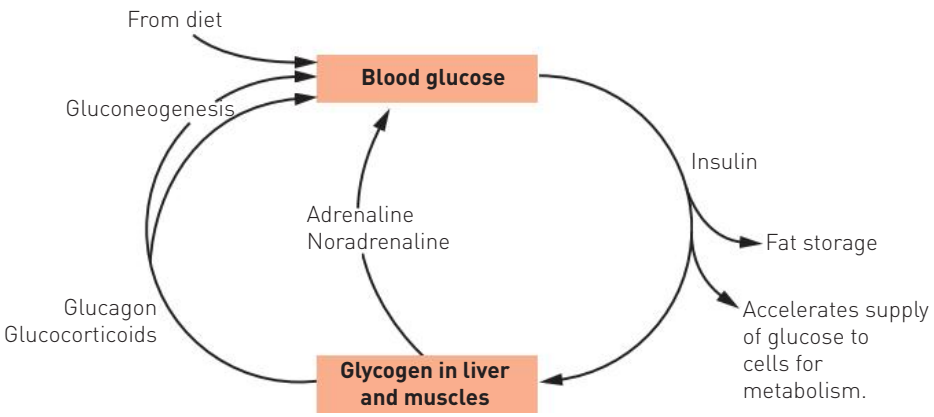


Figure 8.11 A summary of blood sugar homeostasis

An animation and quiz on blood sugar regulation

Regulation of gas concentrations

All cells need a continuous supply of oxygen for respiration; all cells produce carbon dioxide as a waste product of respiration. It is therefore crucial that the levels of these gases in the body be regulated.

The respiratory system is responsible for taking in oxygen and excreting carbon dioxide from the body. In particular, the lungs are the organs in which the exchange of carbon dioxide for oxygen occurs. Changes in breathing therefore change the amount of oxygen taken in and the amount of carbon dioxide excreted.

The circulatory system carries oxygen from the lungs to the cells where it is used. It takes away the carbon dioxide produced and delivers it to the lungs for excretion from the body. Thus the circulatory system is also involved in the regulation of gas concentrations.

Control of breathing

The muscles that cause air to move in and out of the lungs are the diaphragm, a muscle that separates the thorax from the abdomen, and the intercostal muscles, the muscles between the ribs. These are skeletal muscles and require stimulation from nerve impulses to initiate contraction. The diaphragm is stimulated by impulses from the phrenic nerve, while impulses from the intercostal nerves stimulate the intercostal muscles (Figure 8.12). These spinal nerves have their origin in the spinal cord at the level of the neck and thorax. If these nerves are injured, or if there is injury to the spinal cord in the region from which they originate, the result is complete paralysis of the muscles that ventilate the lungs. Death inevitably follows unless some form of artificial respiration is rapidly applied.

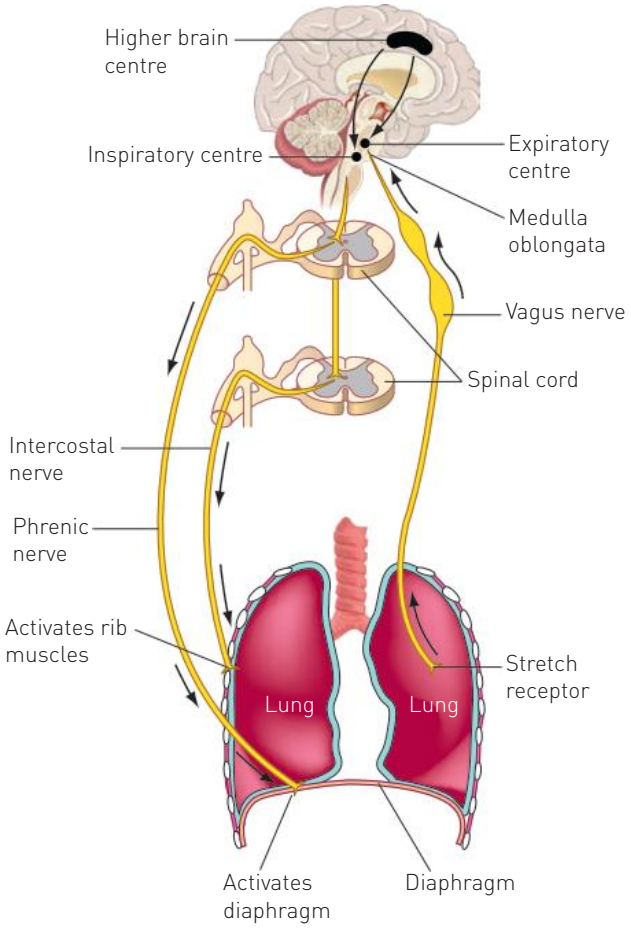


Figure 8.12 Control of breathing by respiratory centres in the brain

The nerve impulses that travel to the diaphragm and intercostal muscles are controlled by a **respiratory centre** located in the medulla oblongata of the brain (see Chapter 5). There are two regions within the respiratory centre: one that controls expiration (breathing out) and one that controls inspiration (breathing in). To coordinate breathing, messages need to pass back and forth between the neurons in these two regions.

Both oxygen and carbon dioxide are carried in the blood and their concentrations affect breathing rate. In addition, the concentration of carbon dioxide in the blood plasma affects the concentration of hydrogen ions. When carbon dioxide dissolves in water, it forms carbonic acid (H_2CO_3), which breaks down readily to form hydrogen ions (H^+) and bicarbonate ions (HCO_3^-), as shown in the following chemical equation.

$$\underset{\text{Carbon dioxide}}{CO_2} + \underset{\text{Water}}{H_2O} \rightleftharpoons \underset{\text{Carbonic acid}}{H_2CO_3} \rightleftharpoons \underset{\text{Hydrogen ion}}{H^+} + \underset{\text{Bicarbonate ion}}{HCO_3^-}$$

Oxygen, carbon dioxide and hydrogen ions all have some effect on the regulation of breathing activity.

Oxygen concentration

As oxygen is consumed by the cells, its concentration in the blood begins to fall. If the concentration of oxygen falls below normal while other factors are held constant, the breathing rate increases. However, within the normal range of blood oxygen concentration, the effect on breathing rate is only slight. The concentration has to fall to very low levels before it has a major stimulatory effect. Thus, under normal circumstances, oxygen plays little part in the regulation of breathing.

There are groups of cells within the walls of the aorta and carotid arteries that are sensitive to changes in the concentration of oxygen in the blood plasma. These groups of chemoreceptors are known as the **aortic** and **carotid bodies** (Figure 8.13). Besides these peripheral chemoreceptors, there are central chemoreceptors in the medulla oblongata. A large decrease in oxygen concentration stimulates the chemoreceptors, and nerve impulses are transmitted to the respiratory centre. These nerve impulses stimulate the transmission of messages to the diaphragm and intercostal muscles, and so the breathing rate increases.

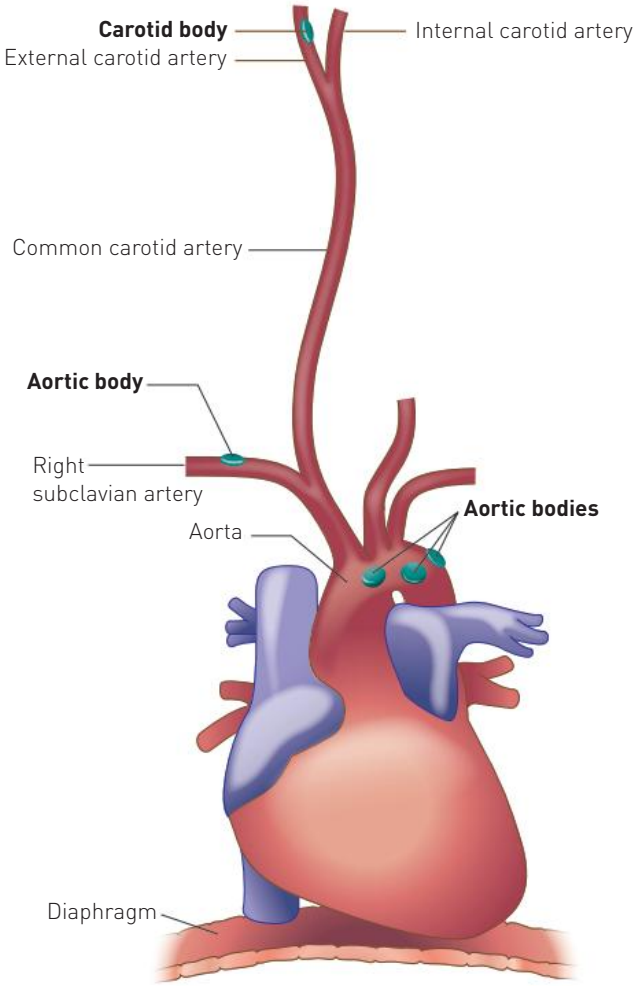


Figure 8.13 Location of the aortic and carotid bodies

Carbon dioxide concentration

The concentration of carbon dioxide in the blood plasma is a major factor in the regulation of breathing rate. A relatively small increase in the concentration of carbon dioxide is enough to cause a marked increase in the rate of breathing. As mentioned above, the concentration of carbon dioxide in the plasma is associated with the concentration of hydrogen ions. Any increase in carbon dioxide results in an associated increase in hydrogen ion concentration. The increase in concentration of both these chemicals in the blood stimulates the central and peripheral chemoreceptors. These in turn transmit nerve impulses to the respiratory centre, resulting in an increase in breathing rate.

The chemoreceptors most sensitive to changes in the concentration of carbon dioxide in the plasma are those located in the medulla oblongata. The neurons making up these central chemoreceptors are separate from, but communicate with, the neurons of the respiratory centre. These chemoreceptors are responsible for 70–80% of the increase in breathing rate that results from an increase in the carbon dioxide concentration of the blood. However, this response takes several minutes. The immediate increase in breathing rate that occurs following an increase in the carbon dioxide concentration of the plasma is produced by the stimulation of the aortic and carotid bodies (Figure 8.13). These are stimulated by the associated increase in hydrogen ion concentration.

Hydrogen ion concentration

As the hydrogen ion concentration of the blood increases, the pH decreases, causing an increase in the breathing rate. A decrease in the pH directly stimulates chemoreceptors in the aortic and carotid bodies, which then transmit impulses to the respiratory centre, resulting in an increase in the breathing rate.

The regulation of the breathing rate in response to changes in the concentration of carbon dioxide and hydrogen ions (pH) is illustrated in Figure 8.14.

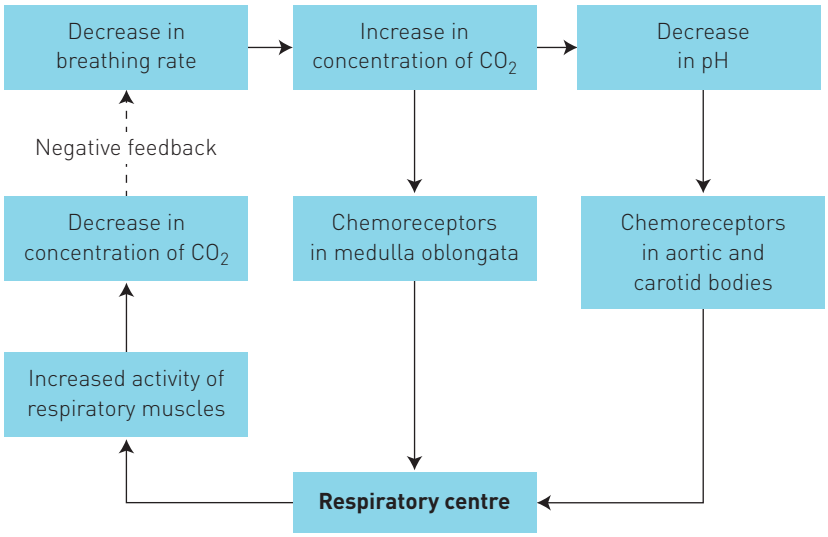


Figure 8.14 Negative feedback control of breathing rate through changes in the concentration of carbon dioxide and the pH of the blood plasma

None of the three factors (oxygen concentration, carbon dioxide concentration and hydrogen ion concentration) is independent in the regulation of breathing rate. Each factor interacts with the others. Nor are these the only factors to play a role in the control of breathing. At any instant, therefore, the rate of breathing is regulated by a number of factors, and the sensitivity of some factors, such as oxygen, is generally not as great as the sensitivity of others, such as carbon dioxide.

Voluntary control of breathing

Humans are able to voluntarily control their rate and depth of breathing, factors very important in speech. We can even stop breathing for a limited period. This voluntary control comes via connections from the cerebral cortex to descending tracts in the spinal cord. Voluntary control thus bypasses the respiratory centre in the medulla oblongata. This is a protective device as it enables us to prevent irritating gases and water from entering the lungs. However, we cannot stop breathing forever! The build-up of carbon dioxide in the plasma stimulates the inspiratory centre to send impulses to the inspiratory muscles. Thus, we are eventually forced to take a breath whether we want to or not (Figure 8.15).

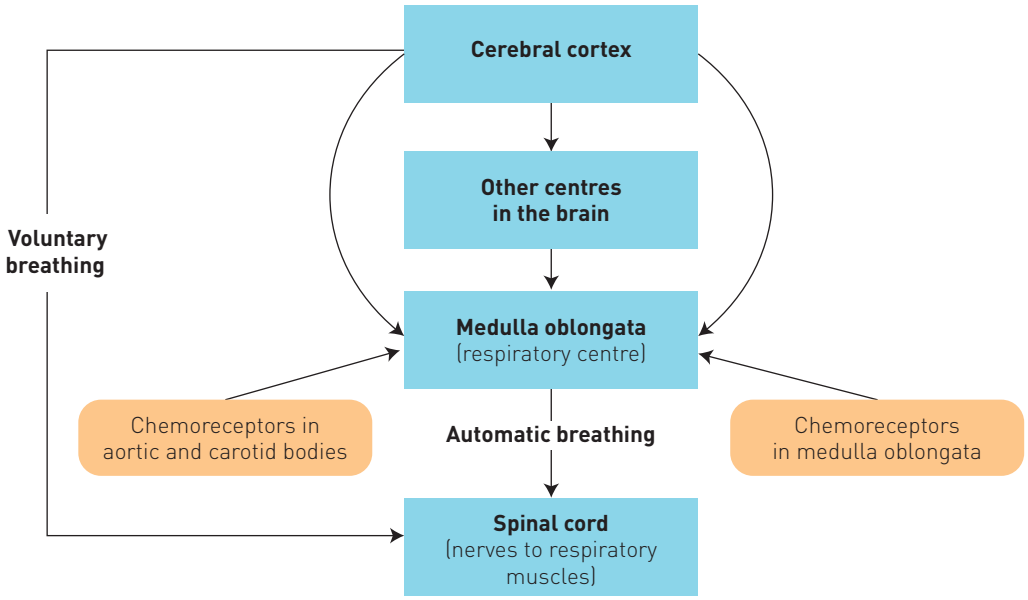


Figure 8.15 The control of breathing rate by the central nervous system

Rapid, deep breathing can provide more oxygen than required and remove more carbon dioxide than necessary. This is called **hyperventilation**. It can occur voluntarily or may be stimulated by physical stress such as severe pain or emotional stress such as extreme anxiety. Hyperventilation usually corrects itself because the reduction in carbon dioxide concentration means that the chemoreceptors are not stimulated and there is no urge to breathe until carbon dioxide levels return to normal.

A very dangerous practice is to hyperventilate before swimming under water. It does allow a person to stay under water longer, but this is not because of extra oxygen in the blood – it is due to the loss of carbon dioxide. The breath-holding ability could be increased to such an extent that the individual loses consciousness from lack of oxygen to the brain before feeling the urge to breathe. Many drowning deaths in Australia have been the direct result of hyperventilation.

WS
Homeostasis of gas concentrations

Exercise and breathing

During exercise the contracting muscle cells require large amounts of oxygen and produce large amounts of carbon dioxide. In responding to this increased demand for gas exchange, the respiratory system increases both the rate of breathing and the depth of breathing.

During heavy exercise, the volume of air going into and out of the lungs each minute may increase ten- to twentyfold. The same factors that influence breathing at rest appear to be involved in this increase – that is, the concentrations in the blood plasma of carbon dioxide, hydrogen ions and, to a lesser extent, oxygen.

Regulation of breathing
This website provides more information on the regulation of breathing.

Heart rate and blood pressure

The heart pumps the blood that carries oxygen to the tissues and transports carbon dioxide away from the tissues. Output of blood from the heart is therefore crucial to maintaining homeostasis of gases in the body fluids.

The **heart rate** is the number of times the heart beats per minute, while the **stroke volume** is the volume of blood forced from the heart with each contraction. A combination of both factors determines the **cardiac output** – the amount of blood leaving the heart every minute. Thus:

Cardiac output (mL/min) = **heart rate** (beats/min) × **stroke volume** (mL)

Blood pressure is the force with which the blood presses on the walls of the blood vessels. The blood pressure at a particular time depends on:

- the cardiac output – as cardiac output increases, blood pressure increases
- the diameter of blood vessels – constriction of blood vessels increases pressure and dilation decreases blood pressure.

Blood pressure is closely related to cardiac output: any increase in the heart rate and the force of contraction will increase blood pressure. Conversely, any decrease will lower blood pressure. However, factors that affect the diameter of the blood vessels also act to control blood pressure.

Regulation of heart rate

Within the heart are two small groups of specialised cells capable of initiating nerve impulses to stimulate muscle contraction without any outside influence from the nervous system. Left to its own devices, therefore, the heart would have a constant beat. The bundles of specialised cells controlling the heart's activity are called the **sinoatrial node (SA node)** and the **atrioventricular node (AV node)**. The SA node is often described as the 'pacemaker' as it is responsible for the rhythmical contractions of the heart.

As Figure 8.16 shows, the SA node is located in the wall of the right atrium just below the opening of the superior vena cava. This node initiates each heartbeat with an impulse that spreads out over both atria, causing them to contract. As the impulse spreads over the atria, it eventually reaches the AV node. This node is situated in the wall between the two atria near the atrioventricular valves. From the AV node, conducting fibres pass through the septum that separates the right and left ventricles of the heart. The fibres then divide into two branches, one branch going down each side of the septum. Within the muscle of the ventricles, these branches divide into a network of fine nerve fibres (Figure 8.16).

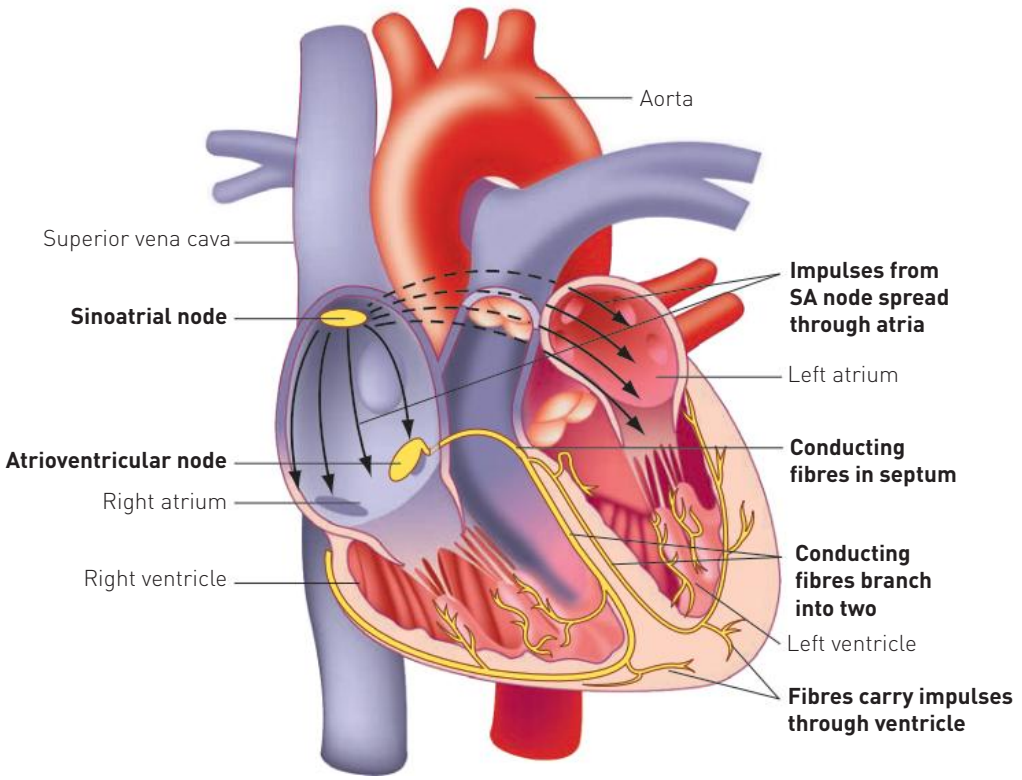


Figure 8.16 The conduction of nerve impulses through the heart

When the heart beats, the sequence of events is as follows:

1. The SA node sends out nerve impulses that spread through the atria.
2. The stimulus reaches the AV node. At about this time, contraction of the muscle of the atrium begins.

3 Stimulation of the AV node causes it to send out its own impulses. These travel down the fibres in the septum between the ventricles.
4 The impulses then spread through the muscles of the ventricles. Atrial contraction is now complete and ventricular contraction begins.

Although the SA node can stimulate the heartbeat on its own, its activity is influenced by the autonomic nervous system. This system, with its sympathetic and parasympathetic divisions (see Chapter 4), has neurons that carry impulses to the SA and AV nodes as well as to the atria of the heart. These neurons bring impulses from the medulla oblongata of the brain. In the medulla oblongata is a network of nerve cells with axons that extend to the heart and to the muscles in the walls of the blood vessels. This region within the medulla oblongata is known as the **cardiac centre** or **cardiovascular regulating centre**.

Nerve impulses and the heart
This website shows a simulation of the passage of nerve impulses through the heart.

The autonomic control of the heart is, therefore, the result of balancing the opposing influences of the stimulatory effects of the sympathetic neurons and the inhibitory effects of the parasympathetic neurons. At rest, parasympathetic activity is dominant. During exercise, however, the activity of the sympathetic neurons increases, while that of the parasympathetic neurons decreases, causing the heart to beat faster. Whenever one division is stimulated, the activity of the other is inhibited.

Sensory impulses from receptors in different parts of the cardiovascular system act upon the cardiovascular regulating centre so that a balance between stimulation and inhibition is maintained.

Some of the receptors involved in this task are the chemoreceptors in the aortic and carotid bodies and in the medulla oblongata. Although they are more important in controlling respiration they do influence heart rate. Any increase in CO_2 concentration or decrease in pH influences the cardiac centre to increase cardiac output.

Nervous control of the heart
This website provides more information about regulation of the heart

Changes to blood flow during exercise

To maintain the activity of the muscle cells during exercise, a large increase in blood flow is required to ensure an adequate supply of oxygen and nutrients, and to remove the carbon dioxide and heat produced. Thus, cardiac output may increase from 5 L per minute at rest to a maximum of 30 L per minute in a trained athlete.

During exercise it is the contracting muscles that require the extra blood flow. Other organs do not need extra oxygen and nutrients and do not release extra carbon dioxide. To ensure that blood supply to the muscles is increased, blood vessels in internal organs such as the alimentary canal constrict. At the same time there is dilation of blood vessels in the muscles. Blood is directed away from organs that do not require increased blood flow to the contracting muscles that do require more blood.

When a person is about to begin exercising, there is an anticipatory response brought about by the autonomic nervous system and by release of the hormone adrenaline. Heart rate and stroke volume increase and there is an increase in the blood flow to skeletal muscles.

The effect of behaviour

Our behaviour – what we do – can affect all the variables described in this chapter. For example, suppose you are about to take part in a long-distance race. The mental stress will cause your blood glucose to rise and, in anticipation of the increased muscular activity, your heart rate and blood pressure will increase.

When the race begins, breathing rate and depth will increase, cardiac output will rise further and blood glucose will continue to be at a high level. There will be an increase in blood supply to the working muscles and a corresponding decrease in supply to internal organs such as the stomach and intestines.

The role of homeostasis is to keep the environment of the cells at the optimum level for their normal operations. During prolonged, steady exercise, many factors such as heart and breathing rates are homeostatically controlled at a higher level than when sitting at rest. When exercise ceases, homeostasis returns all these functions to their normal level.

Science inquiry

ACTIVITY 8.1 Breathing rate

In this activity you will consider the stimuli that could be involved in regulating breathing rate.

YOU WILL NEED

Stopwatch or clock with second hand; large paper bag

WHAT TO DO

Warning: Do not act as a subject for this activity if you suffer from any respiratory or heart problems.

Work with a partner. Read through these instructions and draw up a suitable table in which to record your results.

1. Each member of the pair should count his or her own breathing rate (in breaths per minute) while sitting quietly at rest. Record the resting breathing rate.
2. After a normal quiet expiration hold your breath for as long as you can. Count and record your breathing rate immediately after holding your breath.
3. Flatten a brown paper bag so that it has little air in it. Place the opening of the bag over your nose and mouth and breathe into and out of it for one minute (so that you are re-breathing the same air). Count and record your breathing rate immediately after breathing into the bag.

STUDYING YOUR RESULTS

1. How did your breathing rate change after holding your breath and after breathing into the paper bag?
2. Suggest reasons for the changes in breathing rate.
3. What could be the stimulus that regulates a person's rate of breathing?
4. How does the evidence from the activity you have just done support your answer to Question 3?

ACTIVITY 8.2 Investigating behaviour and homeostatic mechanisms

Design an investigation to test links between one type of behaviour and one aspect of homeostasis.

Some behaviours from which you could choose are:

- moderate physical exercise, such as a brisk walk or a jog
- performing relaxation exercises
- playing an exciting computer game
- watching a scary movie
- soaking in a warm bath
- debating a controversial topic with a friend or family member
- listening to a particular type of music; for example, relaxation music, metal or techno
- any other behaviour that you think could affect homeostasis.

Aspects of homeostasis that you could investigate are:

- blood pressure
- heart rate
- breathing
- urine production
- any other aspect of homeostasis that you can observe or measure.

PLANNING YOUR INVESTIGATION

Some of the questions that you will need to answer in your planning are as follows.

- What hypothesis will you test? The hypothesis should link the behaviour you are going to test with the aspect of homeostasis that you are going to investigate. Make sure your investigation really will test your hypothesis.
- How will you make your observations objective? Measurement is the best option, if it is possible.
- What variables will you control and how you will go about controlling them?
- How will you make sure that your results are valid and reliable? How many repetitions will you perform?
- How will you record your results? Will it be possible to present the results as a table and/or a graph?

CONCLUSIONS

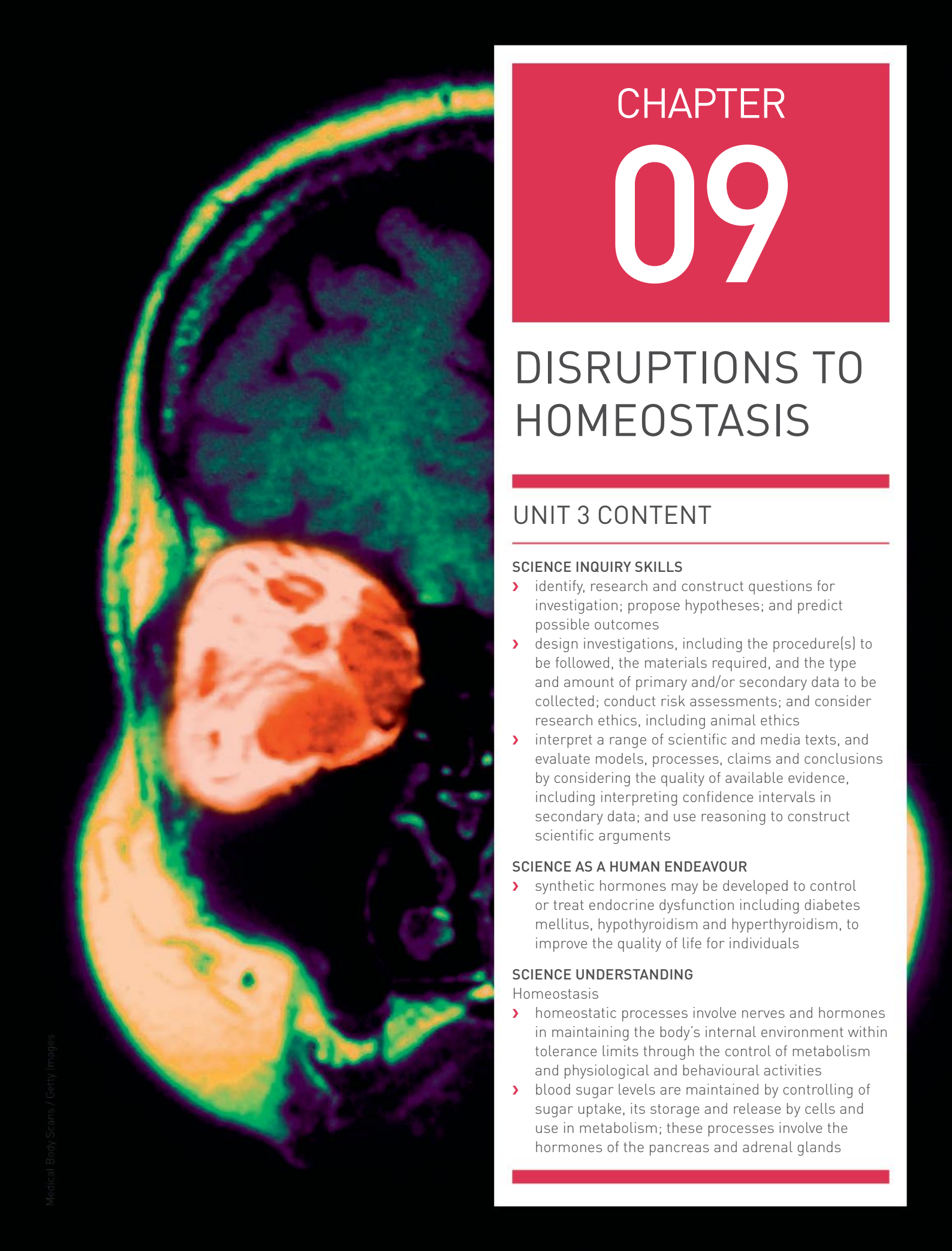
Your teacher may want you to write a formal report of your investigation (see report format on page 14). If a report is not required, you should still write a conclusion discussing the relationship between your results and your hypothesis, and be prepared to present your findings to your class.

Review questions

1 What is the role of the liver in regulating blood sugar concentration?
2 Distinguish between glycogenesis, glycogenolysis and gluconeogenesis.
3 **a** Which gland is involved in the secretion of insulin and glucagon? Identify the location of the gland.
b Describe how insulin and glucagon regulate the concentration of glucose in the blood.
c How are the levels of these hormones in the blood determined?
4 Describe the influence of the hormones of the adrenal glands on blood sugar concentration.
5 After a meal, the blood sugar level often rises well beyond the normal level. Explain why this occurs.
6 Describe the effects of the following factors on breathing rate.
a Concentration of oxygen in the blood
b Concentration of carbon dioxide in the blood
c Hydrogen ion concentration (pH) in the blood
7 Explain how the respiratory centre controls the rate of breathing.
8 Describe the role of the aortic and carotid bodies in regulating breathing rate.
9 Why is it dangerous to hyperventilate before swimming under water?
10 Define 'cardiac output'.
11 Describe how the autonomic nervous system influences cardiac output.
12 Describe the roles of the sinoatrial (SA) and atrioventricular (AV) nodes in regulating heart rate.

Apply your knowledge

1 Apply the stimulus-response-feedback model (Figure 6.5 on page 77) to the response of the pancreas to rising blood sugar.
2 Compile a table that summarises the role of each of the following systems in regulating blood sugar level: nervous system, digestive system, endocrine system, circulatory system, muscular system, excretory system.
3 We cannot voluntarily control our heart rate or blood sugar level, yet we can voluntarily control our breathing.
a Explain why it is important for us to be able to voluntarily decide when to take a breath and how deep the breath should be.
b We cannot voluntarily stop breathing indefinitely. Explain why.
4 People sometimes hyperventilate in stressful situations. The hyperventilation may cause dizziness and tingling of the fingers and toes. In such cases, the person may be advised to breathe into a paper bag and re-breathe the same air that was breathed out. How would such a procedure help to overcome the problems of hyperventilation?
5 Calculate the cardiac output for an individual with a heart rate of 75 beats per minute and a stroke volume of 70 mL per beat.
6 Explain why an increase in cardiac output is an advantage during exercise.
7 Draw a stimulus-response-feedback diagram to show what happens to breathing rate when:
a the concentration of carbon dioxide in the blood increases
b the hydrogen ion concentration of the blood increases.
For each diagram label the receptor, modulator and effector, and show how the feedback occurs.
8 What do you think would happen to heart rate and stroke volume during prolonged, strenuous exercise?



Medical Body Scans / Getty Images

CHAPTER

09

DISRUPTIONS TO HOMEOSTASIS

UNIT 3 CONTENT

SCIENCE INQUIRY SKILLS

- identify, research and construct questions for investigation; propose hypotheses; and predict possible outcomes
- design investigations, including the procedure(s) to be followed, the materials required, and the type and amount of primary and/or secondary data to be collected; conduct risk assessments; and consider research ethics, including animal ethics
- interpret a range of scientific and media texts, and evaluate models, processes, claims and conclusions by considering the quality of available evidence, including interpreting confidence intervals in secondary data; and use reasoning to construct scientific arguments

SCIENCE AS A HUMAN ENDEAVOUR

- synthetic hormones may be developed to control or treat endocrine dysfunction including diabetes mellitus, hypothyroidism and hyperthyroidism, to improve the quality of life for individuals

SCIENCE UNDERSTANDING

Homeostasis

- homeostatic processes involve nerves and hormones in maintaining the body's internal environment within tolerance limits through the control of metabolism and physiological and behavioural activities
- blood sugar levels are maintained by controlling of sugar uptake, its storage and release by cells and use in metabolism; these processes involve the hormones of the pancreas and adrenal glands

Sam knew there was something seriously wrong with his body. He had been feeling very tired and lethargic for quite some time. He was continuously feeling thirsty but was also urinating frequently. His vision had become blurred and he had lost weight. His doctor tested a sample of Sam's urine and found that the amount of glucose in the urine was much higher than normal. Sam was suffering from diabetes, a condition that results from disruption to homeostasis of blood glucose. If untreated Sam's condition would be life threatening.

Homeostasis is the maintenance of a constant internal environment so that the cells can function at their optimum level. In Sam's case, his cells were not functioning normally because there was too much glucose in his blood. Diabetes is just one example of what can happen when homeostasis goes wrong. In this chapter we discuss just a few of the disruptions to homeostasis that may occur and some of the treatments that are available for these disruptions.

Hormonal causes of disruptions

Many hormones are involved in homeostasis. For example, insulin and glucagon regulate the level of sugar in the blood, the secretion of thyroxine regulates metabolic rate and antidiuretic hormone regulates the amount of water lost from the body in urine. Too little, or too much, of any of these hormones will have a big impact on homeostasis. There are many ways in which hormones can cause disruption to homeostasis. Two of these are described below.

Diabetes

Diabetes, or more correctly **diabetes mellitus**, is a good example of a hormonal problem causing serious disruption to homeostasis. A person with diabetes has an abnormally high blood glucose level, a condition called **hyperglycaemia**. A balance between the hormones insulin and glucagon usually keeps the blood glucose at the correct level for normal body functioning (see Figure 8.9 on page 106). A diabetic (a person with diabetes) does not produce enough insulin, or their cells have an abnormal resistance to the effects of insulin.

The main role of insulin is to stimulate cells to take in glucose from the blood. It also stimulates conversion of glucose into glycogen by liver and muscle cells. If a person produces insufficient insulin, or if their cells are resistant to the effects of insulin, the amount of glucose in the blood remains high and they excrete large quantities in the urine. There are two forms of diabetes.

Type 1 diabetes

Type 1 diabetes, sometimes called **insulin-dependent diabetes**, usually begins in childhood and therefore used to be called juvenile diabetes. In Australia, 10–15% of diabetes patients suffer from type 1. It occurs because a fault in the patient's immune system causes the destruction of beta cells in the islets of Langerhans of the pancreas (see pages 29 and 30). Because beta cells produce insulin, a person with type 1 diabetes does not produce insulin. In most cases the person's cells respond to insulin in the normal way, so the disease can be managed by giving the person insulin.

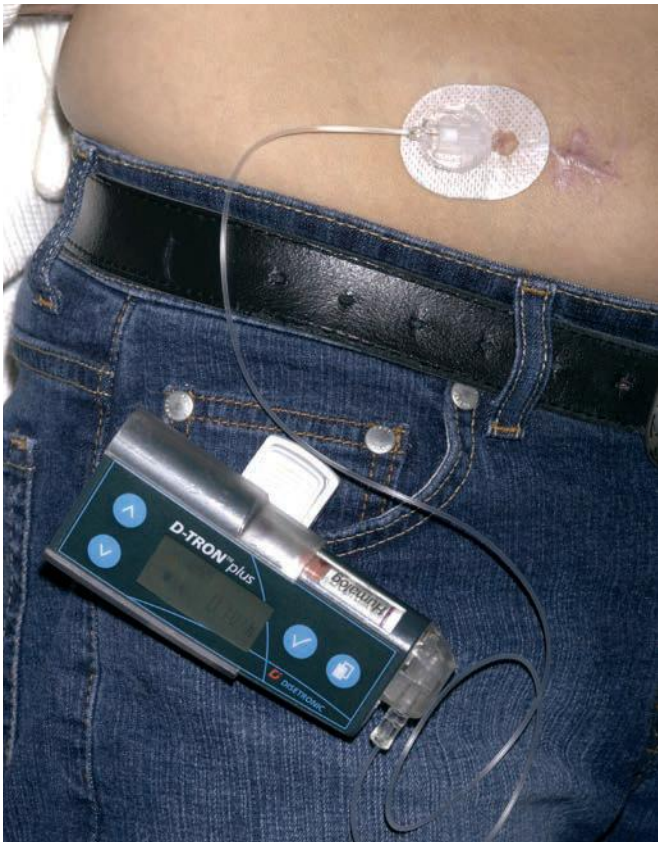
Insulin cannot be taken in tablet form because it is digested in the alimentary canal. The only treatment is regular injections of insulin or use of a programmable pump that provides a continuous supply of insulin under the skin (Figures 9.1 and 9.2). Insulin injections do not cure type 1 diabetes. The patient must have regular injections to stay alive, but even with injected insulin the long-term effects are likely to be kidney failure, heart attack, stroke, amputations, blindness or nerve damage.

Type 2 diabetes

Type 2 diabetes (also known as non-insulin-dependent or **adult-onset diabetes**) usually develops in people over the age of about 45 years, although increasing numbers of younger people are now being diagnosed. Unlike type 1 diabetes, type 2 patients are able to produce insulin but their cells do not respond to it.

Science Photo Library/Saturn Stills

Figure 9.1 A person suffering from diabetes is injecting herself with insulin using a NovoPen®, a device that measures the correct insulin dose from a portable cartridge.



Science Photo Library/Dr. P. Marazzi

Figure 9.2 An insulin pump. The pump delivers a constant, small dose of insulin with a larger dose before meals or whenever the blood glucose level needs correcting.

Type 2 diabetes is a lifestyle disease; it is more common in people who are not physically active and are overweight or obese. The incidence of type 2 diabetes in Australia and other affluent countries is increasing rapidly due to the large number of people who do not adopt a healthy lifestyle. Lifestyle factors that increase the risk of developing type 2 diabetes include:

- lack of physical activity
- being overweight or obese
- a diet that is regularly high in fat, sugar and salt, and low in fibre
- high blood pressure
- high blood cholesterol
- smoking.

There are so many Australians developing the disease that it has become a health crisis. A high proportion of people in our society are overweight and obese, including many younger people, and they are increasingly being diagnosed with the disease.

Type 2 diabetes develops gradually and often there are no symptoms or they are not noticed. It is estimated that about half of the Australians who have type 2 diabetes have not yet been diagnosed. Because the cells do not respond to insulin, they do not take up glucose from the blood. (A fasting blood test is used to detect abnormally high levels of glucose.) There is no cure for type 2 diabetes, but the earlier a diagnosis is made, the better the chances of successful management of the condition. If it remains undiagnosed or untreated, there is an increasing risk of complications such as heart disease, stroke, kidney disease, eye problems, nerve damage, and skin and foot problems.

The treatment of type 2 diabetes involves a management program that aims to keep blood glucose levels within the normal range. Management includes a careful diet, regular physical activity, maintaining a healthy weight, monitoring blood glucose and sometimes medication if blood glucose cannot be controlled by other measures.

Diabetes
The Diabetes Australia website provides more information on diabetes, as well as links to many other useful sites including state-based organisations.

Type 2 diabetes is preventable. The chances of suffering from the disease can be reduced by adopting a healthy lifestyle.

EXTENSION

Uncontrolled diabetes may result in unconsciousness or diabetic coma.

Find out:

- the three different types of diabetic coma and the cause of each
- the relationship between each type of coma and the two types of diabetes
- the first aid and treatment for diabetic coma.

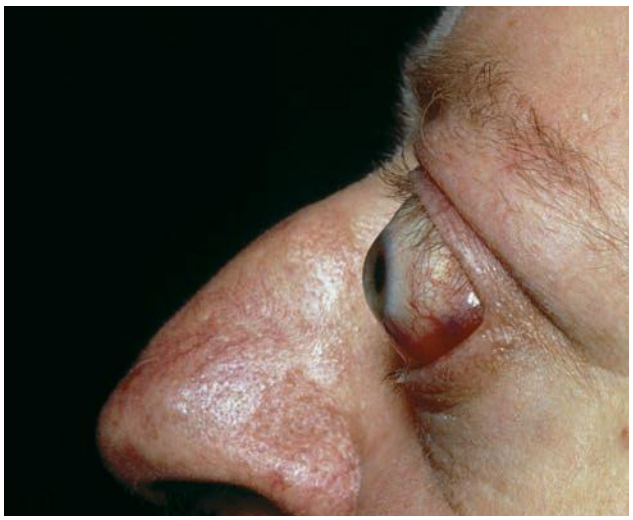
Excess and deficiency of thyroid hormones

Another example of a hormonal disruption to homeostasis is the over- or under-secretion of thyroid hormones. The thyroid gland is located in the neck (see Figures 2.5 and 2.6 on page 27) and it secretes two hormones: **thyroxine** (T4) and **tri-iodothyronine** (T3). Both have the same effect but the major form is thyroxine. Thyroxine affects nearly every tissue in the body by stimulating carbohydrate, protein and fat metabolism. Thus, the secretion of thyroxine from the thyroid regulates basal metabolic rate. Some of the energy released from the chemical reactions stimulated by thyroxine is in the form of heat, which is important in maintaining body temperature. Thyroid hormones are therefore also important in the long-term homeostasis of body temperature, such as in the gradual change in metabolic rate that occurs from summer to winter.

Secretion of thyroxine is controlled by thyroid-stimulating hormone (TSH). TSH is secreted by the anterior lobe of the pituitary but its release is controlled by the hypothalamus in the brain (see pages 25 and 26). An excess of or a deficiency in thyroxine can cause disorders. In some cases the imbalance of thyroxine can be due to an imbalance in TSH.

Hyperthyroidism

Too much thyroxine, called **hyperthyroidism**, occurs when the thyroid gland produces too much hormone. The most common type of hyperthyroidism is known as **Graves' disease**. It is an enlargement of the thyroid caused by an immune system reaction. Although not inherited, there does seem to be a genetic predisposition for the condition. Because the cells are overstimulated, the symptoms of hyperthyroidism are rapid heartbeat, weight loss, increased appetite, fatigue, sweating, anxiety and, in the case of Graves' disease, protruding eyeballs (known as exophthalmia) (see Figure 9.3).



Getty Images/Science Photo Library

Figure 9.3 Exophthalmia, protruding eyeballs, is a symptom of Graves' disease, the most common result of an overactive thyroid gland.

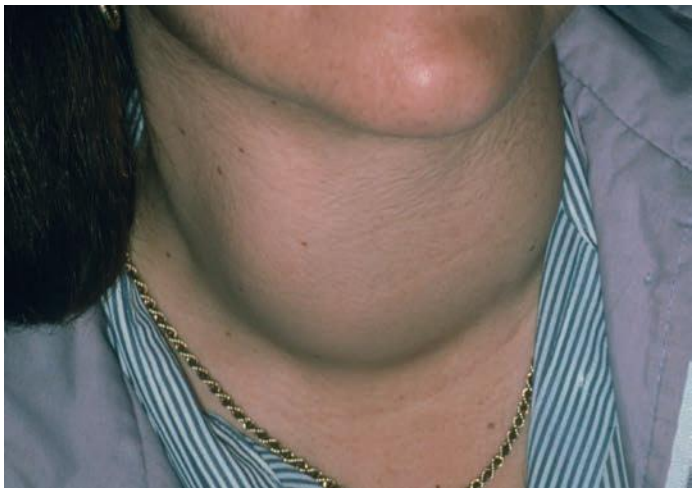
Hyperthyroidism can be treated with drugs that block the thyroid gland's use of iodine or by surgery to remove some or all of the gland. A third method of treatment is to give the patient a drink containing radioactive iodine. The radioactive iodine molecules are taken up by the thyroid cells, which are then killed by the radioactivity. Cells elsewhere in the body do not absorb iodine and are unaffected. The radioactive iodine is eventually excreted in the urine.

Hypothyroidism

Too little thyroxine, **hypothyroidism**, is much more common than hyperthyroidism. About 6–10% of Australian women, and a smaller proportion of men, may be affected. Hypothyroidism occurs either through problems with the thyroid gland or due to problems with the pituitary gland or hypothalamus. Symptoms of hypothyroidism may include slow heart rate, unexplained weight gain, fatigue or a feeling of lack of energy, intolerance to cold, swelling of the face and goitre.

One thyroid gland problem is due to lack of iodine. A thyroxine molecule contains four iodine atoms (hence T4) and a tri-iodothyronine molecule contains three atoms of iodine (T3). Thus, a deficiency of iodine in the diet can prevent the thyroid gland from making enough hormones. The thyroid gland may then become enlarged in an effort to increase hormone production. Enlargement of the thyroid is known as **goitre** (Figure 9.4).

Many people may suffer from iodine deficiency without it being severe enough to produce visible swelling of the neck. In Australia, about 46% of people are affected, so iodine deficiency is now a public health problem. To try to ensure that people get sufficient iodine, the federal government introduced compulsory addition of iodine into most breads in October 2009. All bread, except organic bread and bread mixes for baking at home, must now be made with iodised salt (Figure 9.5).



Science Photo Library

Figure 9.4 Enlargement of the thyroid gland – goitre

www.dlibrary.com.au / Saxa

Figure 9.5 Using iodised table salt during cooking and with meals can reduce the risk of suffering from hypothyroidism due to iodine deficiency.

Adequate iodine in the diet is especially important during pregnancy. Deficiency of iodine in the mother's diet affects development of the baby's brain and also retards physical development. In serious cases, the baby may be born with severely retarded mental and physical growth and impaired movement or hearing, a condition known as **cretinism**.

Although a severe deficiency of iodine can cause hypothyroidism, the most common cause is an attack on the thyroid gland by the patient's immune system. This is known as Hashimoto's disease. Another cause is surgery for cancer of the thyroid that involves removal of all, or a large part, of the gland.

If the cause of hypothyroidism is a lack of iodine, it is easily treated by the inclusion of extra iodine in the diet. For treatment of other causes, tablets containing thyroid hormone are prescribed. There is no cure and the hormone tablets must be taken for the rest of the person's life. The dose of thyroid hormone must be carefully monitored because too little will not relieve the symptoms of hypothyroidism but too much will result in hyperthyroidism.

Dietary iodine
This website provides more information on iodine and iodine deficiency.

Thyroid gland
The Thyroid Australia website provides more information about the thyroid and links to relevant websites.

Treatment of hormone deficiencies using synthetic hormones

Diabetes

Type 1 diabetes, and sometimes type 2 diabetes, are treated by injections of insulin. The insulin for treatment of diabetics used to be obtained from the pancreases of cows and pigs. Supplies of insulin were therefore expensive and limited. The extracts had to be purified, and patients sometimes suffered allergic reactions or infections from the animal-derived insulin.

In the 1980s, genetically engineered human insulin began to be produced. The gene for human insulin was inserted into bacterial DNA and the bacteria were cultured to make human insulin. This insulin, produced from recombinant DNA, was marketed as Humulin®. Yeast is now used in a similar way to make insulin and so almost all the insulin used throughout the world is now biosynthetic recombinant 'human' insulin rather than animal insulin.

More detail on the production of recombinant insulin is provided in Chapter 13.

Getty Images/Voker Steger/SPL

Figure 9.6 Scientists working in a facility for the production of recombinant human insulin from the fermentation of yeast cells in these large vats

Thyroid deficiency

Hypothyroid patients used to be treated with tablets made from the dried and powdered thyroid glands of animals, mainly pigs. The tablets contain both thyroid hormones T3 and T4 but not necessarily in the same proportions as produced by the human thyroid. They also contain traces of other hormones. Although these 'natural' tablets are still available, today most patients are treated with hormones made synthetically by a chemical process.

Levothyroxine is the most commonly prescribed drug for thyroid hormone replacement. It is a synthetic form of T4.

Human growth hormone

Human growth hormone (hGH) is synthesised and secreted by cells in the anterior pituitary. It is essential for normal growth and metabolism. A deficiency of hGH results in growth retardation or dwarfism, and can result from either inheritable or acquired disease. Children with severely retarded growth can be treated with injections of growth hormone. In the past, hGH had to be extracted from the pituitary glands of deceased people, but a single year's supply of the hormone required up to 50 pituitary glands, creating significant shortages. In addition, use of the hormone involved the risk of transmission of viral and other diseases. With the advent of recombinant DNA technology, hGH is now made by genetically engineered *E. coli* bacteria (see Chapter 13). This has resulted in a virtually unlimited supply of the hormone and it has come to be used not only to treat growth problems but also to enhance athletic performance and in anti-ageing treatments.

Behavioural causes of disruption

Many of the things that we do can disrupt the stable internal environment of the body. A few examples are described here to illustrate how our behaviour can disrupt normal functioning.

Drugs

Many medicinal drugs help the body to maintain homeostasis. For example, drugs are available for the treatment of high blood pressure, high blood cholesterol and irregular heart rhythms. The use of insulin for controlling blood glucose and thyroxine for regulating metabolic rate has already been described, and there are a great many more.

Non-medicinal drugs, such as alcohol or ecstasy, may disrupt homeostasis. Many of them do this by binding to receptor proteins on neurons and other cells. The drug molecule may be similar to a particular neurotransmitter, and by binding to the receptor site it can speed up or slow down the transmission of nerve impulses.

Excessive activity

Exercise is good for you. Health experts are constantly telling us that, regardless of age, regular exercise is beneficial in maintaining health. This is true, but you can have too much of a good thing. Some people become hooked on exercise and feel a compulsion to exercise for long periods every day.

Excessive activity can cause physical damage to structures such as tendons, muscles, ligaments, cartilage, bones and joints. Apart from physical damage, over-exercise can also disrupt homeostasis. If nutrition is inadequate, excessive exercise can cause the protein in muscle to be broken down for energy. Instead of building muscle, muscle mass may be reduced. There is a strong link between eating disorders, such as anorexia and bulimia, and excessive exercise.

Eating habits

What we eat, and how much we eat, can have huge effects on the constant environment inside our bodies. Inadequate levels of certain vitamins and minerals in the diet can lead to **deficiency diseases**. For example, we have already discussed how, through lack of iodine, the body cannot produce enough thyroid hormone to maintain normal metabolic rate and therefore body temperature.

Another example is a deficiency of iron in the diet. Without iron the body cannot make haemoglobin, the pigment in red blood cells that carries oxygen. A deficiency of haemoglobin, or of red blood cells, is called **anaemia**. With insufficient haemoglobin the blood cannot carry enough oxygen to the cells. This slows the rate of cellular respiration and thus the release of energy. An anaemic person may feel weak, fatigued and breathless and have a high heart rate. Another cause of anaemia is a deficiency of vitamin B_{12} in the diet. This is known as **pernicious anaemia**.

Energy balance is also an important aspect of homeostasis. Appetite and body weight are crucial factors in maintaining a balance between energy intake and energy use. Regulation of appetite is very complex and involves the alimentary canal, many hormones, the central nervous system and the autonomic nervous system. The hypothalamus (see Figure 2.3 on page 24) is the main regulator of appetite. It receives hormonal messages from the alimentary canal and from adipose, or fat storage, tissue.

Disease disrupts homeostasis

A **disease** is any condition in which normal functioning is impaired. It could therefore be argued that any disease disrupts homeostasis because any abnormal functioning will upset the stable internal environment in some way. The effects of deficiency diseases on homeostasis have already been mentioned.

Examples of diseases that have direct effects on homeostasis include the following.

- **Emphysema** is a lung disease in which the walls of the alveoli (air sacs) break down, resulting in abnormally large air spaces. This reduces the surface area available for gas exchange, so the patient has difficulty taking in enough oxygen. The most common cause of emphysema is smoking.
- **Fever** is an elevation in body temperature. It is not a disease but a symptom of infectious or other diseases (see Chapter 10). In the case of infectious disease, the higher body temperature seems to help the immune system to overcome the infection, but it may affect many of the reactions occurring in the body, and thus disrupt homeostasis.
- **Hypertension**, or high blood pressure, occurs when homeostatic responses are unable to keep the blood pressure at the normal level. Factors that can contribute to hypertension include genetic factors, excessive salt intake, overweight or obesity, lack of exercise, high alcohol consumption and kidney disease.

Injuries may directly affect homeostasis. For example, excessive blood loss would limit the supply of oxygen and glucose to the cells and the removal of carbon dioxide and other wastes. A punctured or collapsed lung would impair the exchange of gases.

Homeostasis is a very fine balance and it does not take much to upset that balance. As we have seen in this section, there are many factors that can disrupt homeostasis and any disruption can have serious consequences.

EXTENSION

Each of the following diseases is relatively common in our society: asthma, gastroenteritis, glandular fever, influenza and pneumonia. For each disease investigate:

- how the disease affects homeostasis of the patient
- how treatment for the disease helps to restore homeostasis.

Disruptions to homeostasis

Science inquiry

ACTIVITY 9.1 Regulation of blood sugar

Two men (A and B) were subject to a glucose tolerance test. Each was given 100 g of glucose at the start of the experiment. The table below shows their blood glucose concentration during the period of the experiment.

Time since start (hours)	Man A (mg/100 mL)	Man B (mg/100 mL)
0	80	170
$\frac{1}{2}$	100	250
1	160	310
$1\frac{1}{2}$	130	300
2	80	280
3	60	210
4	55	180
5	90	160

1 Plot the data for the two men as a graph.
2 One of the men had a diseased pancreas. Which man was it? Give reasons to support your answer.
3 What is the name of the disease from which the man was suffering?

Research workers who were investigating blood glucose regulation injected hormones singly, or as mixtures, into the vein of a dog for five hours. They then measured any increase in blood glucose above the normal level.

Their results are shown in this table.

Hormone injected	Rise in blood glucose level (mg/100 mL)
Adrenaline	30
Glucagon	10
Cortisol	3
Adrenaline and glucagon	58
Adrenaline and cortisol	58
Glucagon and cortisol	35
Adrenaline, glucagon and cortisol	140

4 Which parts of the endocrine system are responsible for releasing each of the hormones listed in the table?
5 A technician suggested giving the hormones to the dog by adding them to its drinking water. Would this method be effective? Explain.
6 Compare the effects of these hormones when acting:
a singly
b together.

7 What do the data indicate about the response of body tissues to the hormone mixtures?
8 In light of your answers to questions 6 and 7, explain how stress could raise blood glucose levels. What would be the advantage of this response?
9 Describe at least three major criticisms of the design of the experiment on the dog.

ACTIVITY 9.2 Thyroid hormone

A scientist injected radioactive iodine into a person's arm. He then measured the concentration of iodine in the arm, in the blood and in the thyroid gland for the next 40 minutes.

Figure 9.7 is a graph showing the concentrations of iodine measured by the scientist.

1 Suggest a hypothesis the scientist may have been testing.
2 Why was the scientist using iodine, rather than some other substance, to investigate the thyroid gland?
3 Why was radioactive iodine used?
4 What do you think the scientist was trying to demonstrate with this experiment?
5 Using the graph, explain what happened to the iodine in the 40 minutes after it was injected into the arm.
6 An important part of the investigation was to measure the concentration of iodine in the person's arm. Why was this necessary?
7 Would it have made any difference to the investigation if the iodine had been injected into the person's leg?

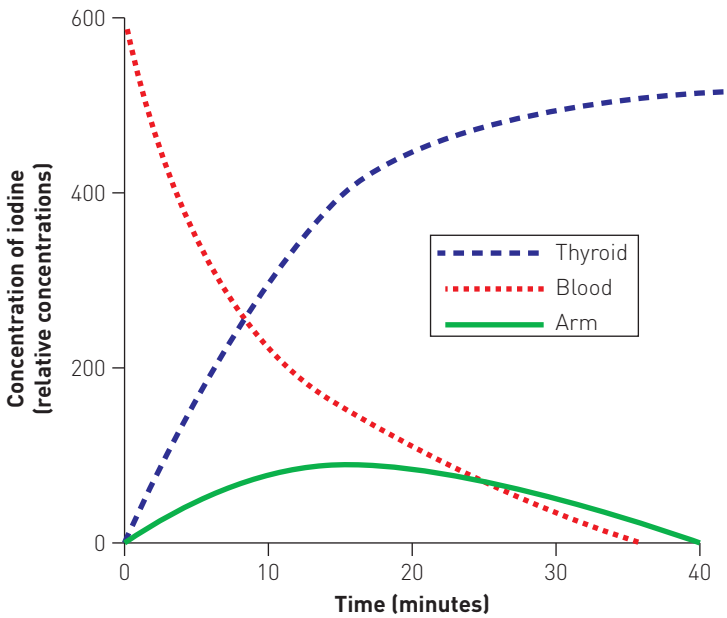


Figure 9.7 Graph showing iodine concentrations in the thyroid and blood over time, after injection into an arm

Review questions

1 Explain the differences between type 1 and type 2 diabetes.
2 Which of the two types of diabetes can frequently be treated by modifying the patient's behaviour? Explain the nature of the behaviour modification that is necessary for effective treatment.
3 How can a person minimise the chance of developing type 2 diabetes later in life?
4 Explain the difference between hyperthyroidism and hypothyroidism.
5 Explain how a dietary deficiency can cause hypothyroidism.
6 Describe how biosynthetic insulin is produced.
7 Drugs used to treat thyroid deficiency are produced synthetically. What advantages are there in using synthetic drugs rather than those obtained naturally?
8 **a** What is a deficiency disease?
b Describe one dietary deficiency that may have an effect on homeostasis.
9 Describe two examples to illustrate how disease can affect homeostasis.

Apply your knowledge

1 The most commonly used test to see whether thyroid function is adequate is a blood test for thyroid-stimulating hormone (TSH).
a How would a blood test for TSH show whether the thyroid is functioning normally?
b A test for TSH in the blood can also be used to determine whether a person's diet has sufficient iodine. How would such a test be able to show whether iodine levels are adequate?
2 Imagine that you are a doctor. One of your patients is overweight and complains of feeling constantly hungry and thirsty. You suspect the patient may have type 2 diabetes.
a What tests would you do to find out whether the person is suffering from type 2 diabetes?
b If type 2 diabetes is positively diagnosed, what treatment would you recommend for the patient?
3 Design a poster, or a leaflet, to make the public aware of the dangers of iodine deficiency and how to avoid it.
4 Goitre, enlargement of the thyroid gland, can be associated with both over-production and under-production of thyroid hormone. Explain how this is possible.
5 List the ways in which homeostasis might be affected if a person lost a litre of blood in an accident.
6 Graves' disease is caused by an abnormality of the immune system. The immune system produces an antibody that behaves in the same way as TSH. Explain how this would lead to hyperthyroidism.
7 Pregnant women need up to three times more insulin than normal. If the body is unable to produce that much insulin, a condition called gestational diabetes develops. Find out how gestational diabetes could affect the developing foetus.

CHAPTER

10

PROTECTION AGAINST INVADERS

UNIT 3 CONTENT

SCIENCE INQUIRY SKILLS

- identify, research and construct questions for investigation; propose hypotheses; and predict possible outcomes
- design investigations, including the procedure(s) to be followed, the materials required, and the type and amount of primary and/or secondary data to be collected; conduct risk assessments; and consider research ethics, including animal ethics
- conduct investigations, including the collection of data related to homeostasis and the use of models of disease transmission, safely, competently and methodically for the collection of valid and reliable data

SCIENCE UNDERSTANDING

Response to infection

- infectious diseases caused by invasion of pathogens in the form of viruses and bacteria can be transmitted from one host to another
- transmission of pathogens occurs by various mechanisms, including through:
  - direct and indirect contact
  - transfer of body fluids
  - disease-specific vectors
  - contaminated food and water
- the body's external defence mechanisms against pathogens include features of the:
  - skin
  - digestive tract
  - urogenital tract
  - respiratory system
  - the ear
  - the eye
- pathogens that enter the body are targeted by non-specific immune responses of inflammation and fever

The human body has a number of mechanisms to protect it from invading organisms. If the body's defences are overcome, the invaders may cause disease. **Communicable** or **infectious diseases** (also called transmissible diseases) are diseases that are caused by foreign organisms invading the body and multiplying there. Such disease-causing organisms are called **pathogens**. Some communicable diseases are said to be **contagious**; this means that they are passed on by direct contact with a person suffering from the disease, or by contact with something touched by the person. Other communicable diseases may be spread from person to person by **vectors**, intermediate hosts of the pathogen, such as mosquitoes or fleas.

The body has defences against pathogens. External defences stop pathogens from entering the body. Internal defences are also available should the invaders get past the external barriers.

Pathogens

The most common pathogens that affect the human body are bacteria and viruses, although fungi and animal parasites can also be involved.

Bacteria

The great majority of bacteria are harmless to humans; they are non-pathogenic. Indeed, many bacteria are essential to life on Earth, through their role in the decomposition of organic material and the cycling of the elements. Some bacteria are used in industrial processes. For example, *Lactobacilli* are used to make yoghurt and sauerkraut; and the flavour of cheeses depends on the type of bacteria used in their production.

Huge numbers of bacteria live on our skin, in our alimentary canal and in other parts of the body. In the armpit of an adult male, there are more than two million bacteria per square centimetre of skin surface, and in the intestines, bacteria are so numerous that they form a major part of the digestion process. These bacteria have no ill effect on our health, yet there are others that may cause illness or death when present in relatively small numbers.

Bacteria all consist of a single cell (Figure 10.2a, page 130) and can be seen only with a microscope. Under the light microscope, about all that can be seen of bacteria is the shape of their cells. Cell shape is used to classify bacteria (Figure 10.2b).

Some of the better-known diseases that are caused by bacteria are shown in Table 10.1 on page 131.

Getty Images/Steve Gschmeissner

Figure 10.1 Bacteria that have invaded the body can be cultured and then identified by testing procedures.

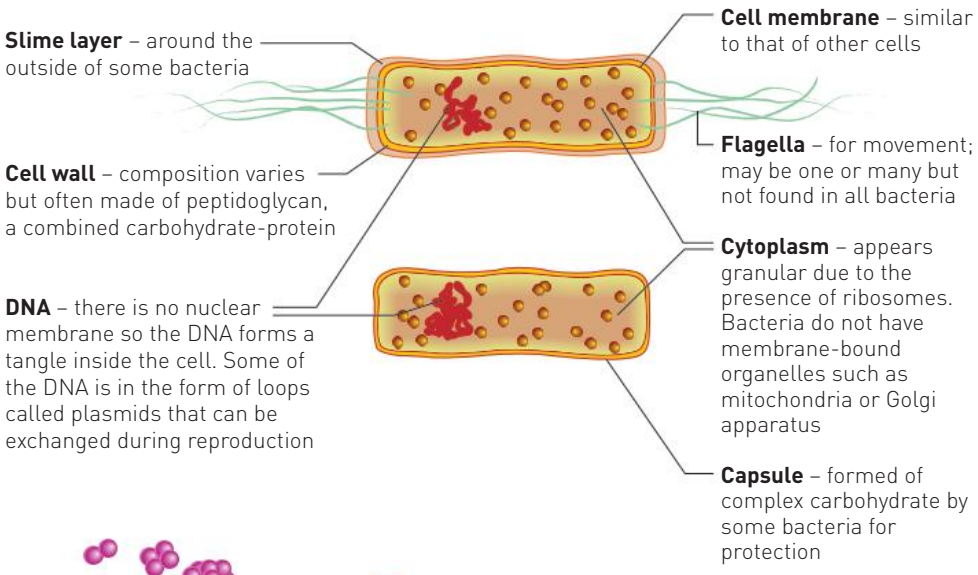
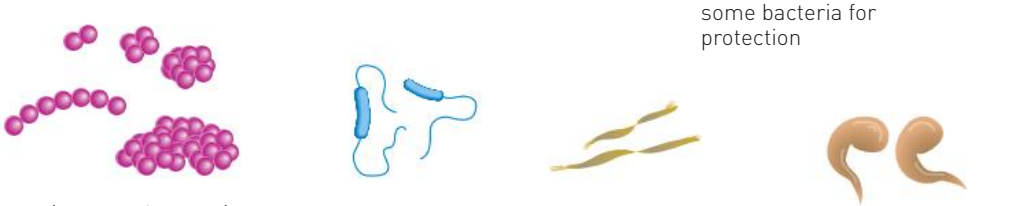


Figure 10.2a The structure of a typical bacterial cell



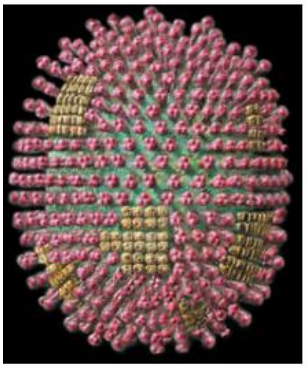
Cocci (singular 'coccus') are spherical cells that may occur singly, in pairs (diplococci), in clusters (staphylococci) or in chains (streptococci)

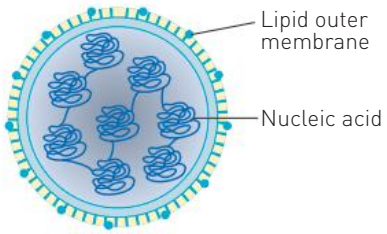
Bacilli (singular 'bacillus') with **flagella** have rod-shaped cells; many have flagella for movement

Spirilla (singular 'spirillum') have twisted cells

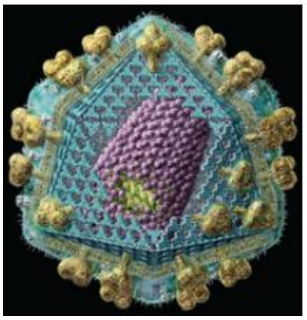
Vibrio are like curved rods and are often shaped like a comma

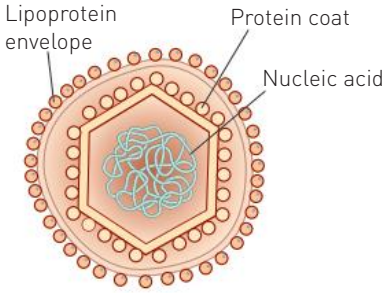
Figure 10.2b Types of bacteria, classified according to the cell shape





Influenza virus has a lipid outer membrane. The RNA is in eight segments.

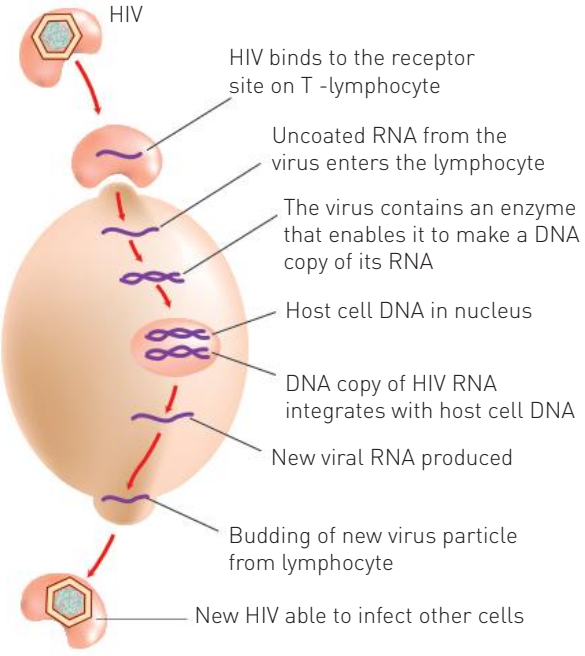




Human immunodeficiency virus (HIV) has a lipoprotein envelope with an internal protein coat.

Viruses all contain either DNA or RNA but not both. Around the nucleic acid is a protein coat, and some viruses have an additional envelope of lipid and protein molecules.

Figure 10.2c Viruses



Viruses cannot reproduce themselves. They attach to the outside of a host cell and the nucleic acid enters the cell. New viral genes are produced by the host cell, and so hundreds of new virus particles are formed.

Figure 10.2d The process of viral replication illustrated by HIV

Viruses

The discovery, by scientists such as Pasteur and Koch in the late nineteenth century, that some diseases were caused by bacteria was a great step forward for medical science. There were, however, certain diseases for which no bacterial cause could be found. For example, Pasteur tried in vain to find a bacterium that caused the disease rabies. The causes of these diseases are **viruses**, structures too small to be seen with an ordinary light microscope.

It was not until 1938 that scientists, using an electron microscope, first saw viruses. Subsequent studies showed that they had distinctive structures and differing sizes. All viruses were found to contain genetic material in the form of a molecule of either DNA (deoxyribonucleic acid) or RNA (ribonucleic acid), but they never contained both. The molecule of DNA or RNA is surrounded by a coat of protein (Figure 10.2c).

When the virus infects a living cell, its DNA or RNA induces the cell to manufacture more virus particles. The new virus particles are then able to leave the host cell to infect others (Figure 10.2d). Some viruses multiply in bacterial cells, causing the death of the bacterium. Such viruses are known as **bacteriophages**.

Some diseases caused by viral infections are shown in Table 10.1. However, not all viruses are harmful.Viruses are now used to insert new genes into other organisms. Bacteria that have been genetically modified in this way are used to produce insulin to treat diabetes.

Table 10.1 Pathogenic organisms and some of the better-known diseases that they cause

Bacteria	Viruses	Fungi	Animal parasites
Anthrax	HIV/AIDS	Ringworm	*Protozoans*
Botulism	Bird flu	Thrush	Amoebic dysentery
Bubonic plague	Chickenpox	Tinea	Amoebic meningitis
Chlamydia	Cold sores (herpes)		Malaria
Cholera	Colds		Sleeping sickness
Dental caries (tooth decay)	Encephalitis (viral)		Toxoplasmosis
Diphtheria	Ebola		*Platyhelminthes (flatworms)*
Gastroenteritis	Genital herpes		Blood flukes
Gonorrhoea	Glandular fever		Hydatids
Impetigo (school sores)	Hepatitis A, B, C, D, E and G		Liver flukes
Legionnaire's disease	Influenza		Tapeworms
Leprosy	Measles		*Nematodes (round worms)*
Meningitis (bacterial)	Meningitis (viral)		Hookworms
Peptic ulcers	MERS (Middle East respiratory syndrome)		Roundworms
Pneumonia	Mumps		Threadworms
Scarlet fever	Poliomyelitis		*Arthropods*
Syphilis	Rabies		Lice
Tetanus	Ross River virus		Scabies (mites)
Trachoma	Rubella		Ticks
Tuberculosis	SARS (severe acute respiratory syndrome)		
Typhoid	Shingles		
Whooping cough	Smallpox		
	Warts		
	Yellow fever		

EXTENSION

Infections that pass from animals to humans are called zoonotic infections (or zoonoses). New pathogens affecting humans by 'jumping' from other species are being reported at an increasing rate. SARS, MERS and bird flu (avian influenza) are recent examples. Find out:

- some diseases that originated in other animals but now occur in humans
- possible reasons why zoonotic infections are increasing
- the dangers of zoonotic infections
- what can be done to reduce the risk of zoonotic infections.

Transmission of pathogens

Communicable disease may be spread by the transmission of a pathogenic organism from one person to another. This transfer can occur in a number of ways.

- **Transmission by contact** involves the spread of the pathogen by actual physical contact. The contact may be *direct*, actually touching an infected person, or *indirect*, touching an object that has been touched by an infected individual. Skin infections and sexually transmissible infections are spread by contact.
- **Transfer of body fluids** from one person to another results in the transmission of a number of infections. When blood or other body fluids from an infected person comes into contact with the mucous membranes (in many parts of the body such as the nose, mouth, throat and genitals) or the bloodstream of an uninfected person, such as through a needle stick or a break in the skin, then pathogens may enter the body of that person. The human immunodeficiency virus, and hepatitis B and C, are spread in this way.
- **Infection by droplets** may occur when tiny droplets of moisture, harbouring pathogenic organisms, are emitted when breathing, talking, sneezing or coughing. The droplets may be breathed in by others, or may settle on food or utensils to be later ingested with food. Many viral infections, such as those causing measles, mumps, colds and influenza, may be spread by droplets.
- **Ingestion** of food or drink contaminated with pathogens may result in disease. Dysentery, typhoid fever and *Salmonella* food poisoning are transmitted in this way.
- **Airborne transmission** of some diseases may occur. When the moisture in exhaled droplets evaporates, many bacteria are killed, but viruses and some bacteria remain viable and can cause infection when inhaled.
- **Transmission by vectors** is the transfer of pathogens by other animals, such as insects, ticks or mites. Some vectors transfer the pathogen directly; others, such as house flies, may spread the pathogen to food or water, which is then ingested. Many vector-borne diseases are spread by a specific vector. For example, malaria and dengue fever are spread by mosquitoes, trypanosomiasis (African sleeping sickness) is spread by the tsetse fly, Lyme disease is spread by ticks, and bubonic plague is spread by fleas from rats and mice.

Defences against disease

Our bodies have a number of defences that protect us against invasion by pathogenic micro-organisms. Often, we are exposed to pathogens without realising it. Many pathogens are prevented from entering the body or, if they do enter, they are dealt with before they can cause symptoms of disease. Even if we do become ill, our defence system often enables us to recover without any medical intervention.

Non-specific defences work against all pathogens. They are the body's first line of defence. In the remainder of this chapter, we will discuss some non-specific defences.

Specific defences are directed at a particular pathogen. For example, if you become infected (or vaccinated) with chickenpox virus, the body will make antibodies to combat the virus. Those antibodies are only effective against the chickenpox virus; they will not work against any other virus or bacterium. Specific resistance to infection will be discussed in the next chapter.

Non-specific defences

External defences

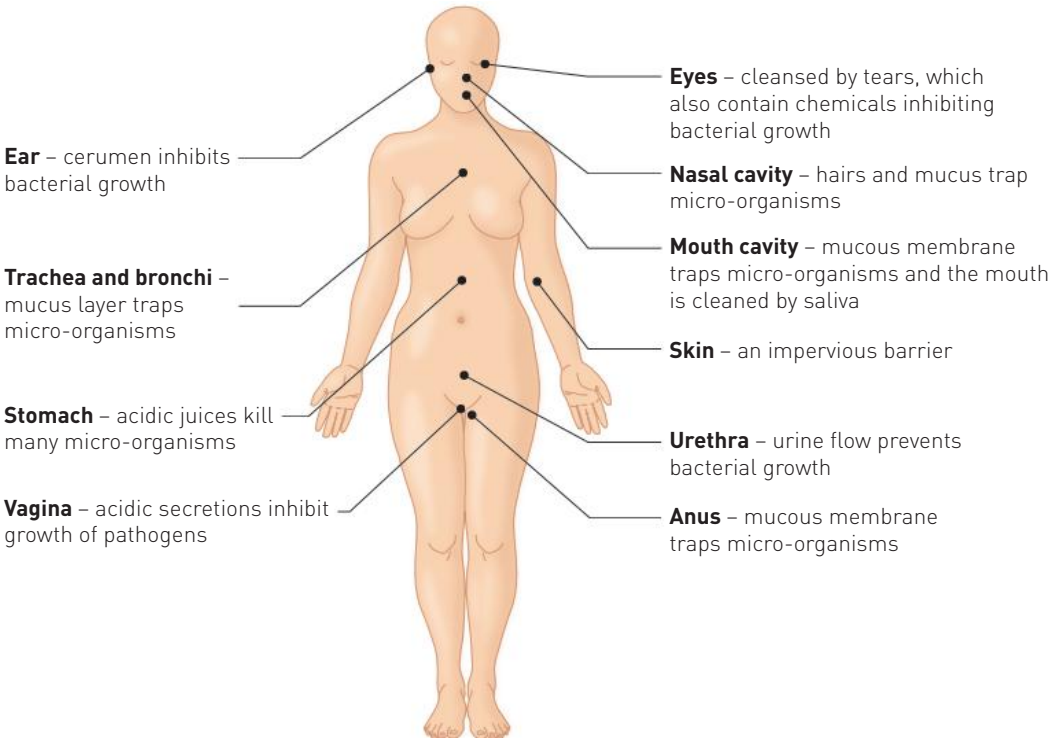
The body has many external defences to try to stop pathogens from entering. All are non-specific. Some of the external defences that prevent pathogens from invading our tissues are as follows.

- The **skin** is an effective barrier covering the outside of the body. It is very good at stopping the entry of micro-organisms, provided it is not broken by cuts and abrasions. At openings in the skin, such as the mouth, eyes and anus, special protection is provided by other defences. Huge numbers of bacteria live on the skin all the time. These normal bacteria occupy the area, and so potential pathogens find it difficult to become established. In addition, the skin has other protective mechanisms. An oily secretion called **sebum** is produced by oil glands in the skin. It contains substances that kill some pathogenic bacteria. **Sweat** secreted onto the skin contains salts and fatty acids that prevent the growth of many micro-organisms.
- **Mucous membranes** line body cavities that open to the exterior. They secrete mucus, which inhibits the entry of micro-organisms to the organs of the body. The whole of the digestive, urinary and reproductive tracts are protected in this way.
- **Hairs** are found in the nose cavity and the ears. In the nose, the hairs and a layer of mucus enable the nose to trap up to 90% of particles inhaled when breathing.
- **Cilia** are tiny hair-like projections from cells that are capable of a beating motion. The mucous membranes lining the nose cavity, the trachea and other air passages have cilia. The beating of the cilia moves mucus, containing trapped particles and micro-organisms, towards the throat, where it may be coughed up or swallowed.
- **Acids**. Stomach juices are strongly acidic. The acid kills many of the bacteria taken in with food or those contained in mucus swallowed from the nose and windpipe. The vagina also has acid secretions that reduce the growth of micro-organisms. The sweat on the skin is slightly acidic.
- **Lysozyme** is an enzyme that kills bacteria. The eyes are protected by the flushing action of tears, which contain this enzyme. Lysozyme is also found in saliva, sweat, secretions of the nose and tissue fluid.
- **Cerumen** (ear wax) protects the outer ear against infection by some bacteria. It is slightly acidic and contains lysozyme.

Nibsc/Science Photo Library

Figure 10.3 Scanning electron micrograph showing the cilia of cells lining the respiratory system; the structures between the cilia are mucus-secreting cells.

› The **flushing action** of body fluids helps to keep some areas relatively free of pathogens. Urine flowing through the **urethra**, the tube that empties the bladder to the outside, has a cleansing action. This prevents bacterial growth and helps to stop bacteria reaching the bladder and kidneys. Women have a shorter urethra than men and so they tend to suffer more bladder infections. Tears, sweat and saliva are also involved in flushing and cleansing.
The body's external defences are summarised in Figure 10.4.



External defences
This website provides an explanation of the external defences against disease.

Figure 10.4 The body's external defences against entry of pathogenic micro-organisms

Protective reflexes

A reflex is an automatic, involuntary response to a stimulus. Protective reflexes help to protect the body from injury, such as the blink reflex, or from infection, such as vomiting. Four reflexes help to protect against infection.

1 *Sneezing*: The stimulus for sneezing is irritation of the walls of the nasal cavity. The irritation may be caused by noxious fumes or dust particles, which are likely to be carrying micro-organisms. Forceful expulsion of air from the lungs carries mucus, foreign particles and irritating gases out through the nose and mouth.
2 *Coughing*: For coughing, the stimulus is irritation in the lower respiratory tract – the bronchi and bronchioles. In a manner similar to sneezing, air is forced from the lungs to try to remove the irritant. The air drives mucus and foreign matter up the trachea towards the throat and mouth.
3 *Vomiting*: Psychological stimuli, excessive stretching of the stomach and bacterial toxins can all induce vomiting. It is not contraction of the stomach but contraction of the muscles of the abdomen and the diaphragm that expel the stomach contents.
4 *Diarrhoea*: Irritation of the small and large intestines by bacteria, viruses or protozoans can cause diarrhoea. The irritation causes increased contractions of the muscles of the wall of the intestines so that the irritant is removed as quickly as possible. Material does not stay in the large intestine long enough for water to be absorbed, so the faeces are very watery.

Internal non-specific defences

If pathogens get past our external defences, there are internal non-specific defences that can help deal with the invaders.

Phagocytes

Organisms that penetrate our external defences are attacked by phagocytes. **Phagocytes** are cells that can engulf and digest micro-organisms and cell debris (Figure 10.5). They are very important in defence against disease.

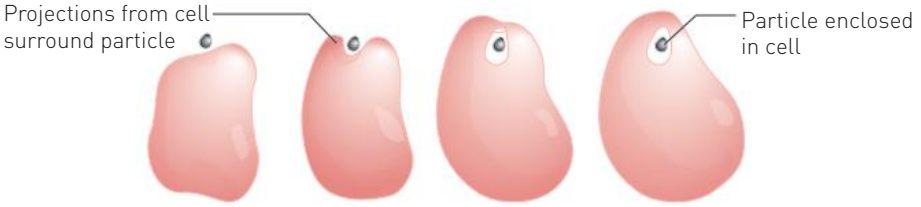
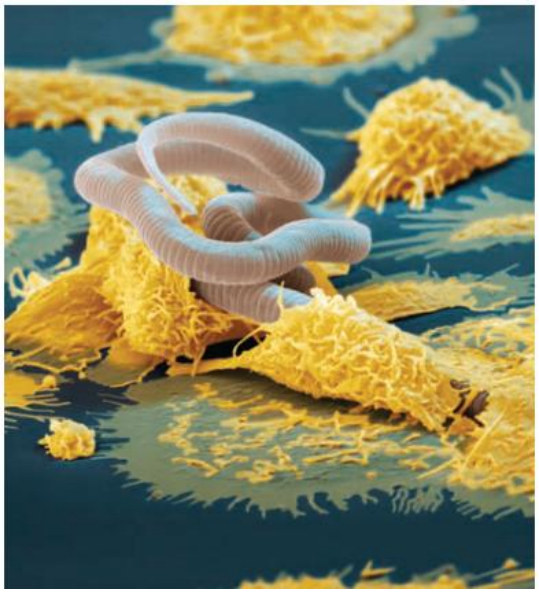


Figure 10.5 The process of phagocytosis

Phagocytosis
This website provides an animation of phagocytosis.

Leucocytes are white blood cells. There are several types of leucocytes and all play a part in phagocytosis. Leucocytes are able to leave the blood capillaries and migrate through the tissues to places of infection or injury. Some leucocytes secrete substances that destroy bacteria before engulfing them, whereas others engulf live bacteria and digest them.

Macrophages are large phagocytic cells that develop from some leucocytes. Some of them are wandering cells that move through the tissues looking for pathogens and destroying them. Others are fixed in one place and only deal with the pathogens that come to them. Like leucocytes, macrophages either engulf and digest the micro-organisms or release substances that destroy them. These processes eliminate many pathogens before an infection has a chance to take hold. Figure 10.6 shows macrophages actively attacking the larva of a parasitic nematode worm.



Eye Of Science/Science Photo Library

Figure 10.6 Scanning electromicrograph showing macrophages (yellow) attacking the larva of a parasitic nematode worm. The larvae are transmitted from one human to another by mosquito bites.

The inflammatory response

Inflammation is a response to any damage to the tissues. The purposes of inflammation are to:

- reduce the spread of any pathogens, to destroy them and to prevent the entry of additional pathogens
- remove damaged tissue and cell debris
- begin repair of the damaged tissue.

Words ending in *-itis* indicate inflammation of specific organs or tissues. For example, tonsillitis is inflammation of the tonsils; meningitis is inflammation of the meninges, the membranes around the brain; and laryngitis is inflammation of the larynx. Inflammation of the skin provides readily observable inflammatory responses to, say, a mosquito bite, a scratch or a bacterial infection in a pimple.

There are four signs of inflammation, and if you think of an infected cut, a pimple or a mosquito bite you will be able to relate to each of the four signs. These are redness, swelling, heat and pain.

Damage to tissues stimulates an integrated series of steps in the inflammatory response, which is shown in Figure 10.7.

1 When stimulated by mechanical damage or by local chemical changes, mast cells release histamine, heparin and other substances into the tissue fluid. **Mast cells** are special cells that are present in most tissues. They stimulate and coordinate inflammation by releasing chemicals.
2 **Histamine** increases blood flow through the area and causes the walls of the blood capillaries to become more permeable so that fluid is filtered from the blood. It is the increased blood flow that causes the heat and redness associated with inflammation, and the escape of fluid from the blood causes the swelling.
3 **Heparin** prevents clotting, so the release of heparin from the mast cells prevents clotting in the immediate area of the injury. A clot of the fluid around the damaged area does form and this slows the spread of the pathogen into healthy tissues.
4 The chemicals released by the mast cells attract **phagocytes**. Macrophages and leucocytes actively consume micro-organisms and debris by phagocytosis.
5 The abnormal conditions in the tissue stimulate pain receptors, and so the person feels **pain** in the inflamed area.
6 The phagocytes, filled with bacteria, debris and dead cells, begin to die. The dead phagocytes and tissue fluid form a yellow liquid called **pus**.
7 New cells are produced by mitosis and **repair** of the damaged tissue takes place.

Inflammation
This website provides an animation of the process of inflammation.

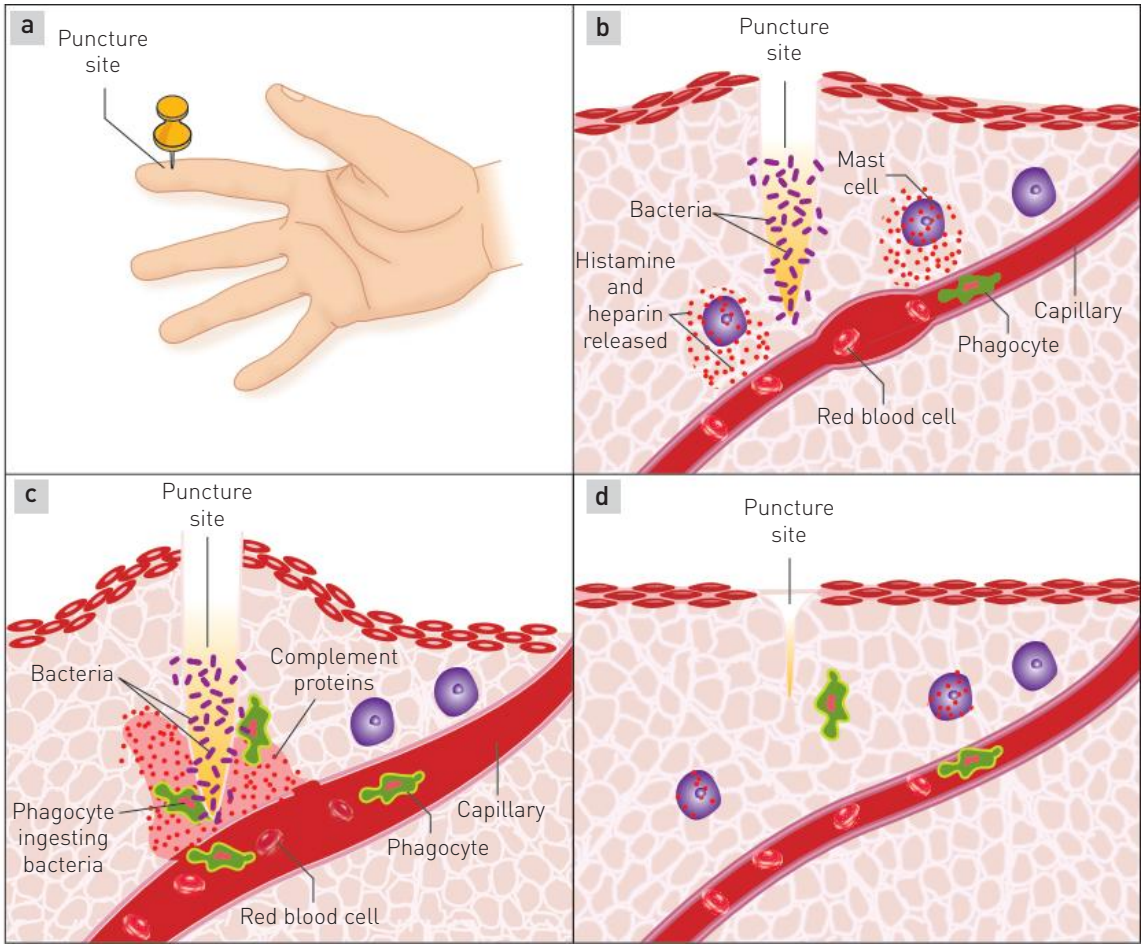


Figure 10.7 The inflammatory response: **a** When the skin is broken, a non-specific inflammatory response is triggered. **b** Mast cells release histamine and heparin. Histamine diffuses into capillaries, causing them to dilate and become leaky. The area becomes red and swells. Heparin prevents clotting in the immediate area. **c** Certain proteins are activated and attract phagocytes to the area, which engulf and digest dead cells and bacteria. **d** The tissue heals when histamine and protein signalling finish and phagocytes are no longer attracted to the area.

Fever

During the course of an infection, such as the common cold or influenza, individuals frequently experience an elevation of body temperature, often called a **fever**. This change in body temperature is due to a resetting of the body's thermostat, controlled by the hypothalamus (see Chapter 2), to a higher level. Thus, when a person has a fever, the body temperature is regulated in response to heat or cold, but always at a higher set level.

The onset of fever is frequently gradual, but it is most striking when it occurs rapidly. In these cases it is as though the body's thermostat were suddenly raised. The person feels cold and, as a consequence, vasoconstriction in the skin and shivering occur (Figure 10.8). Both these activities conserve heat and increase heat production, driving the body temperature up rapidly. When the fever breaks, the point called the crisis, it is as though the body's thermostat has been reset to normal. In this situation the person feels hot and appears flushed, as skin vasodilation and profuse sweating take place.

Fever is beneficial, up to a point. High body temperature is believed to inhibit the growth of some bacteria and viruses. In addition, heat speeds the rate of chemical reactions, which may in turn help body cells repair themselves more quickly during a disease. However, fever can be harmful if the body temperature goes too high. Generally speaking, death will result if the body temperature reaches 44.4–45.5°C.

The resetting of the body's thermostat is thought to be due to substances called pyrogens. These are released by white blood cells during the inflammatory response to a foreign intruder and they act directly on the hypothalamus.

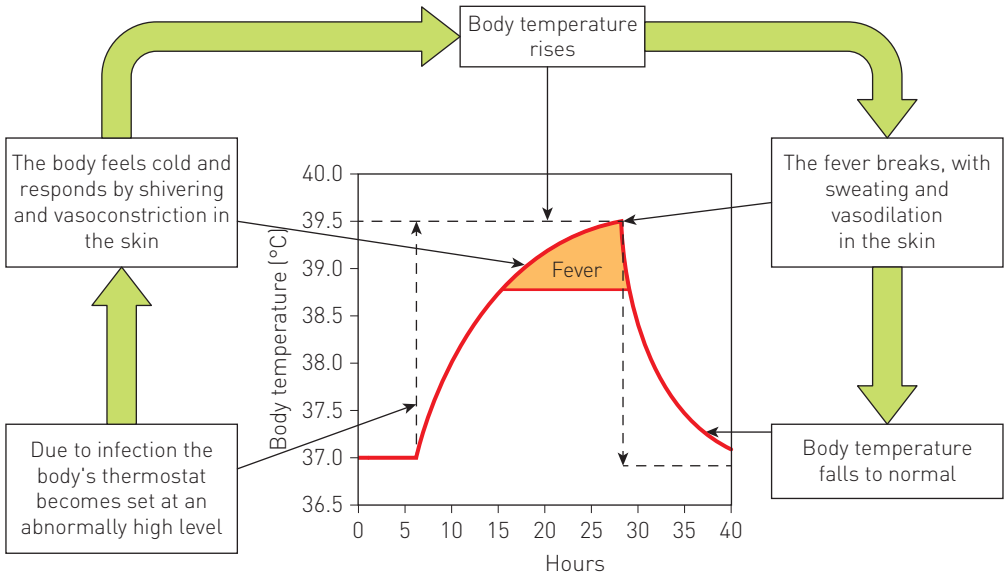


Figure 10.8 Body temperature during fever

The lymphatic system and non-specific defence

The **lymphatic system** consists of:

- a network of lymph capillaries joined to larger lymph vessels
- lymph nodes, which are located along the length of some lymph vessels.

The main function of the lymphatic system is to collect some of the fluid that escapes from the blood capillaries and return it to the circulatory system. In addition to this main function, the lymphatic system is an important part of the body's internal defence against pathogenic organisms.

The lymphatic system was discussed in Chapter 7 of *Human Perspectives Units 1 & 2 ATAR* (in particular, refer to Figure 7.13 on page 86).

Lymph entering the lymph nodes contains cell debris, foreign particles and micro-organisms that have penetrated the body's external defences. Some of these micro-organisms may be pathogenic and, if not destroyed, could cause disease.

Lymph nodes occur at intervals along the lymphatic vessels. Each contains masses of lymphoid tissue, the cells of which are criss-crossed by a network of fibres. Larger particles, such as bacteria, are trapped in the meshwork of fibres as the lymph flows through the spaces in the nodes. Macrophages (Figure 10.6) destroy these particles. The macrophages ingest the particles by phagocytosis. Projections from the macrophage surround the particle and take it into the cell, where it is destroyed by enzymes (Figure 10.5). Most bacteria ingested in this way are killed within 10–30 minutes.

When infections occur, the formation of lymphocytes increases and the lymph nodes become swollen and sore. For example, an infected finger may result in swelling and tenderness in the armpit, where there are a large number of lymph nodes. Most lymphocytes are important in the *specific* immune response to a particular pathogen.

EXTENSION

Two groups of proteins, interferon and complement protein, provide short-term, non-specific resistance to infection by bacteria and viruses.

Find out:

- the source of each of these proteins
- the role of each in non-specific defence.

Helping the body's non-specific defences

Good hygiene

Many positive things can be done to reduce the risk of infection with pathogens. If we do happen to be infected, such as with a cold or the flu, these same practices will reduce the possibility of passing the infection on to others.

Wash your hands, especially:

- before preparing or eating food
- after using the toilet
- before and after providing first aid
- after handling blood or body fluids
- before and after caring for an ill person
- after coughing or sneezing
- before breastfeeding.

Thorough hand washing with soap and water is the most effective way of reducing the spread of micro-organisms from person to person. Listed below are some other habits that you should develop.

- *Cover your mouth* when you cough or sneeze, so that you reduce the spread of infection to others.
- *Wear gloves* when cleaning up blood or other body fluids. If there is a risk of fluids splashing, wear safety glasses.
- *Wipe surfaces with disinfectant* if they have been contaminated with blood or other body fluids, or if they are just plain dirty.
- *Use tongs, pliers or tweezers* or wear heavy gloves when picking up discarded syringes or condoms. Use a puncture-proof container, such as a tin with a lid, to dispose of syringes and needles.
- *Never share personal articles* such as toothbrushes, razors, towels or syringes.

Mechanical barriers

Mechanical barriers provide an obstacle to invading pathogens and therefore reduce the risk of getting a disease. One of the most common mechanical barriers is a surgical mask, and people frequently wear them when there is a high risk of inhaling disease-causing pathogens. During the SARS epidemic in 2003, many people wore a surgical mask when in public places (Figure 10.9). A surgical mask also diminishes the chance that the wearer will breathe out pathogenic organisms, and therefore reduces the spread of disease.

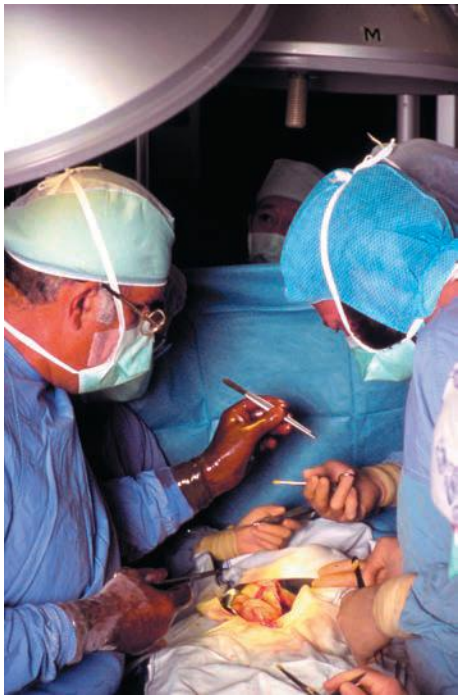
Corbis/Alan Hindle

Figure 10.9 People wearing surgical masks in Hong Kong during the SARS outbreak

Surgeons wear masks because most operations involve cutting through the skin. This means the body's first line of defence has been breached and pathogens can easily enter the tissues. For the same reason surgeons 'scrub up' before an operation and wear sterile gloves (Figure 10.10).

Other mechanical barriers include protective clothing, gloves, and safety glasses when there is a chance that the eyes may be affected. Protective clothing is important in areas where an individual may be bitten by insects, ticks or mites. For example, mosquitoes spread malaria, Ross River virus and other pathogens, so people visiting an area where there are mosquitoes should ensure that their bodies are well covered by clothing to reduce the chance of being bitten.

To reduce the risk of contracting a sexually transmitted infection (see Chapter 21 of *Human Perspectives Units 1 & 2 ATAR*), mechanical barriers such as condoms can be used during sexual activity.



Getty Images/Hank Morgan

Figure 10.10 To avoid spreading disease, surgeons and nurses wear gloves, gowns and masks in the operating theatre.

WS

Protection against invaders

Working scientifically

ACTIVITY 10.1 Fever

Fever is when a person's body temperature is higher than the normal 37°C. It can result from injury, infection, toxins, reaction to a drug or a number of other causes. At one time, it was thought that fever was harmful to the body and that everything possible should be done to reduce a high temperature. It is now known that, provided a person's temperature is not too high (over 40°C), fever can actually speed recovery.

Table 10.2 shows the temperature recorded for a person who suffered a viral infection and recovered after about 10 days.

Table 10.2 Temperature recorded for a patient during a viral infection

Day	Time	Body temperature (°C)
1	8.00 a.m.	37.1
	8.00 p.m.	37.4
2	8.00 a.m.	37.2
	8.00 p.m.	38.1
3	8.00 a.m.	38.6
	8.00 p.m.	39.2
4	8.00 a.m.	39.1
	8.00 p.m.	38.9
5	8.00 a.m.	39.2
	8.00 p.m.	39.3
6	8.00 a.m.	38.8
	8.00 p.m.	39.0
7	8.00 a.m.	39.1
	8.00 p.m.	38.7
8	8.00 a.m.	38.3
	8.00 p.m.	38.1
9	8.00 a.m.	37.7
	8.00 p.m.	37.4
10	8.00 a.m.	37.2
	8.00 p.m.	36.9
11	8.00 a.m.	37.1
	8.00 p.m.	37.2

WHAT TO DO

1. Plot these data on a graph. Make sure your graph conforms to all the conventions for drawing scientific graphs (see Chapter 1, page 13).
2. Describe in words what happened to the patient's temperature over the 11-day period covered by the data.
3. Calculate the patient's average temperature from 8.00 a.m. on day 3 to 8.00 p.m. on day 8.

4 During a fever, the body's 'thermostat' is set to a higher level. Explain how your graph illustrates this characteristic of a fever.

ACTIVITY 10.2 Reye's syndrome

Reye's syndrome (pronounced 'rise') is a serious disorder that sometimes occurs in children after a viral infection such as chickenpox or the flu. It was first recognised as a distinct disorder in 1963 by R. Douglas Reye, an Australian pathologist. Reye's syndrome mainly affects children between the ages of 4 and 16 years, and statistics show that it can be triggered by the use of drugs that reduce fever, such as aspirin.

Use the Internet to research Reye's syndrome. See if you can find out:

1 the signs and symptoms
2 the long-term consequences
3 how often Reye's syndrome occurs in Australia
4 the causes
5 how to prevent it
6 expert opinions on whether Reye's syndrome is associated with aspirin use, or is a distinct disorder.

ACTIVITY 10.3 Skin bacteria

Washing hands is recommended as a way of reducing the spread of bacteria. Antiseptics are used to further reduce the risk of infection.

The purpose of this activity is to determine the effect of hand washing or antiseptic solution on the bacterial population of the skin. The presence of bacteria on the skin of the fingers can be demonstrated by pressing the fingers onto the surface of the medium in a sterile culture plate. A culture plate is a Petri dish with a thin layer of agar jelly in the bottom. The agar contains nutrients for any micro-organisms that may grow on its surface.

After pressing fingers onto the agar, the plate is incubated (kept in a warm place) for several days. Bacteria that were transferred from the fingers to the agar will reproduce and form colonies that can be seen with the naked eye. The more colonies, the more bacteria there were on the skin.

YOU WILL NEED

For each pair or group: 6 or more sterile nutrient agar plates; 2 large beakers; soap or soap solution; antiseptic solution such as Dettol®, Solyptol or Cetavlon®; marking pen; adhesive tape; an incubator (if available)

WHAT TO DO

When handling the culture plates you should take the following precautions.

1 Do not open the lid of the sterile culture plate until you are ready to press your skin onto the surface. It is most important that exposure of the plates to the atmosphere be kept to an absolute minimum.
2 Press gently on the surface; do not push your fingers into the agar.
3 Replace the lid on the culture plate as quickly as possible.
4 Label the plate.
5 Tape the lid onto the plate with two pieces of adhesive tape so that it cannot be accidentally removed.
6 Never remove the lid after the plate has been exposed. The plate should be destroyed with the lid still in place. At the conclusion of the investigation the plates must be autoclaved at 120°C for 20 minutes under 100 kPa pressure to make sure that any micro-organisms are destroyed.
7 Incubate the plates upside down so that any moisture condensing on the lid of the plate cannot drip onto the nutrient medium.
8 After washing your hands, or using antiseptic, rinse them and shake off the excess water. Do not dry your hands or touch the tap or any other objects.

At the end of the incubation period, you can count the number of bacterial colonies that have grown on the agar. If there are a large number you may have to estimate by counting just one-quarter or one-eighth of the plate. You could also count the number of different species of bacteria – the colonies will have a different colour or texture.

Using this method you could:

- test for the presence of bacteria on the fingers before and after hand washing
- test the effect of different periods of hand washing
- compare hand washing and the use of antiseptic solution
- test the effectiveness of different brands of antiseptic
- compare bacterial populations on the fingers and toes
- compare bacterial populations on the fingers and lips
- compare the effectiveness of bacterial wipes and antiseptic solution
- compare the effectiveness of natural antiseptics, such as tea tree oil, lavender oil and thyme oil, with manufactured antiseptics
- try any other comparisons you wish to make.

Propose a hypothesis and then design your experiment.

1. What will be your independent variable – what variable are you investigating?
2. What will be your dependent variable – what variable will change because of the changes you make to the independent variable?
3. What variables will you need to control – what variables will have to be the same for all trials?

Draw up a suitable table in which to record your results (see Chapter 1, page 13, for the correct format for a results table). You may be able to combine results with other groups that have tested the same hypothesis.

STUDYING YOUR RESULTS

Discuss the results of your investigation. Your discussion should include answers to the following questions.

1. Was your hypothesis supported or disproved?
2. What were some sources of error in your investigation?
3. How confident are you of your results?
4. What further investigations need to be made?
5. What improvement could be made to your experimental procedure?

Review questions

1 What is a communicable disease? Give five examples of such diseases.
2 Explain the difference between:
  a a pathogen and a vector
  b RNA viruses and DNA viruses
  c bacteria and bacteriophages.
3 **a** Bacteria were first seen in 1683 but viruses were not seen until 1938. Why?
  b List four differences between bacteria and viruses.
4 List the external defences that prevent the entry of pathogenic organisms into the body.
5 **a** How do protective reflexes help to defend the body from infection by pathogenic organisms?
  b List four reflexes that help to protect against infection.
6 **a** What is a phagocyte?
  b Describe the process of phagocytosis.
  c Explain the importance of phagocytes in defence against disease.
7 **a** What are the four signs of inflammation?
  b How does the inflammatory response cause the four signs?
8 In the inflammatory response, describe the role of:
  a mast cells
  b histamine
  c heparin
  d phagocytes.
9 How is fever during the course of an infection thought to be beneficial?
10 List behavioural practices that can be adopted to help reduce the spread of disease.
11 What are mechanical barriers and how do they reduce the spread of infectious diseases?

Apply your knowledge

1 Leprosy (Hansen's disease) is endemic to the Northern Territory of Australia, where it is found mainly among Australian Aboriginal people. It is not very contagious but it is found in unhygienic, overcrowded conditions. What could be done to reduce the incidence of leprosy in Australia?
2 An economist claimed that, economically, the virus causing the common cold was the most important of the viruses that cause disease in humans. What do you think would be the economic importance of the cold virus?
3 The Russian composer Tchaikovsky died of cholera during an epidemic in Moscow in 1893. It is believed that Tchaikovsky drank unboiled water during the epidemic, some think in a deliberate attempt to commit suicide. Why would drinking unboiled water increase the risk of cholera infection?
4 Hepatitis B is a disease that is causing concern in Australia. Why are medical authorities so concerned about the disease? What precautions can you take to avoid the disease?
5 Draw a flow chart showing the events that occur in an inflammatory response.
6 Explain why someone with an infected toe may develop a lump in the groin.
7 Outbreaks of virulent forms of influenza, and other diseases such as SARS and Ebola, create major problems for health agencies around the world that are seeking ways to control their spread. What action could these agencies take to protect the citizens of their countries?
8 During a fever, people often have severe chills and can shiver uncontrollably even though their temperature is above normal. Explain how this is thought to come about.
9 It has been possible to keep Australia relatively free of infectious diseases such as typhoid, cholera and yellow fever. Why has AIDS, however, been able to become so widespread in Australia?

CHAPTER

11

SPECIFIC RESISTANCE TO INFECTION

UNIT 3 CONTENT

SCIENCE INQUIRY SKILLS

- communicate to specific audiences, and for specific purposes, using appropriate language, nomenclature, genres and modes, including scientific reports

SCIENCE AS A HUMAN ENDEAVOUR

- the decision to participate in immunisation programs can be influenced by the social, economic and cultural context in which it is considered

SCIENCE UNDERSTANDING

Response to infection

- antiviral and antibiotic drugs are used for treating infections and differ in their specificity to pathogens
- passive immunity can be acquired as antibodies gained through the placenta, or antibody serum injections; active immunity can be acquired through natural exposure to the pathogen, or the use of vaccines
- immunity is gained through the exposure to specific antigens by the production of antibodies by B lymphocytes and the provision of cell-mediated immunity by T lymphocytes; in both cases memory cells are produced

A T-lymphocyte

Our bodies have a number of defences that protect us against invasion by pathogens. Very often we are exposed to pathogens without realising it. As discussed in the previous chapter, many pathogens are prevented from entering the body or, if they do enter, are dealt with before they can cause symptoms of disease. Even if we do become ill, the body's defence system often enables recovery without any medical intervention.

Defence against pathogens can be either non-specific or specific. Non-specific defences, described in Chapter 10, work against all pathogens, while specific defences target one particular pathogen. Non-specific defences include external defences, protective reflexes and internal non-specific defences.

Pathogenic organisms attempting to get into your body must first get past defences such as the skin and mucous membranes. Next they must get past a series of other defences that include patrolling phagocytes and granulocytes. Finally, any infectious agent that is able to get past all these non-specific barriers is confronted by the specific defences that are discussed in this chapter.

Lymphocytes and macrophages

Lymphocytes are cells that are involved in both non-specific and specific defence. About 20–30% of the white cells in the blood are lymphocytes. However, these circulating lymphocytes are only a small fraction of the total lymphocytes in the body. The combined weight of lymphocytes in a person's body is over a kilogram.

Most lymphocytes are produced in the bone marrow, but they are also produced in lymphoid tissues, which are described below. Lymphocytes roam throughout the body. They are able to wander through a tissue and then enter the blood, or the lymph, to be transported to another part of the body where they again enter the tissues.

Macrophages are also involved in both non-specific and specific defence. They are large phagocytic cells that develop from a type of white blood cell. Macrophages are able to consume foreign substances and micro-organisms by phagocytosis. They are involved in specific defence by alerting the immune system to the presence of foreign material.

Specific defences

Specific defences are those directed towards a particular pathogen. For example, if you get infected (or vaccinated) with chickenpox virus, the body will make antibodies to combat that virus. Those antibodies are only effective against chickenpox virus and will not work against any other virus or bacterium.

Specific defences are part of our immune system. The **immune system** is composed of different types of cells that occur in most of the organs of the body. These cells protect against foreign organisms, a range of alien chemicals, as well as cancerous and other abnormal cells. Some of these cells are non-specific, such as phagocytes, which are able to engulf and digest micro-organisms and cell debris. However, others such as B-cells and T-cells only provide protection against a specific micro-organism or disease-causing substance. When these cells react it is called the immune response.

The immune response

The **immune response** is a homeostatic mechanism. When micro-organisms or foreign substances enter the body, the immune response helps to deal with the invasion and restore the internal environment to its normal condition.

There are two parts to the immune response. One part, called **humoral response** or **antibody-mediated immunity**, involves the production of special proteins called antibodies, which circulate around the body and attack invading agents. The second part, called **cell-mediated response**, involves formation of special lymphocytes that destroy invading agents. Both

these aspects of the immune response involve lymphoid tissue. Most **lymphoid tissue** is in the lymph nodes but it also occurs in other parts of the body, such as the spleen, the thymus gland and the tonsils (Figure 11.1; see also Chapter 7, *Human Perspectives Units 1 & 2 ATAR*).

Much of the lymphoid tissue is composed of the two types of lymphocytes that are involved in the immune response – the B-cells and T-cells. **B-cells** provide antibody-mediated immunity and **T-cells** provide cell-mediated immunity. Both these cells are produced in the bone marrow, and both end up in the lymphoid tissue, but they mature by following two different routes between bone marrow and lymphoid tissue. About half the cells produced by the bone marrow go to the thymus (see Figure 2.9 on page 28), where they mature into T-cells before being incorporated into the lymphoid tissues (Figure 11.2). The other half of the cells mature in the bone marrow to become B-cells and then also become part of the lymphoid tissues (Figure 11.3). (T-cells are so-called because they mature in the thymus; B-cells because they mature in the bone marrow.)

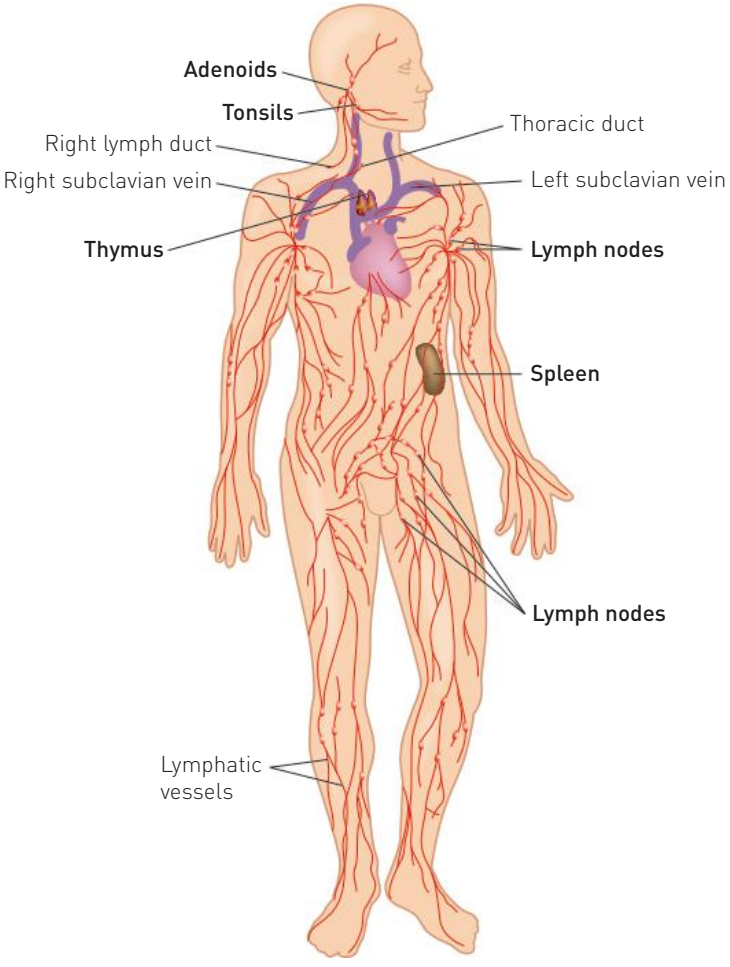
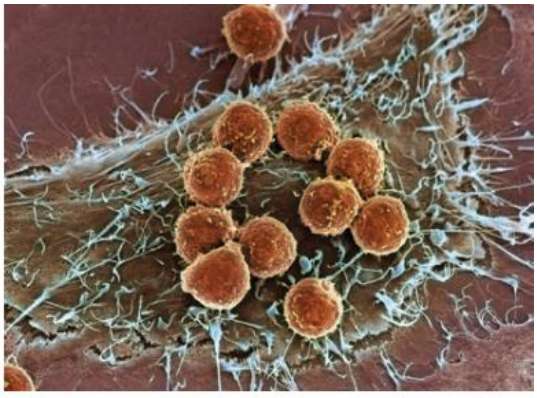
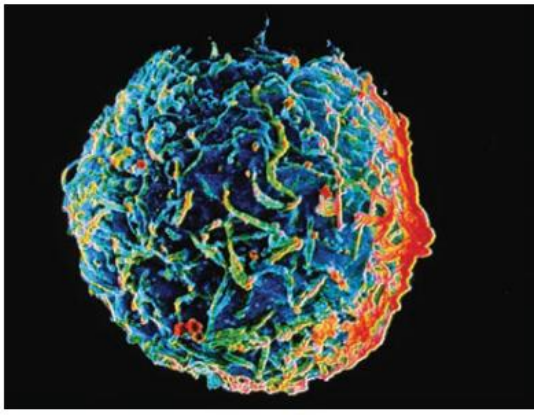


Figure 11.1 Lymphoid tissue occurs throughout the body.



Science Photo Library/Steve G.Schmeissner

Figure 11.2 Coloured scanning electron micrograph of T-lymphocyte cells (orange) attached to a cancer cell



Science Photo Library/CNRI

Figure 11.3 Coloured scanning electron micrograph of a B-lymphocyte. The cell surface is covered with ridges that help it to bind to its target.

Antigens

Antibody-mediated and cell-mediated immunity are triggered by antigens. An **antigen** is any substance capable of causing a specific immune response. Such a substance, introduced to the body, causes the body to produce specific antibodies. Antigens are large molecules. They may be proteins, carbohydrates, lipids or nucleic acids. An antigen could be a virus particle or a whole micro-organism, such as a bacterial cell, or part of a bacterium, such as the flagella, cell wall or capsule. Toxins produced by bacteria are also antigens. Antigens are not necessarily associated with micro-organisms. Tissues transplanted from another person, blood cells of a foreign blood group, and such things as pollen grains and egg white contain antigens.

Large molecules produced in a person's own body do not cause an immune response. These are called **self-antigens**. Foreign compounds that do trigger an immune response are **non-self antigens**. The immune system becomes programmed to distinguish between self-antigens and non-self antigens before birth. From then on, it only attacks non-self antigens.

Antibodies

An **antibody** is a specialised protein that is produced in response to a non-self antigen. Antibodies belong to a group of proteins known as **immunoglobulins**, often represented as Ig. There are five classes of these antibodies, which vary in their structure and are designated IgA, IgD, IgE, IgG and IgM.

The antibody produced in response to an antigen can combine with that antigen to form an **antigen–antibody complex**. Antigen molecules have specific active sites and at these sites the antibody can combine with the antigen. The active site on the antigen and the active part of the antibody fit together like a key in a lock. Each antibody can combine with only one particular antigen, in the same way that a key will only open a particular lock (Figure 11.4).

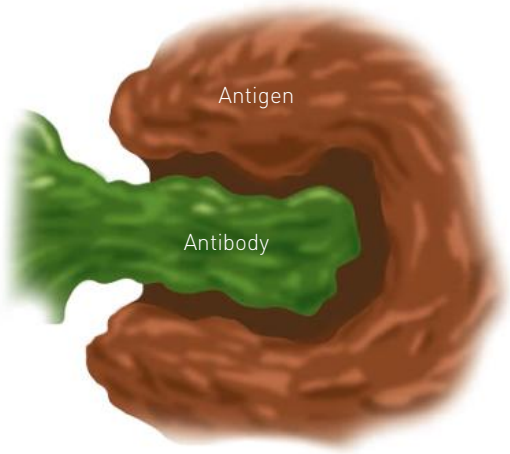


Figure 11.4 The active sites on the antibody and antigen molecules are complementary: they fit together like a lock and key.

Antibody-mediated immunity

The humoral response involves the production and release of antibodies into the blood and lymph. This is antibody-mediated immunity. It provides resistance to viruses, bacteria and bacterial toxins before these micro-organisms or substances enter the body's cells.

Lymphoid tissue contains thousands of types of B-cells. Each type is capable of responding to a specific antigen. When an antigen activates B-cells, they enlarge and divide into a group of cells called a **clone**. Most of the clone become **plasma cells**, which secrete the specific antibody capable of attaching to the active site of the antigen. These antibodies circulate in the blood, lymph and extracellular fluid to reach the site of the invasion of micro-organisms or foreign material (Figures 11.5 and 11.6 on page 148). The B-cells of the clone that did not differentiate into plasma cells remain as **memory cells**. These memory cells spread to all body tissues to allow the response to occur more rapidly should the antigen enter the body again.

On the first exposure to an antigen the immune reaction is called the **primary response**. The body's immune system usually responds fairly slowly, often taking several days to build up large amounts of antibodies. It takes time for the B-cells to multiply and differentiate into plasma cells. As the plasma cells begin to secrete antibodies, the level of that particular antibody in the blood plasma rises. Once it reaches a peak, it begins to decline. However, the primary response leaves the immune system with a memory of that particular antigen.

With a second or subsequent exposure to the same antigen, the response is much faster because of the activity of the memory cells. With this **secondary response**,

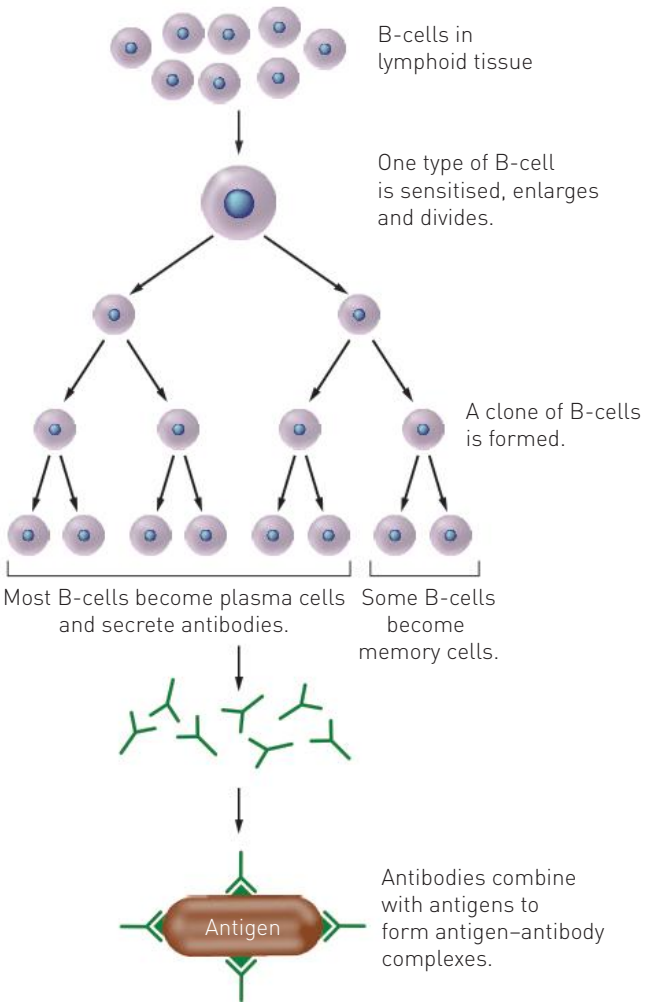


Figure 11.5 Events in the antibody-mediated immune response

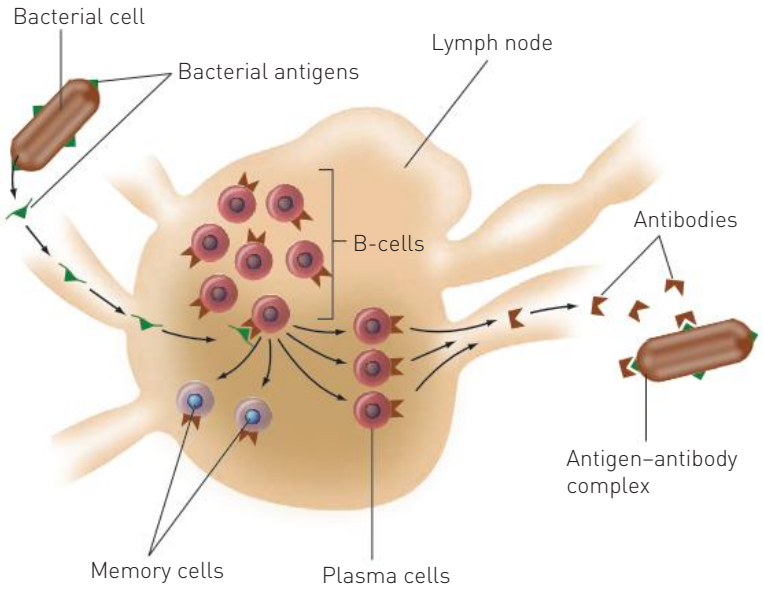


Figure 11.6 Antibody-mediated immune response in a lymph node

plasma cells are able to form very quickly, with antibody levels in the blood plasma rising rapidly. Frequently, this response is so quick that the antigen has little opportunity to exert any noticeable effect on the body and no illness results. Figure 11.7 shows the amount of antibody in the blood plasma after a first and second exposure to an antigen.

How do antibodies work to provide resistance to infection? *All antibodies combine with the antigen for which they are specific* to form an antigen–antibody complex. The response that then occurs varies according to the particular antigen and antibody. Antibodies may:

- combine with foreign enzymes or bacterial toxins, or inactivate them by inhibiting reaction with other cells or compounds
- bind to the surface of viruses and prevent the viruses from entering cells
- coat bacteria so that the bacteria are more easily consumed by phagocytes (Figure 11.8)

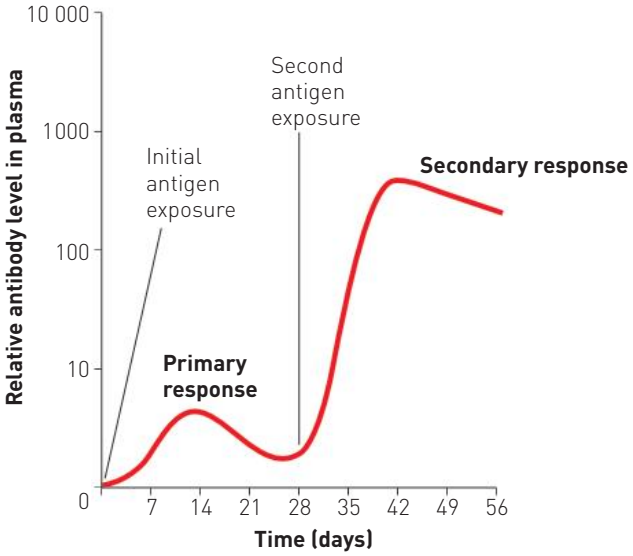
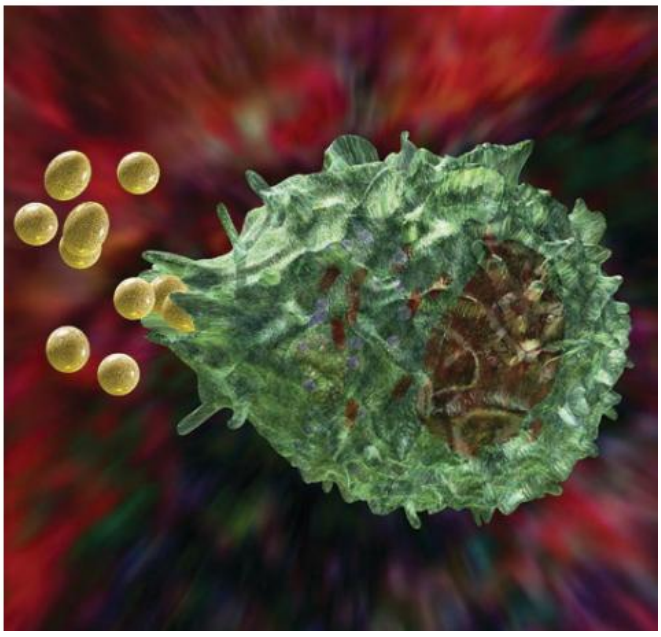


Figure 11.7 The antibody level in blood plasma after a first and a second exposure to an antigen



Science Photo Library/Russell Kightley

Figure 11.8 A macrophage (green) engulfing bacteria (yellow) by the process of phagocytosis

› cause particles such as bacteria, viruses or foreign blood cells to clump together – a process known as **agglutination** (Figure 11.9)
› dissolve organisms
› react with soluble substances to make them insoluble and thus more easily consumed by phagocytes.

Figure 11.10 summarises how antibodies interact with antigens.

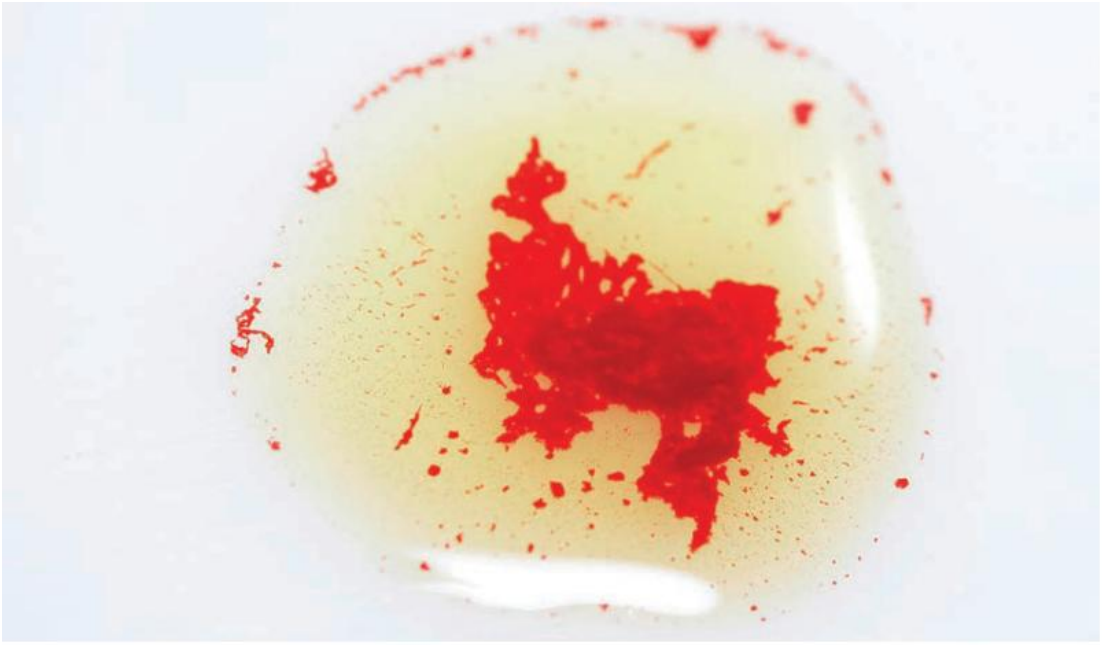


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Figure 11.9 In the drop of serum shown, the agglutination of red blood cells has occurred after blood of one type was mixed with a serum containing non-compatible antigens. Agglutination is where antibodies against the foreign red blood cells bind the cells together in clumps.

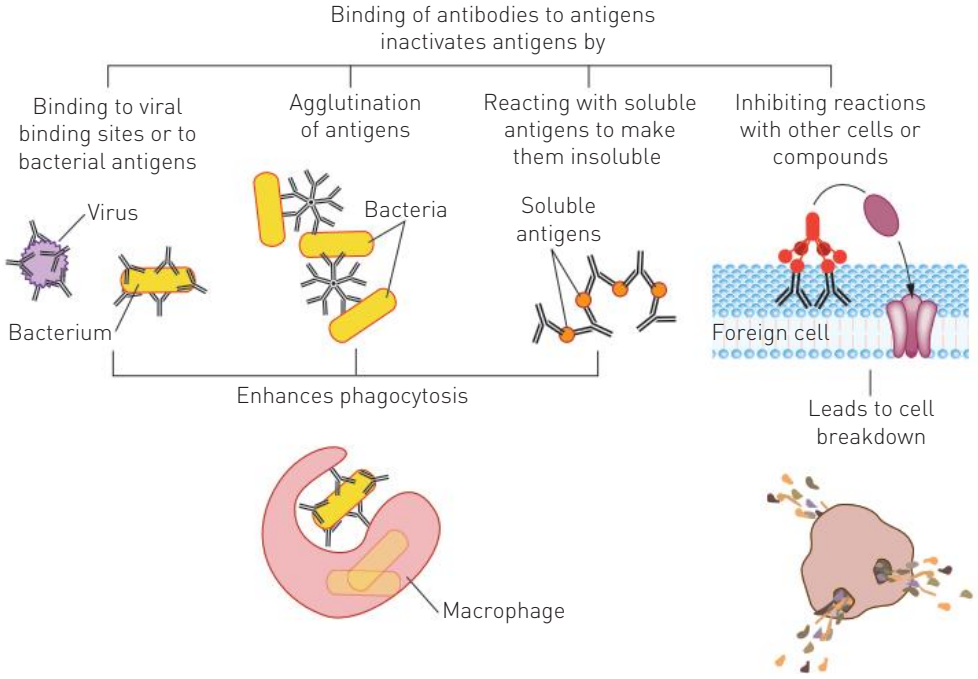


Figure 11.10 A summary of how antibodies interact with antigens to inactivate the antigens

Immune response
This website provides an animated sequence showing the immune response.

Cell-mediated immunity

Cell-mediated immunity (or cellular immunity) provides resistance to the intracellular phase of bacterial and viral infections. These pathogens, such as the bacteria responsible for tuberculosis and legionnaire's disease, specialise in invading and replicating inside their hosts' own cells, making them particularly difficult to overcome.

Cell-mediated immunity is also important in providing resistance to fungi and parasites, and is involved in the rejection of transplants of foreign tissue. It also appears to be important in fighting cancer cells.

The T-lymphocytes are responsible for cellular immunity. They occur in the same lymphoid tissue as B-cells but occupy different areas of the tissue. Like B-cells, there are thousands of types of T-cells, and each type responds only to one particular antigen. When a foreign antigen such as a virus or a bacterium enters the body, the particular type of T-cells that are specifically programmed for that antigen become activated or **sensitised**. This only occurs after a B-cell or macrophage encounters the foreign antigen, travels to the nearest lymph node and presents it to the T-cells.

The sensitised T-cells enlarge and divide, each giving rise to a clone, a group of identical T-cells (Figure 11.11). Some cells of the clone remain in the lymphoid tissue as **memory cells**, which are able to recognise the original invading antigen. If infection with the same antigen should occur again, these memory cells can initiate a much faster response to the second and subsequent infections.

The T-cells that do not become memory cells develop further, producing three different types of T-cell.

- **Killer T-cells** migrate to the site of infection and deal with the invading antigen. They attach to the invading cells and secrete a substance that will destroy the antigen, and then go in search of more antigens.
- **Helper T-cells** play an important role in both humoral and cellular immunity. They secrete a number of substances that:
  - cause lymphocytes at the infection site to become sensitised, thus intensifying the response
  - attract macrophages to the place of infection so that the macrophages can destroy the antigens by phagocytosis (see Figure 11.8)
  - intensify the phagocytic activity of macrophages.
- **Suppressor T-cells** act when the immune activity becomes excessive or the infection has been dealt with successfully. They release substances that inhibit T- and B-cell activity, slowing down the immune response.

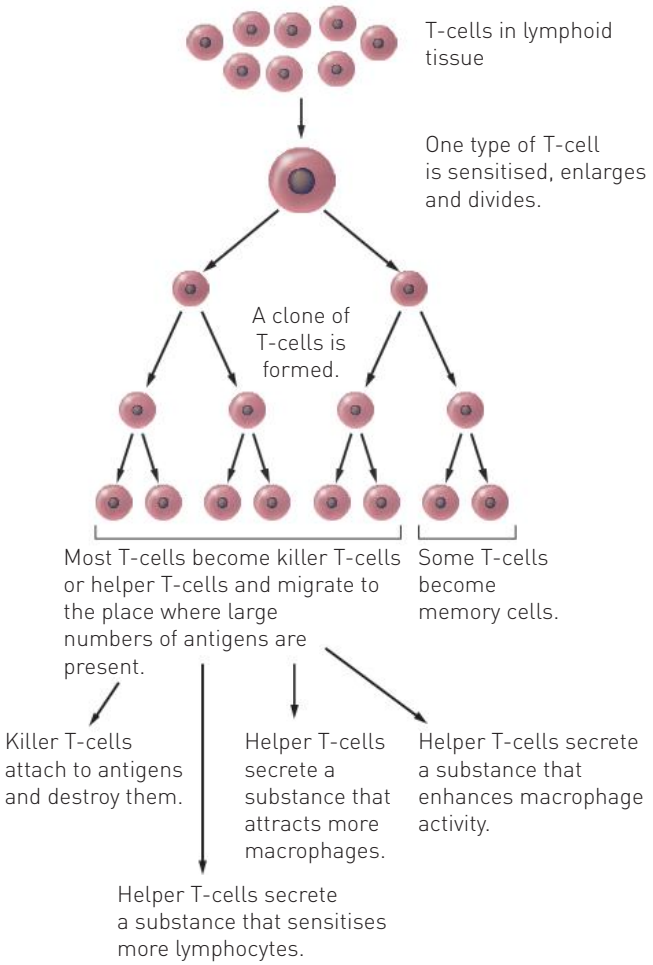


Figure 11.11 Response to T-cells in cell-mediated immunity

Table 11.1 Summary of immune responses

Antibody-mediated immunity (humoral immunity)	Cell-mediated immunity (cellular immunity)
Works against bacteria, toxins and viruses before they enter the body's cells; also against red blood cells of a different blood group than the person.	*Works against transplanted tissues and organs, cancer cells and cells that have been infected by viruses or bacteria; also provides resistance to fungi and parasites.*
1 Foreign antigen reaches lymphoid tissue. **2** Certain B-lymphocytes are stimulated to undergo rapid cell division. **3** Most new B-cells develop into plasma cells, which produce antibodies and release them into blood and lymph. **4** Antibodies combine with the specific antigen and inactivate or destroy it. **5** Some of the new B-cells form memory cells.	**1** Foreign antigen reaches lymphoid tissue. **2** Certain T-lymphocytes are stimulated to undergo rapid cell division. **3** Most new T-cells develop into killer T-cells or helper T-cells, which migrate to the site of the infection. **4** Killer T-cells destroy the antigen, while helper T-cells promote phagocytosis by macrophages. **5** Some sensitised T-cells form memory cells.

Immune response summary
This website summarises the immune response, and includes an animation of a B-cell and a T-cell attacking an invader.

EXTENSION

Lymphokines and interleukins are important substances involved in the immune response. Find out:

- what each of these substances is
- the source of these substances
- their role in the immune response.

Types of immunity

Immunity is resistance to infection by invading micro-organisms. Using the processes just described, the body is able to respond quickly enough to deal with any invasion by pathogenic micro-organisms before symptoms of disease occur. The ability to respond rapidly may be natural or artificial. **Natural immunity** occurs without any human intervention; **artificial immunity** results from giving people an antibody or antigen.

Natural and artificial immunity can be passive or active. **Passive immunity** is when a person is given antibodies produced by someone else. The individual's body plays no part in the production of antibodies. This can occur naturally when antibodies from the mother pass across the placenta to a developing foetus or when the mother's antibodies are passed to the baby in breast milk. It can be gained artificially when a person is injected with antibodies to combat a particular infection. This is often done when a person is exposed to pathogens that cause serious diseases, such as tetanus, diphtheria and rabies. Antibodies are given so that immunity is established immediately. Passive immunity is short-lived: it lasts only until the antibodies are broken down and excreted.

Active immunity results when the body is exposed to a foreign antigen and manufactures antibodies in response to that antigen. This type of immunity is prolonged because, although the amount of the antibody produced gradually decreases, the 'memory' of that antigen persists through the memory cells once the antigen has been dealt with. Should a subsequent infection involving the same antigen occur, the appropriate antibodies can be produced very quickly before the infection can produce any disease symptoms (see Figure 11.7). Such immunity lasts for many years, often for life. Active immunity to a disease can result from an actual attack of the disease (natural active immunity) or from an injection of the antigens associated with the disease (artificial active immunity). Table 11.2 on page 152 summarises the types of immunity.

Table 11.2 Types of immunity

	Natural	Artificial
Passive	Antibodies enter the bloodstream across the placenta or in breast milk.	Antibodies are injected into the bloodstream.
Active	Ability to manufacture antibodies results from an attack of a disease.	Ability to manufacture antibodies results from being given an antigen by vaccination.

EXTENSION

The body's immune system does not normally react against its own antigens – the body is said to have tolerance for its own antigens. However, sometimes this tolerance breaks down.

Find out:

- what autoimmune diseases are
- what causes these diseases
- how autoimmune diseases are treated.

Vaccines

Immunisation means programming the immune system so that the body can respond rapidly to infecting micro-organisms. It can occur naturally or artificially. People who have had diseases such as diphtheria, chickenpox, measles, mumps and poliomyelitis are normally immune to these diseases for the rest of their lives. This is due to the natural active immunity described above. **Vaccination** is the artificial introduction of antigens of pathogenic organisms so that the ability to produce the appropriate antibodies is acquired without the person having to suffer the disease. Thus, there is a slight difference in meaning between vaccination and immunisation, but the two words tend to be used interchangeably.

Science Photo Library/James King-Holmes

Figure 11.12 Vaccines for some viral diseases are produced by allowing the viruses to multiply in living cells: here the influenza virus is being introduced into fertile eggs.

A **vaccine** is the antigen preparation used in artificial immunisation. Traditional vaccines are of four types. One type contains living **attenuated** micro-organisms – micro-organisms of reduced **virulence**; that is, micro-organisms with a reduced ability to produce disease symptoms, so that the immunised person does not contract the disease but manufactures antibodies against the antigen. Louis Pasteur first used this method to immunise chickens against fowl cholera, and sheep and cattle against anthrax. He attenuated the bacteria by exposing them to a temperature of 42°C (5°C higher than normal body temperature) for about a week. Vaccines containing living attenuated micro-organisms include those for immunisation against polio, tuberculosis, rubella (German measles), measles, mumps and yellow fever.

A second type of vaccine contains **dead micro-organisms**. Immunity produced in this way is not usually as prolonged as it would be with immunisation using live attenuated micro-organisms. Examples of vaccines of this type include cholera, typhoid and whooping cough vaccines.

The third type of vaccine is made from filtrates of bacterial cultures containing **toxins**. In cases where bacteria produce their effects in humans by liberating toxins, it is not necessary to use living or dead bacteria for immunisation. The toxins produced by the bacteria can be inactivated, so that when they are injected into

someone they do not make the person ill. Such inactivated toxins are called **toxoids**. Injections of toxoids are used to immunise against diphtheria and tetanus.

A fourth type of vaccine is called a **sub-unit vaccine**. Instead of using a whole dead or attenuated micro-organism, a fragment of the organism is used to provoke the immune response. Sub-unit vaccines are used for vaccination against human papilloma virus (Gardasil®) and hepatitis B.

These traditional types of vaccines have been very effective, but they have certain problems. With some there is a risk of side effects. For example, about one child in every million vaccinated with dead whooping cough bacteria dies from damage to the nervous system. Some older vaccines, such as the cholera vaccine, give good protection against the disease but are effective for only a short period. Developers of modern vaccines try to produce vaccines that are effective for prolonged periods and produce no side effects.

One approach that has been used is to modify the characteristics of the pathogen by slightly changing the DNA in the micro-organism's cell so that the pathogen is less virulent. Another method is to insert certain DNA sequences from the pathogen into harmless bacterial cells. The chosen DNA sequence causes the production of antigens that are characteristic of the pathogen. Vaccination with the harmless bacterium results in immunity against the pathogen. It is likely that a great many future vaccines will be made using this **recombinant DNA** method. (Recombinant DNA will be discussed further in Chapter 13.)

Table 11.3 Types of vaccines involved in immunisation against some diseases

Type of vaccine	Vaccine used to protect against:
Living attenuated micro-organisms	Measles, mumps, rubella, rabies, poliomyelitis, tuberculosis, yellow fever
Dead micro-organisms	Cholera, bubonic plague, typhoid, whooping cough, influenza, hepatitis A
Toxoids	Diphtheria, tetanus
Sub-unit	Human papilloma virus, hepatitis B

Pasteur
This BBC website provides more information on the work of Louis Pasteur.

Vaccine delivery

The most common method of vaccination is to inject the vaccine using a syringe, but other forms of delivery can be used. One type of polio vaccine is given by mouth in a sweet syrup or in lumps of sugar. This method is no longer used in Australia but is still in use in many countries.

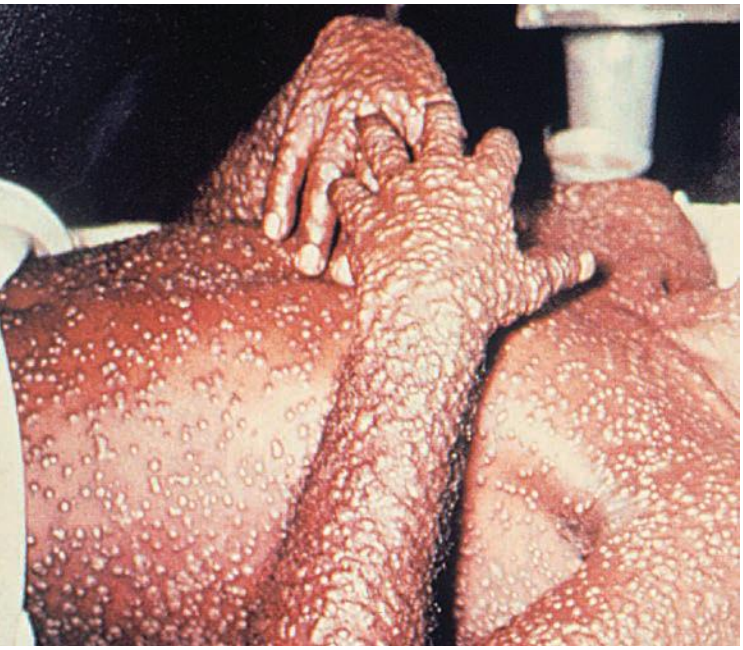
Medical researchers are investigating other methods of delivering vaccines. The use of a very fine spray into the nostrils has been trialled for a number of vaccines. A nasal spray called FluMist® is widely used in the United States for protection against the influenza virus.

Skin patches for delivering vaccines have been tested, with promising results. One suggested advantage for skin patches is that they could be self-administered. Patches could even be sent to people through the post. This type of vaccine delivery would be very useful in developing countries, where medical services are not readily available.

Another line of research was to include vaccines in foods. This line of research has now been abandoned because of difficulties in controlling the dose and because the vaccine production gene could be passed to other varieties of the food plant. Attempts are now being made to engineer non-food plants to produce vaccines. People can be given a measured amount of the plant to include in their food. Scientists in India have genetically engineered several plants to produce a vaccine for hepatitis B.

Vaccination of populations

The World Health Organization (WHO) rates the introduction of vaccines as one of the public health measures that has had the greatest impact on people's health. The use of vaccines in mass immunisation programs has either eradicated or greatly reduced the incidence of certain diseases



Getty Images/Photo Researchers

Figure 11.13 Smallpox causes a rash with raised pustules filled with pus-like fluid.

throughout the world. WHO's greatest success is probably the global elimination of smallpox (Figure 11.13). The last known naturally occurring case was in Somalia in 1977, although a small number of laboratory-acquired infections have occurred since then. The WHO is now determined to eliminate polio using a range of vaccination programs. Since 1988 the number of polio cases globally has decreased from about 350 000 a year to 358 cases in 2014.

Other vaccination programs are on a smaller scale and are frequently used to prevent the possibility of a serious outbreak of a highly infectious disease. In Australia, prior to winter each year, the federal government supports a program to vaccinate the young and the elderly against current strains of the influenza virus. Such vaccination programs not only reduce the chance of disease in the most susceptible individuals but also increase the immunity of the population. Such immunity is referred to as **herd immunity** and depends on a high proportion of individuals being immunised. When there are a large number of immune individuals in a population, there is less chance of the disease being transmitted between them.

One problem for health departments in all countries is that, as the incidence of infectious diseases declines, people become complacent and may decide that the risk of side effects from the vaccine is higher than the risk of contracting the disease itself. If vaccination rates do decline, a serious outbreak of a disease may occur. This happened in the United Kingdom in the 1970s, resulting in large outbreaks of whooping cough. Even in countries where vaccination rates are high, vaccine-preventable diseases have sometimes reappeared. The Netherlands, for example, has one of the highest rates of fully vaccinated people in the world. Nevertheless, there are groups of Dutch people who object to vaccination on religious grounds. In the early 1990s, a large outbreak of polio affected these people, with some suffering severe complications such as paralysis. However, polio did not spread into the rest of the Dutch community because of the protection provided by the high rates of vaccination.

One of the important choices that parents must make is whether to have their children vaccinated in infancy. Childhood vaccination is not compulsory in Australia but 90% of infants have been vaccinated by the age of 12 months. In Australia most people are vaccinated against the diseases for which vaccines are available. Table 11.4 shows a recommended immunisation schedule for Australians from birth through to adult life. For Australians travelling overseas, other vaccinations such as cholera, yellow fever and typhoid may be recommended, depending on the destination.

As Table 11.4 indicates, most vaccinations do not start until a child is 2 months old, and for most diseases more than one vaccination is necessary. Vaccination should not start too soon after birth, as the child's blood contains antibodies from its mother. If a newborn is given a vaccine, the antibodies from the mother that have entered the child's bloodstream via the placenta or in breast milk eliminate the foreign materials in the vaccine. This occurs before the child's immune system can mount an immune response. A few months are necessary for the child's immune system to become activated and therefore able to prevent the child from getting the diseases that they are being vaccinated against.

Unfortunately, one shot of a vaccine is not usually enough to protect a person from the particular disease they are being vaccinated against. When a person is vaccinated, his or her immune system will activate a certain number of B-cells. These cells will multiply and some will produce antibodies. Others will become memory cells. Memory cells can last for decades in a person's body and are able to produce the necessary antibody when exposure to the micro-organism occurs again. In most cases, the first dose of a vaccine does not enable enough B-cells

Table 11.4 Recommended vaccination schedule for Australians

Age	Recommended vaccination
Birth	Hepatitis B
2 and 4 months	Diphtheria, tetanus, whooping cough; polio; hepatitis B; *Haemophilus influenzae* type B (HiB); rotavirus*; pneumococcal**
6 months	Diphtheria, tetanus, whooping cough, polio, HiB, rotavirus, pneumococcal, hepatitis B
12 months	Measles, mumps, rubella (MMR), HiB, meningococcal C***
18 months	Measles, mumps, rubella, chickenpox
4 years	Diphtheria, tetanus, whooping cough, polio, measles, mumps, rubella (MMR only if not given at 18 months)
10–15 years	Hepatitis B, chickenpox, diphtheria, tetanus, whooping cough, human papillomavirus (HPV)
15 years and over	Influenza (for Aboriginal and Torres Strait Islander people), pneumococcal (for Aboriginal and Torres Strait Islander people medically at risk)
50 years and over	Influenza (for Aboriginal and Torres Strait Islander people), pneumococcal (for Aboriginal and Torres Strait Islander people)
Pregnant women	Influenza
65 years and over	Influenza (annually), pneumococcal

Source: NHMRC Australian Standard Vaccination Schedule 1 July 2013

*Protects against a highly infectious disease of the small intestine; most cases occur in children under 5 years.

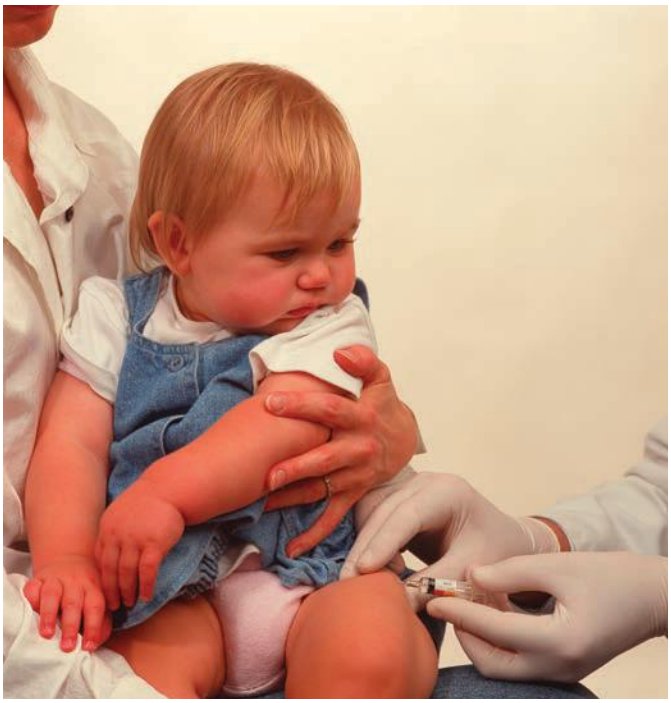
**Protects against a bacterial infection of the lung that may lead to pneumonia if it occurs in children or the elderly.

***Protects against a bacterial infection of the membranes around the brain.

to become activated. Booster shots are required to activate more B-cells. When more B-cells are activated, more antibodies are made. This in turn results in greater protection from the disease-causing micro-organism that the person was vaccinated against (see Figure 11.7).

The timing of a booster shot is also important. If the booster is given too soon after the first vaccination, the antibodies present in the blood will eliminate the material in the vaccine before more B-cells can be activated. To avoid this, a period of time between vaccinations is required, to allow the antibodies in the blood to be eliminated. Usually this takes around two months.

Finally, when a new vaccine is first introduced, just how long it will provide protection is not known. Follow-up studies are required to determine this, and to evaluate the need and timing for booster vaccinations. Interestingly, a recent study in the United States has indicated that for some diseases the duration of protective immunity for many vaccines has been greatly underestimated. If further studies indicate that this is the case, then the recommended vaccination schedule may need to be reviewed.



Science Photo Library/Saturn Stills

Figure 11.14 Childhood vaccinations greatly reduce certain illnesses in children and also prevent the spread of communicable disease.

Issues with the production and use of vaccines

Risks

As with all medical procedures there are risks involved in the use of vaccines. However, before vaccines are made available for general use they are tested for safety and effectiveness, first in clinical trials and then in much larger trials. In Australia, all vaccines on the market are manufactured according to strict safety guidelines. Before marketing approval is granted, they are evaluated by the Therapeutic Goods Administration to ensure they are effective and are at a high standard of quality and safety.

One of the main risks of vaccination is an allergic reaction. This may occur not so much from the vaccine itself but from a reaction to the medium in which the vaccine was cultured. The National Health and Medical Research Council lists the possible vaccine components that may result in an allergic response, in its literature and on its website. For example, many of the influenza vaccines are manufactured in fertilised eggs and people who are allergic to egg protein need to be aware of this. Similarly, people who are allergic to yeast would need to be mindful that some of the older hepatitis B vaccines have yeast as a component.

Another concern that has been expressed regarding vaccines is that it is impossible to completely isolate one virus from others within an animal tissue that is being used as a culture medium. As a result, vaccines could pose a risk of cross-species disease introduction.

In the manufacture of vaccines, certain chemicals are used as preservatives. Preservatives used include formaldehyde, phenol (carbolic acid), aluminium phosphate, alum and acetone. Individuals concerned about vaccination claim that these preservatives can affect the nervous system and lead to other health issues. However, medical authorities believe there is no conclusive evidence linking vaccines to any disorders. Just because a certain medical condition appears after vaccination does not necessarily mean that the vaccine caused it. However, if such an issue is raised, it should be thoroughly researched in an effort to prevent community concern and the possibility of propagating a myth. Such misunderstandings might deter some parents from vaccinating their children. Frequently, studies following such claims have indicated that the association is due to chance alone.

Ethical concerns

The major ethical concerns about the use of vaccines centre on how the vaccine was manufactured, how it was tested and the risks associated with its use.

As viruses can only reproduce in living cells, the manufacture of viral vaccines requires host tissue. For example, influenza virus is cultured in chicken embryos (Figure 11.12) and Japanese encephalitis virus is grown in the brains of mice. Consequently, some people are concerned about the treatment of animals in the production of vaccines.

Many vaccines require human tissue because some viruses that cause disease in humans do not grow well in cells derived from other species. In addition, the use of human tissue avoids the problems of cross-species infection from possible unknown viruses. The source of the human tissue is a concern for many people. For example, rubella vaccine is manufactured using cultured human cells. The original cells for the cultures were obtained from human foetuses. This raises moral questions for people who are opposed to the way in which those original cells were obtained. Parents opposed to the use of such cells have to decide whether to have their child immunised with a vaccine made from cultured human cells. Others argue that the moral principle that ought to govern all decision-making is what is best for the health of the child.

Testing of vaccines

Other moral and ethical concerns arise over the testing of vaccines. Most vaccines are produced in developed countries but many are destined for use in developing countries. Trialling of vaccines to provide protection against infection by the human immunodeficiency virus (HIV) is currently causing some apprehension. Genetically distinct subtypes of HIV have been identified, and different HIV subtypes are found in different regions of the world. Most of these regions are in developing countries where education standards are low and the population may not be aware of the risks involved in trialling an experimental vaccine. The resulting ethical concern is that in testing the effectiveness of such a vaccine, the group selected to be vaccinated may be open to exploitation by the vaccine's manufacturer.

Before clinical trials on humans, most vaccines are tested on animals. The animals used in such testing are frequently mice, but other mammals are also used, along with birds, amphibians and fish. Ever since such testing on animals began, people have expressed concern that the animals may suffer, or that too many are sacrificed in the name of science. Such concern has resulted in legislation to limit the way doctors and scientists can use animals. Legislation of this type was passed in the United Kingdom as early as 1822. However, this has not stopped people arguing that experimentation on animals should be greatly reduced, if not discontinued. The arguments are based on the contention that causing pain to another creature is simply not morally acceptable. It is claimed that the lives of all animals have value and are therefore worthy of respect.

On the other hand, those who support the continued use of testing on animals argue that society as a whole has an obligation to act in ways that will minimise harm and maximise benefits to humans. Discontinuing the testing of vaccines on animals would benefit the animals but could result in serious consequences for humans. Supporters of this viewpoint argue that research on animals has led to the development of new vaccines and that the benefits to humans far outweigh the suffering that a relatively few animals may have to endure.

Decisions

For parents deciding whether to vaccinate their children, the problem of risk is a significant moral question. Should they accept the risk that their children may suffer permanent damage as the result of a faulty vaccine or an adverse reaction? Most people would argue that the benefits far outweigh the risks, and that the benefit is not just for the children but for the whole of society. A high level of herd immunity ensures that a disease does not spread from an infected person, because there are few unimmunised people available to catch it.

A unique ethical and moral problem arises from the use of the vaccine Gardasil, which protects against the human papilloma virus (HPV). HPV is a sexually transmitted virus that causes genital warts and cervical cancer. The most effective use of the vaccine is with girls who have yet to become sexually active, around 11 or 12 years. Many parents and health professionals believe that girls of this age are too young to be discussing such matters, while others are concerned that immunising young women with the vaccine may encourage promiscuous behaviour. On the other hand, supporters of the vaccine argue that it could prevent serious illness later in life and may not have any effect on sexual behaviour.

In all issues relating to vaccines, individuals must be guided by their own beliefs and values. However, before making a decision for or against vaccination, it is the responsibility of each of us to ensure we are fully informed about all the possible consequences of the decision.

Participation

A person's decision to participate in an immunisation program may be influenced by their social, economic or cultural background. In Australia, most immunisation programs are provided free by the government. However, in other countries this may not be the case, and the economic circumstances of an individual may prevent participation. In the broader context, some emerging nations may not have the resources to immunise everyone and may rely on agencies such as the WHO to provide assistance.

In many developing nations, average income level is extremely low and parental education is poor. The level of education of women has a significant influence on vaccination rates of children. Even if parents are aware of the benefits, the costs associated with vaccination may be prohibitive.

Religious belief has often been cited as a reason for some Australian parents refusing to immunise their children. However, none of the major religions in Australia – Christian, Muslim and Jewish – are opposed to immunisation. This is often not the case in other countries. For example, a study conducted in Nigeria showed an immunisation rate of 66% among Christians but only 32% among Muslims. In many places, traditional medicine is considered superior to the evidence-based medicine practised in most developed countries and parents are happy to rely on the advice of traditional healers.

In Australian society the Internet and other media are major sources of misinformation about the risks and benefits of immunisation. In 2014 the NSW Healthcare Complaints Commission ordered an anti-vaccination website to change its name, and a warning was issued about the unreliability of information published on that site. When accessing the Internet for material about immunisation it is essential to check the reliability of the sources.

The recent growth in popularity of complementary and alternative medicine has been partly due to the belief that conventional medicine, including the administration of vaccines, is associated with greater risks than benefits. It is concerning that some practitioners involved with complementary and alternative medicine advise against immunisation when all the scientific data clearly show that the benefits far outweigh the risks.

Unless the great majority of the population participate in immunisation programs against preventable diseases, herd immunity will be low and outbreaks of such disease are likely to occur.

Antibiotics

Antibiotics are drugs that are used to fight infections of micro-organisms, particularly bacteria. Their discovery and application brought about a revolution in the treatment of bacterial infections, and they are now one of the most frequently prescribed drugs. Before antibiotics came to be widely used in the 1940s, a person could die from an infected cut or scratch that today would be considered a minor problem.

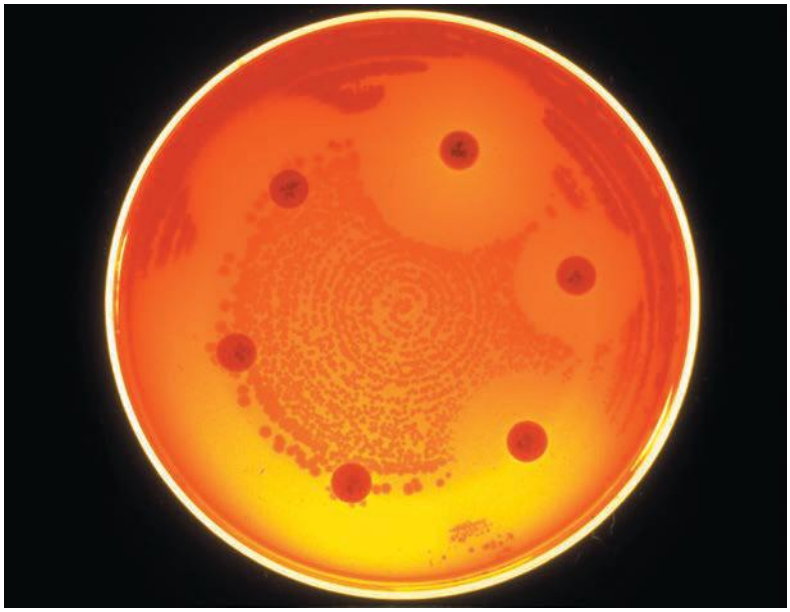
The first antibiotic to be discovered, and one that is still widely used, is penicillin. Penicillin works by preventing the synthesis of the walls of the bacterial cells. In this way, it inhibits the reproduction of bacteria. About 30% of antibiotics used in Australia today are penicillin based. However, the effectiveness of penicillin has been reduced because many bacteria have developed resistance to it. Also, about 10% of people are allergic to penicillin, so there is a continuing search for new antibiotics.

Penicillin was so successful that it stimulated a search for other micro-organisms that produce antibiotic substances. In 1943, **streptomycin** was discovered. It was produced by an actinomycete that lives in soil. **Actinomycetes** are bacteria that produce branching filaments rather like the threads of moulds. Most of the antibiotics in use today, such as erythromycin, neomycin, tetracycline and vancomycin, have been developed from actinomycetes. These substances interfere with protein synthesis in the cells of the target bacteria.

Cephalosporin is an antibiotic that, like penicillin, is derived from a fungus. It has a similar action to penicillin, interfering with synthesis of the cell wall, but is much less likely to result in allergic reactions.

Each antibiotic is effective for only certain types of bacterial infection and cannot be used to treat viral infections. This is why antibiotics are available only on prescription from a doctor. The doctor must assess the most likely cause of the infection and prescribe the most appropriate antibiotic. In some cases, laboratory tests may be necessary to determine which drug will be most effective against the infecting bacterium.

Bacteria may be identified by staining techniques or by the appearance of the bacterial colonies when they are cultured in a Petri dish. Cultures can also be tested with a range of antibiotics to determine those to which they are most sensitive (Figure 11.15).



Phototake/Bart's Medical Library

Figure 11.15 Comparing antibiotic sensitivity of bacteria using a culture plate with antibiotic assay discs. Notice the clear area where bacterial colonies have not grown around some of the discs. The antibiotic impregnated in each of those discs is effective against that species of bacteria.

There are two types of antibiotics. **Bactericidal antibiotics** kill bacteria by changing the structure of the cell wall or cell membrane, or by disrupting the action of essential enzymes. **Bacteriostatic antibiotics** stop bacteria from reproducing, usually by disrupting protein synthesis. Both types are effective in treating bacterial infections.

Some antibiotics affect a wide range of different types of bacteria. These are **broad-spectrum antibiotics**. Others, **narrow-spectrum antibiotics**, are effective only against specific types of bacteria.

The widespread use of antibiotics has created a major problem. Some of the bacteria that antibiotics are used to kill have gradually evolved and become resistant to them. In the early days of antibiotic use, the problem was easily solved by changing to a different antibiotic. However, some strains of bacteria are now resistant to most or all available types of antibiotics. This is known as **multiple drug resistance** and such bacteria are often referred to as 'super bugs'. In 2012 it was reported that 12 cases of tuberculosis in Mumbai, India, were resistant to all known drugs; that is, they showed **total drug resistance**. Totally resistant strains of the bacterium that causes gonorrhoea have been detected in Australia, Japan and Europe.

Multiple drug resistance has been hastened by the overuse of antibiotics in medicine and in agriculture. Doctors have prescribed antibiotics to prevent infection rather than to treat an existing infection. Farmers use antibiotics as 'growth promoters' in poultry, pigs and cattle. International

efforts are now being made to reduce the use of antibiotics so that the development of further strains of multiple drug-resistant bacteria will be delayed.

Prevention of misuse and abuse of antibiotics will slow the development of resistance but there is no way of stopping it altogether. Strategies being used to overcome the problem are to develop new classes of antibiotics to which bacteria have no resistance, to revive old antibiotics by using them in combination with other substances, and to genetically engineer bacteria to disable antibiotic-resistant genes.

The situation has become so serious that in September 2014, President Obama ordered the United States Government to create a national plan to fight resistant micro-organisms by early 2015.

Antibiotics
This website provides information on how antibiotics work.

Natural antibiotics
This CSIRO website provides more information on antibiotics, including a natural antibiotics experiment that you can do (with a little help from your teacher).

EXTENSION

Antibiotic-resistant strains of bacteria develop by natural selection, but how do bacteria acquire the genes for antibiotic resistance in the first place? Research the various ways in which bacterial genes can change so that the bacteria become resistant to antibiotics.

Antivirals

Antiviral drugs are used specifically for treating viral infections. Because antibiotics are ineffective against viruses, there is still no treatment for common ailments such as colds, chickenpox and measles. This has led to a hunt for chemicals that can be used as antivirals.

Viruses enter a host cell and the virus DNA or RNA induces the cell to produce new virus particles. These particles can then leave the cell and infect new host cells. The way in which viruses replicate makes it difficult to find drugs that will treat viral infections. Because the host cell produces the new virus particles, any drug that interferes with virus replication is likely to be toxic to the host. Early research involved culturing cells, infecting them with a virus and then trying different chemicals to see whether the amount of virus decreased. This time-consuming and hit-or-miss technique produced little result.

In the 1980s, it became possible to determine the genetic sequences of viruses so that scientists could find out exactly how viruses work. Research today is aimed at identifying viral proteins that can be disabled by specially designed chemicals. If the proteins are very different from human proteins, there should be few side effects from the use of such drugs.

Unlike most of the antibiotics that destroy pathogenic bacteria, antivirals inhibit the development of the virus. Most antiviral drugs that are now available target HIV, herpes, hepatitis B and C, and influenza A and B.

Some examples of antivirals that you may have heard of are Tamiflu® and Relenza® for influenza, acyclovir (marketed as Zovirax®) for herpes infections, interferons for hepatitis B and C, and zidovudine (AZT) for human immunodeficiency virus. A great deal of research is being carried out to develop drugs that will target other viruses

EXTENSION

Research has been taking place for many years now to try to find effective drugs to fight viral infections. Use references to find out:

- the antiviral treatments available for influenza
- how these treatments work
- current lines of research to combat viral infections.

Specific resistance to infection

Science inquiry

ACTIVITY 11.1 A briefing paper

Imagine that the minister for health in your state's parliament employs you as a research officer. The government is proposing to introduce compulsory vaccination for a number of diseases. You have been asked to prepare a briefing paper for the minister. To engage in debate the minister will need to know the arguments that are likely to be put forward by the opposition and have information with which to rebut those arguments. In addition, she will need to know such things as:

- the traditional methods of preparing vaccines
- new techniques for the manufacture of vaccines
- common side effects that are linked to the use of vaccines
- examples of the success rates associated with vaccine use
- any other relevant information.

Your task is to compile a briefing paper for the minister, including all the information that you think will be necessary to engage in a meaningful debate in the parliament.

ACTIVITY 11.2 Should animal testing be used in the manufacture of vaccines?

Hold a class discussion on the scientific and ethical issues arising from the use of animals in the research and manufacture of vaccines. Assign the roles of interested parties to some of the members of the class, who will then assume that role in the discussion. The roles could include:

- a person suffering from a disease for which researchers are trying to develop a vaccine
- a spokesperson for an animal rights group
- a doctor specialising in immunology
- a member of the public opposed to the activities of animal rights groups
- an employee of the health department responsible for control of infectious diseases
- a scientist researching new vaccines
- a person opposed to the use of vaccines because of the risks involved.

As well as moral and ethical issues, the discussion could consider questions such as these.

- Why do people's opinions differ about what activities should be allowed in the development and manufacture of vaccines?
- How can society best consider the wide range of views that people hold on these issues?
- Who should be allowed to decide whether testing on animals should be permitted?
- What are the responsibilities of the scientists who use animals for their testing programs?
- Who should set standards for laboratories and researchers that use animals for the manufacture and testing of vaccines?

After listening to the opinions expressed during the discussions, prepare a list of arguments for and against the use of animals for the manufacture and testing of vaccines.

ACTIVITY 11.3 Supporting immunisation programs

Immunisation programs are only effective if most individuals in society are vaccinated. As mentioned in this chapter, vaccination programs are designed not only to reduce the disease in the most susceptible individuals, but also as an attempt to increase the immunity of the population. This herd immunity depends on a high proportion of individuals being immunised.

A problem that can arise is that, as the incidence of infectious diseases declines, people become complacent and may not understand the importance of maintaining their levels of immunity. Design a poster that encourages people to be actively involved in keeping up to date with their vaccinations.

Review questions

1 **a** Why is the immune response said to be a specific response?
b What are the two parts of the immune response and what is the main difference between them?
2 Why are B-cells and T-cells so named?
3 **a** What is an antigen?
b Explain the difference between self-antigens and non-self antigens.
4 **a** What is an antibody?
b Explain how an antibody can be specific to a particular antigen.
5 Describe the events that occur in a humoral immune response.
6 List the ways in which the antigen–antibody complex helps to overcome the effects of invading micro-organisms.
7 Describe the events that occur in a cell-mediated immune response.
8 List the ways in which killer T-cells and helper T-cells can deal with an invading antigen.
9 Why is the secondary immune response so much faster than the primary response?
10 Why is it rare to get a disease such as measles or chickenpox more than once?
11 What is the difference between:
a natural and artificial immunity?
b active and passive immunity?
12 **a** How can passive immunity be gained artificially?
b How can active immunity be acquired naturally?
13 **a** What is a vaccine?
b Describe three ways in which older types of vaccines are produced.
c How are modern vaccines developed?
d List the risks associated with the manufacture of vaccines.
14 What is herd immunity? Why is it of interest to the health professions?
15 List some of the social, economic and cultural factors that may lead to some people deciding not to participate in vaccination programs.
16 What is the difference between:
a an antibiotic and an antiviral?
b a bactericidal and a bacteriostatic antibiotic?
c a broad-spectrum and a narrow-spectrum antibiotic?
17 **a** Explain how strains of bacteria can become resistant to an antibiotic.
b What are some of the problems that arise from bacterial resistance?
18 Why has it been difficult to develop drugs that are effective against viral infections?

Apply your knowledge

1 Why do people tend to get fewer colds as they get older?
2 Why is it that diseases such as diphtheria and chickenpox have not been completely eliminated from Australia?
3 Typhoid is caused by a bacillus. To make a positive diagnosis of typhoid, a sample of the patient's blood is taken and mixed with typhoid bacilli. If the bacilli agglutinate (clump together), the patient has typhoid.
a Why is this a positive diagnosis for the disease?
b Could the person be suffering from some other disease?
4 Investigate and report on the issues surrounding the use of vaccines to protect against human papilloma virus (HPV). In your report ensure that you provide a balanced discussion of both sides of the subject.

5 In October 2014 a new vaccine for meningococcal B was approved for use in the United States.
   a Use references to find out if the vaccine is to be used in Australia.
   b What are the symptoms of the disease?
   c If you were vaccinated against meningococcal B, could you still get meningitis?

6 Find out why it is difficult to prepare vaccines for viral infections such as the common cold or HIV.

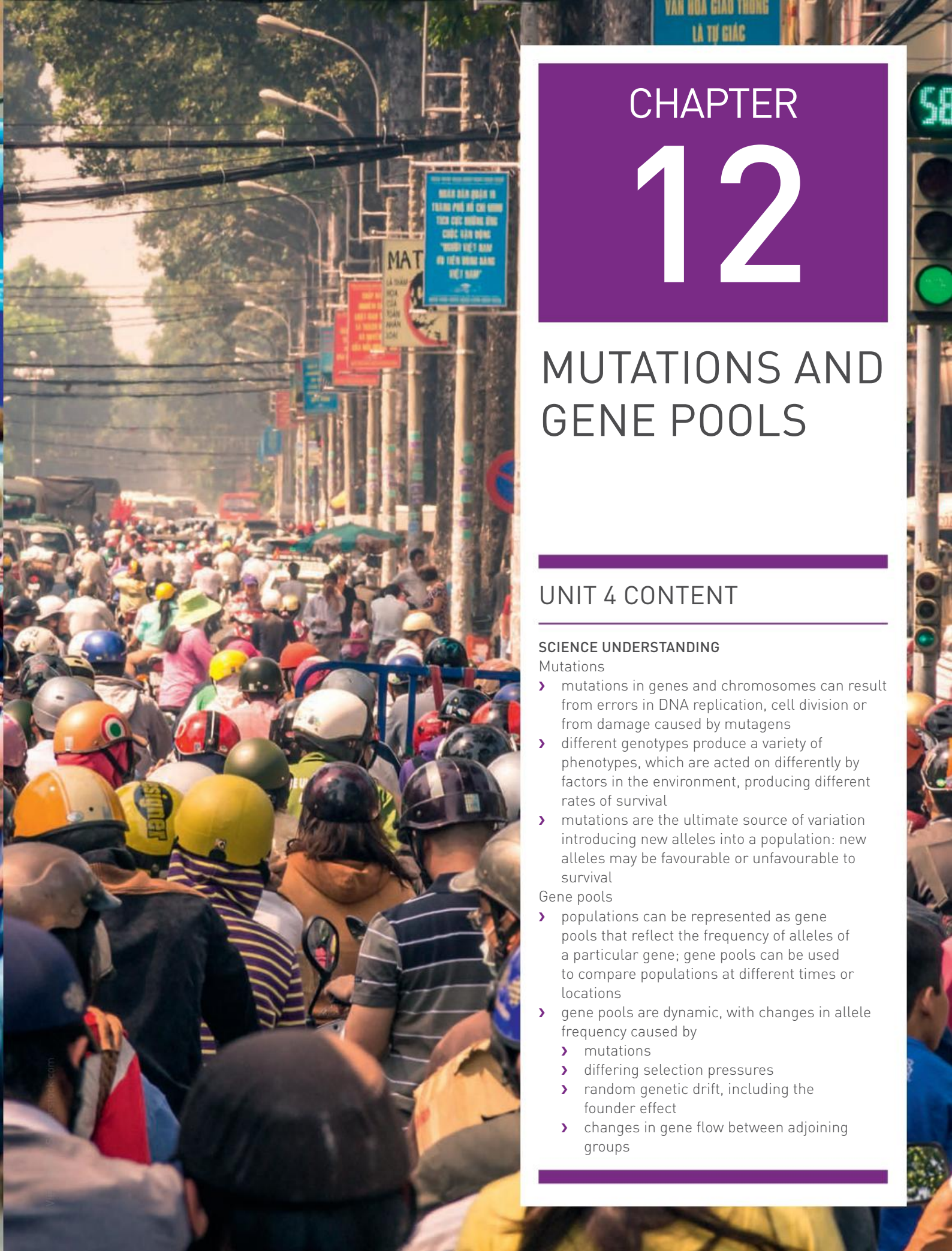
7 In this chapter, ethical concerns about the manufacture of a vaccine against rubella were discussed. The manufacture of other vaccines, such as that for chickenpox, has also caused anxiety among some members of society. Find out the basis for these concerns.

8 Antibiotics were first developed in the 1940s, whereas antiviral drugs have only become available in relatively recent times. Suggest possible reasons for this situation.

9 A person was prescribed an antibiotic for a bacterial infection of the throat. While taking the antibiotic tablets the patient developed a bacterial infection in their big toe. Explain why the antibiotics that the patient was taking for the sore throat did not prevent the growth of bacteria in the toe.

10 Multiple drug resistance is an increasingly serious problem. List some strategies that could be used to help overcome it.

UNIT 04 HUMAN VARIATION AND EVOLUTION



CHAPTER 12

MUTATIONS AND GENE POOLS

UNIT 4 CONTENT

SCIENCE UNDERSTANDING

Mutations

- mutations in genes and chromosomes can result from errors in DNA replication, cell division or from damage caused by mutagens
- different genotypes produce a variety of phenotypes, which are acted on differently by factors in the environment, producing different rates of survival
- mutations are the ultimate source of variation introducing new alleles into a population: new alleles may be favourable or unfavourable to survival

Gene pools

- populations can be represented as gene pools that reflect the frequency of alleles of a particular gene; gene pools can be used to compare populations at different times or locations
- gene pools are dynamic, with changes in allele frequency caused by
  - mutations
  - differing selection pressures
  - random genetic drift, including the founder effect
  - changes in gene flow between adjoining groups

All humans, from whatever part of the world and whatever ethnic background, have basic similarities and are capable of interbreeding to produce fertile offspring. That is, all humans belong to the same species. A **species** is a group of individuals that share many characteristics and are able to interbreed under natural conditions to produce fertile offspring.

Alleles are alternative forms of a gene. The pairs of alleles that each person inherits from their parents control and determine the characteristics of that individual. During reproduction, about half of each parent's alleles are passed on to the next generation. In this chapter we will consider the inheritance of alleles not in individuals but in populations.

Gene pools

A **population** is a group of organisms of the same species living together in a particular place at a particular time. When studying populations, **geneticists**, scientists who specialise in the study of inheritance, prefer to consider the characteristics of the population as a whole and not those of the individuals that make up the population. They find it convenient to pool the genotypes of all the individuals capable of reproducing and refer to this as the gene pool. Thus the **gene pool** is the sum of all the alleles in a given population.

In studying a population, geneticists are interested in how often each allele of a gene occurs in the gene pool for that population. (Refer to Chapter 22 in *Human Perspectives Units 1 & 2 ATAR* for a discussion of genes and alleles.) These are called the **allele frequencies** for the population. Knowing how often a characteristic occurs in a population, geneticists are able to work out the frequency of each of the alleles for a particular gene. For example, an allele for cystic fibrosis is found on chromosome number 7. If the frequency of the cystic fibrosis allele in a given population is 5%, then among population members, five in every 100 of chromosome 7 will carry that allele. Ninety-five out of 100 chromosome 7s will have the normal form of the gene. Remember that alleles are alternative forms, or expressions, of a gene.

Populations that differ in the characteristics they possess are likely to have different frequencies of the various alleles of a gene in their respective gene pools. For example, Scandinavians commonly have blue eyes whereas black Africans have brown eyes. The frequency of the allele for blue eyes would be much higher in the Scandinavian gene pool than in the African gene pool. Thus, any two populations having differing characteristics are likely to have different gene pools.

Over time, the frequency of particular alleles in a population may change or, in other words, the composition of the gene pool changes. Such changes may be due to chance events – for example, a mutation that alters the expression of a gene – or to more natural means, where changes in the environment may result in variations of the allele frequencies. Changes to the frequency of alleles in a gene pool allow populations to be compared at different times or in different locations. A number of examples where this has occurred in human populations will be discussed in the next chapter.

Mutations

Offspring may show variations that do not resemble either parent and have never occurred before in the history of the family. These may occur quite suddenly and purely by chance. Characteristics occurring like this are referred to as **mutations**. Not all mutations are harmful, but many are. An organism with a characteristic resulting from a mutation is called a **mutant**. There are two main types of mutations: **gene mutations**, which are changes in a single gene so that the traits normally produced by that gene are changed or destroyed; and **chromosomal mutations**, in which all or part of a chromosome is affected.

Gene mutations occur during the replication of the DNA molecule before cell division. DNA is a molecule in the cells of all living things; it contains genetic information that determines the characteristics of the organism (see Chapter 13). DNA is a complex molecule and any subtle alteration in its structure can produce changes in the usual characteristics of the species. If a

mistake occurs when the DNA molecule is copied, the change may have significant effects on the characteristics of the organism. When a cell divides, the genetic information is normally passed on correctly. If a mistake has occurred it will be faithfully copied each time the DNA molecule replicates, so the mutation may be passed on from generation to generation.

However, there are relatively few mutations in human populations, considering the millions of cell divisions that occur. Those that do occur sometimes result in traits better suited to a particular environment, and so may contribute to human survival.

Mutations
This website provides more information on mutations.

Mutagens

Mutations occur without any known cause but a number of agents are known to increase the rate at which they occur. These are called **mutagenic agents** or **mutagens**. Some known mutagens are mustard gas, formaldehyde, sulfur dioxide and some antibiotics. Ionising radiation of all kinds – including ultraviolet light, X-rays, cosmic rays, radiation from radioactive waste, and fallout from atomic and nuclear explosions – is also mutagenic. If a woman is treated with large doses of X-rays during the first three months of her pregnancy, the child may be born with mental retardation, skeletal malformations, or a small head in relation to the rest of its body. For this reason, doctors try to avoid using X-rays early in pregnancy.

Somatic and germline mutations

Mutations can occur in the body cells or in the reproductive cells of a person. The first case, where the body cells, or somatic cells, are involved is known as a **somatic mutation**. Only the individual with the somatic mutation is affected. Each time the mutant body cell divides, the mutation is passed on to the daughter cells. The reproductive cells are not affected and once the individual dies, the mutation is lost. Somatic mutations are involved in many cancerous growths that may be a result of a mutagenic agent.

If the reproductive cells are affected, the mutation can occur in the gametes and may then be passed on to the next and subsequent generations. These are known as **germinal** or **germline mutations**. In this case the individual in whom the mutation occurs is not usually affected. However, that individual produces gametes with changed DNA. If conception occurs involving one of the affected gametes, the embryo is often naturally aborted early in the pregnancy. Diseases such as **phenylketonuria (PKU)** can arise through a mutation during the formation of gametes and can be passed on to an offspring.

It is also important to realise that not all mutations are harmful. Some may have little effect and some may have definite advantages for the individual.

Effects of mutations

Gene mutations

DNA is composed of a double helix, each side of which is a long string of four types of nucleotides (see Figure 13.1 on page 178). Each nucleotide possesses identical sugar–phosphate groups that contribute to the DNA framework but differs in the base that links the two frameworks. Within genes, the sequence of the bases in the DNA is the code for the amino acids used to build a protein. Each group of three bases is the code for an amino acid.

When it was recognised that genetic information is contained in the sequence of bases in the DNA, it became possible to understand the chemical nature of gene mutations. A change in just one base, known as a **point mutation**, could alter a protein, have no effect at all, or prevent the protein from being produced. Thus if the DNA of a particular gene is altered, the protein for which it codes may be missing or abnormal. Just one missing or abnormal protein

Fairfax Photos/Sahlan Hayes

Figure 12.1 A group of people with albinism, an inherited condition caused by a mutation that results in just one missing protein

can have an enormous effect on the entire body. Albinism, for instance, is the result of one missing protein. **Albinism** is marked by an absence of pigment from the hair, skin and eyes (Figure 12.1). The hair of a person with albinism tends to be whitish blond, the skin extremely pale and the eyes pinkish.

Another condition that may occur through gene mutation is the **Duchenne** form of **muscular dystrophy** (Figure 12.2). This may arise through a mutation in the mother, which can then be inherited by her sons. The mutation may also occur in a male zygote so that the child develops the disease. This disease results in a wasting of the leg muscles and later the arms, shoulders and chest. Duchenne muscular dystrophy usually becomes apparent around the age of 3 to 5 years, when muscle weakness becomes evident. Eventually death occurs due to failure of the respiratory muscles. Boys with the Duchenne form of muscular dystrophy are unlikely to live for more than 20 to 25 years.

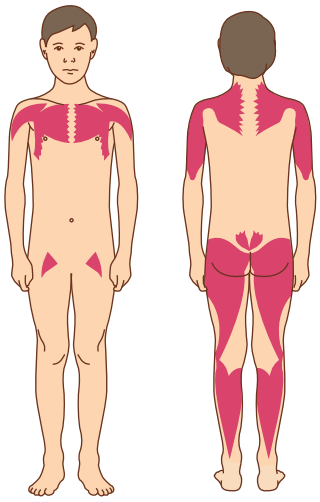


Figure 12.2 The muscles that are affected by Duchenne muscular dystrophy

Cystic fibrosis is another genetically determined disease caused by a mutation. The mutation occurs in a huge gene on chromosome number 7. The gene has the code for 1480 amino acids that make up a protein that regulates the passage of chloride ions across the cell membrane. Without the correct protein the affected person suffers from a variety of symptoms: salty-tasting skin; persistent coughing, wheezing or pneumonia; digestive and other problems. The mutant allele is recessive, so to suffer from cystic fibrosis a person must inherit the mutant allele from both parents.

EXTENSION

Western Australia has been a world leader in the application of carrier detection to reduce the incidence of Duchenne muscular dystrophy.

Find out:

- what carrier detection involves
- what takes place following the detection of a carrier
- what is preventing the complete elimination of Duchenne muscular dystrophy.

Lethal recessives

Most gene mutations produce a recessive allele because they prevent the gene from producing a protein that will be able to function in the body. A person could therefore have large numbers of mutations in the genes and be totally unaware of them. If the person reproduced with a partner who had the same recessive mutation, the recessive condition could appear in their offspring. This is what happens when couples unexpectedly have a child with cystic fibrosis.

Some recessive mutations are lethal if they are not masked by a dominant normal allele. These **lethal recessives** cause the death of the embryo or foetus (a miscarriage or spontaneous abortion) or the early death of the child. **Tay-Sachs disease (TSD)** is a disorder of lipid metabolism that is inherited in an autosomal recessive pattern. It is a lethal recessive condition as the missing enzyme results in the accumulation of a fatty substance in the nervous system. A baby with two recessive alleles for TSD develops normally for the first few months, and then deterioration causing mental and physical disabilities begins. Death usually occurs in early childhood.

It is easy to see how a lethal recessive mutation could cause changes in the composition of a gene pool. People who inherit two such alleles would die before their alleles could be passed on to the next generation, so the proportion of lethal recessive alleles in the gene pool would gradually be reduced.

Chromosomal mutations

Chromosomal mutations involve all or part of a chromosome and therefore affect not just one but a number of genes. Types of chromosomal mutations are:

- deletion – part of a chromosome is lost
- duplication – a section of chromosome occurs twice. This may happen if part of a chromatid breaks off and joins on to the wrong chromatid
- inversion – breaks occur in a chromosome and the broken piece joins back in, but the wrong way around. This changes the order of genes on the chromosome and may disrupt the pairing of homologous chromosomes during meiosis
- translocation – part of a chromosome breaks off and is re-joined to the wrong chromosome
- non-disjunction – during meiosis, a chromosome pair does not separate and so one daughter cell has an extra chromosome and one daughter cell has one less than the normal number. These are sometimes not referred to as mutations but as **aneuploidy** – a change in the chromosome number.

Chromosomal mutations cause abnormalities so severe that miscarriage often occurs early in the pregnancy.

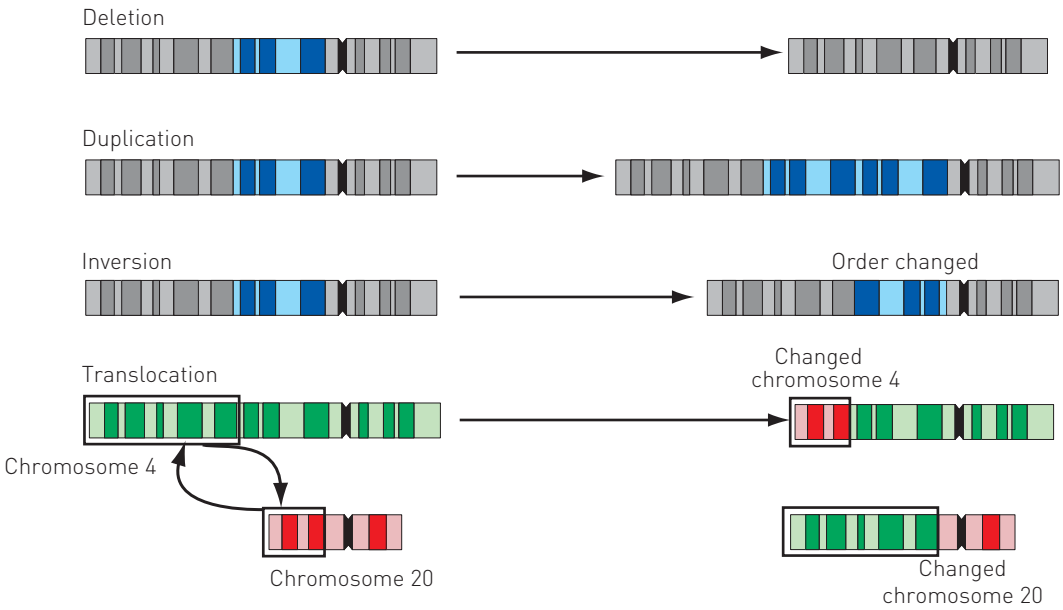
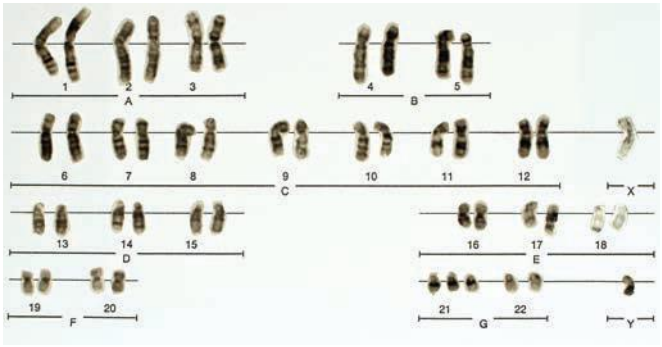


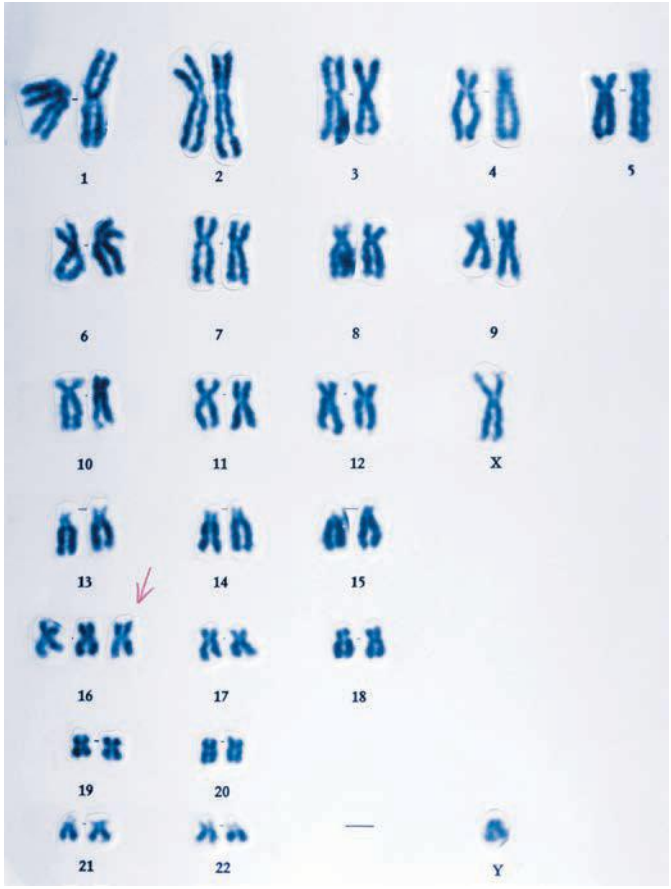
Figure 12.3 Types of chromosomal mutations

A chromosomal mutation that occurs relatively frequently, especially in children of older mothers, is **Down syndrome**, or **trisomy 21** (Figure 12.4), where the child has three of chromosome 21 instead of the normal two. Trisomy is a result of non-disjunction – failure of one or more chromatids to separate in the second division of meiosis. The eggs or sperm formed when non-disjunction occurs have one chromosome too many or one chromosome missing. In the case of Down syndrome, the affected gamete has an extra chromosome 21. When this gamete contributes the extra chromosome 21 to the embryo, trisomy 21 results.



Jens Goepfert / Shutterstock.com

Figure 12.4 Karyotype of Down syndrome (note the extra chromosome 21)



Getty Images/CNRI CNRI

Figure 12.5 A karyotype of trisomy 16; the extra chromosome is indicated by an arrow

Many of the symptoms of Down syndrome can also occur when part of an extra copy of chromosome 21 is attached to one of the other chromosomes. This is called partial trisomy.

Trisomy also occurs with other human chromosomes. **Patau syndrome** is when an extra chromosome 13 produces individuals with mental retardation, a small head, an extra finger on each hand, a cleft palate and/or cleft lip, and malformations of the ears and eyes. The extra chromosome 13 can come from either the mother's egg cell or the father's sperm cell. The features of trisomy 13 result from having this extra chromosome in each of the body's cells. Trisomy 13 occurs in about 1 out of every 5000 live births. However, more than 80% of children with trisomy 13 die within a month of birth.

Trisomy 16 (Figure 12.5) is the most common trisomy in humans, occurring in more than 1% of pregnancies. This condition also usually results in spontaneous miscarriage in the first three months of pregnancy.

Trisomy can also occur with the sex chromosomes. In males, non-disjunction may occur during either the first or the second meiotic division, producing individuals with either an extra X chromosome (*XXY*) or an extra Y chromosome (*XYY*). Individuals with trisomy *XXY* are normal as boys but develop **Klinefelter's syndrome** as adults (Figure12.6). They have small testes that do not produce sperm, the breasts are enlarged and body hair is sparse. Occasionally, the individual is mentally retarded.

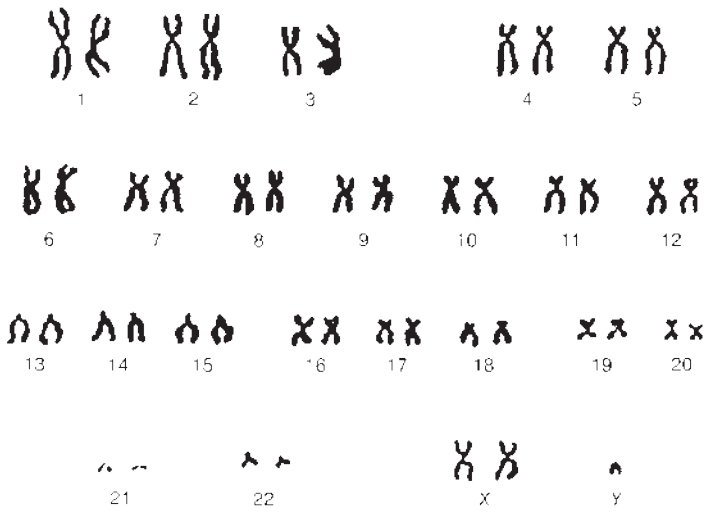


Figure 12.6 Karyotype for Klinefelter's syndrome

Monosomy is where an individual is missing a chromosome – they have only one copy instead of the normal two. If an autosome is completely missing, monosomy usually results in severe malformations and miscarriage. If only part of a chromosome is missing it is referred to as **partial monosomy**. Part of the chromosome has two copies, but part has only one copy. An example of partial monosomy is **Cri-du-chat syndrome** (from the French for 'cry of the cat'), a rare genetic disorder due to a missing portion of chromosome 5. The syndrome gets its name from the characteristic cry of infants born with the disorder. The infant sounds just like a meowing kitten, due to problems with the larynx and nervous system.

Monosomy can also occur with the sex chromosomes. Individuals with a chromosome set with only one *X* chromosome (monosomy *X*) suffer from **Turner's syndrome** (Figure 12.7). These females are short in stature, lack secondary sexual characteristics and are infertile.

The chromosomal abnormalities described above can frequently be diagnosed before birth by analysing cells in the amniotic fluid or from the placenta. A chromosome analysis, whether performed on a blood sample, cells from the amniotic fluid, or placenta, would provide the parents with information about the karyotype of the foetus. If a serious abnormality were indicated, the parents would then be in a position to decide whether to go ahead with the pregnancy or to terminate.

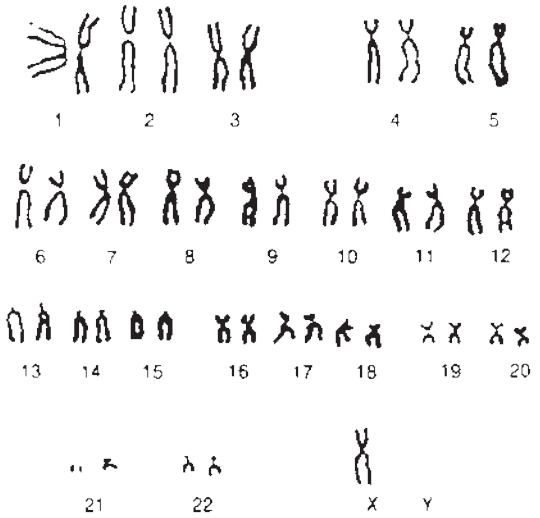


Figure 12.7 Karyotype for Turner's syndrome

Chromosomal mutations
This website provides more information on chromosomal mutations

WS

Mutations

Science inquiry

ACTIVITY 12.1 The incidence of cancer in Australia

Many cancers arise through mutations in somatic cells, and sometimes these mutations are caused by mutagens to which the patient has been exposed. Use references to find out:

- the incidence of different cancers in Australia
- whether there is any relationship between type of cancer and locality in Australia
- what groups of Australians are exposed to mutagens that can cause cancer
- what is being done to limit exposure of Australians to cancer-causing mutagens
- the age groups at which particular cancers are more common in Australia
- whether there are any upward or downward trends in the incidence of particular cancers in Australia.

There are many websites with information about cancer, such as:

- The Cancer Council Australia: www.cancer.org.au
- The Cancer Council Western Australia: www.cancerwa.asn.au
- The Cancer Council New South Wales: www.cancercouncil.com.au
- The Cancer Council Victoria: www.cancervic.org.au.

There are also websites for organisations that deal with specific types of cancer.

As with any information that you use from the Internet, make sure that it has come from a reliable source.

ACTIVITY 12.2 Venusians

Venusians are an imaginary group of people from the planet Venus. Because of the intense heat, their skin is jet-black; all individuals are homozygous for skin colour. If a mutation occurs resulting in a Venusian of a lighter skin colour, the individual usually dies before being able to reproduce. However, one such mutation created a brown-skinned individual who did survive and reproduced, passing the new allele to some of his children. The skin of the individuals affected by this mutant allele was extremely thick, providing them with added resistance to a lethal biting insect.

As time went by, the number of Venusians with the mutant allele increased. However, when two of these individuals produced children, homozygotes (that is, people with two of the mutant alleles) died in infancy.

In this activity we will investigate how the mutant allele becomes distributed through the population over time. To simplify our activity, we will start with heterozygotes (those with just one mutant allele), and assume that all those who are homozygous for the mutant allele die before they can reproduce. We will also assume that one out of every three Venusians who are homozygous for the normal allele dies from a lethal insect bite.

YOU WILL NEED (FOR EACH PAIR)

Two containers: 2 L ice-cream containers work well; 20 black beads or counters to simulate the black skin allele (B) in each gamete; 20 white beads or counters to simulate the brown skin allele (b) in each gamete; felt pen; tally sheet; pencil

WHAT TO DO

1. Label one container 'Male Parent' and the other 'Female Parent'.
2. Place 10 of the black beads in each container, then 10 of the white beads in each.
3. Prepare a tally sheet similar to the one below using the symbol B for the black skin allele and b for the brown skin allele.

	Genotypes in the Venusian offspring			
	BB	**Bb**	**bB**	**bb**
1				
2				
3				
4				
5				
6				
7				
8				
9				
10				

4 Simulate reproduction by shaking the containers well and drawing out one bead (gamete) from each. Place a tick in the relevant box on the tally sheet, then replace the beads.
5 When you have completed 10 draws, place the beads back into the containers. Your partner should repeat steps 1 to 4 above. Together you should have two completed tally sheets.

STUDYING YOUR DATA

1 Because the first column contains individuals that are homozygous for black skin (*BB*), only two out of every three survive to adulthood. Tally the number of offspring that will survive to produce the next generation.
2 Individuals with the genotype *bb* will all die in the first year. If you eliminate these individuals how many surviving offspring do you now have?
3 What is the ratio of black skins to brown skins that survive to adulthood?
4 Combine your data with the other groups in your class to obtain a bigger sample. What is the ratio now?

INTERPRETING YOUR DATA

1 How has this activity shown that mutations that increase an individual's chances of survival and reproduction affect the proportions of particular characteristics in a population?
2 What has happened to the proportion of the allele b in the population? Has it been entirely eliminated? Do you think it ever will be?
3 Summarise how this chance mutation has helped the survival of the Venusian population.

Review questions

1 a Define a population.
b What do scientists mean when they speak of a 'gene pool'?
2 a Define 'mutation'.
b Explain the difference between somatic and germline mutations.
3 a Distinguish between gene mutations and chromosomal mutations.
b Give an example of a congenital disorder (a disorder present from birth) that can be caused by a gene mutation and one that can be caused by a chromosomal mutation.
4 Describe four different types of chromosomal mutations.
5 a What are mutagens (or mutagenic agents)?
b List five examples of mutagenic agents.
c Why does special care need to be taken when pregnant women require X-rays?
6 What is a lethal recessive?
7 Summarise the pattern of inheritance that occurs in genetic disorders such as Duchenne muscular dystrophy. When there is no history of such disorders in a family, how are they thought to arise?
8 a Distinguish between trisomy and monosomy.
b Give an example of each condition.
9 Explain how Klinefelter's syndrome and Turner's syndrome come about.
10 Explain how mutations could change the proportion of certain alleles in a gene pool.

Apply your knowledge

1 Discuss why mutations occurring in the reproductive cells are considered more important than those occurring in the body cells. In your discussion, describe the possible long-term effects of the two situations.
2 A large number of mutagenic agents can be found in the environment. Consider those that could possibly affect you in your lifetime and discuss steps that you can take to minimise any risks from exposure to those agents.
3 The more often cells divide, the greater the risk of errors and mutations. For this reason, scientists have hypothesised that when a baby is born with a congenital disorder caused by an error in cell division, the father is the parent more likely to have contributed the gene with the mutation. Compare the number of eggs produced by a female with the number of sperm produced by a male and explain why scientists have proposed this hypothesis.
4 Some naturally occurring viruses are considered mutagenic, because they can insert themselves into host DNA. Explain why this ability would make them mutagenic.
5 What is the sex of the individual whose karyotype is shown in Figure 12.5?
6 Lethal recessive alleles result in the death of an individual. How would this affect the allelic composition of the gene pool?
7 The risk of a having a baby with Down syndrome increases as the mother gets older. Table 12.1 shows the relationship between Down syndrome and maternal age.
a Draw an appropriate graph to display the data in Table 12.1.
b The risk of a baby having any chromosome abnormality increases dramatically with increasing maternal age. Suggest reasons for this.

Table 12.1 Mother's age and risk of having a baby with Down syndrome

Age of mother (years)	Risk of Down syndrome
20	1 in 1667
23	1 in 1429
26	1 in 1176
29	1 in 1000
32	1 in 769
37	1 in 227
40	1 in 106
43	1 in 50
46	1 in 23
48	1 in 14
49	1 in 11

University of New South Wales Embryology, https://embryology.med.unsw.edu.au/embryology/index.php/Genetic_risk_maternal_age, viewed 13 July 2012.

8 Figure 12.8 shows the sequence of the genes A to M on a chromosome. What type of chromosomal mutation is represented by each of **a**, **b** and **c**?

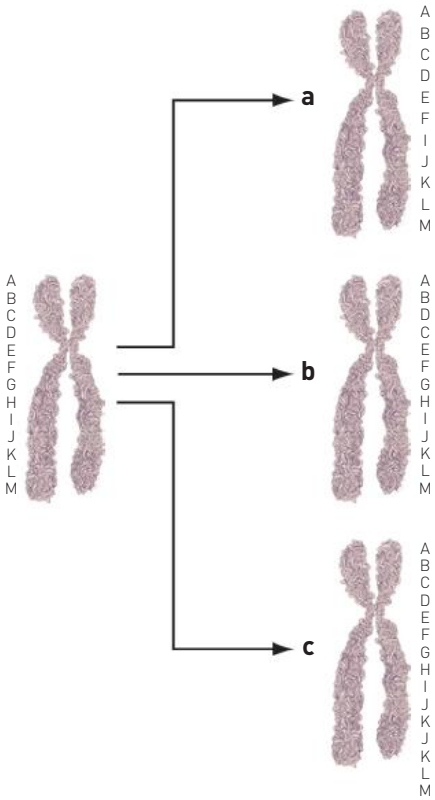


Figure 12.8 Some types of chromosomal mutations

CHAPTER

13

TECHNIQUES IN BIOTECHNOLOGY

UNIT 4 CONTENT

SCIENCE INQUIRY SKILLS

- conduct investigations, including the use of virtual or real biotechnological techniques of polymerase chain reaction (PCR), gel electrophoresis for deoxyribonucleic acid (DNA) sequencing, and techniques for relative and absolute dating, safely, competently and methodically for valid and reliable collection of data

SCIENCE AS A HUMAN ENDEAVOUR

- gene therapy can be used to treat a range of diseases, including diabetes mellitus (Unit 3)
- hormones and vaccines are developed using recombinant DNA and associated biotechnological techniques (Unit 3)
- developments in biotechnology have increased access to genetic information of species, populations and individuals, existing now or in the past, the interpretation and use of which may be open to ethical considerations

SCIENCE UNDERSTANDING

Evidence for evolution

- biotechnological techniques provide evidence for evolution by using PCR (to amplify minute samples of DNA to testable amounts), bacterial enzymes and gel electrophoresis to facilitate DNA sequencing of genomes

Do you eat bread, cheese or yoghurt? If so, you are consuming foods that are produced by biotechnology. **Biotechnology** uses cellular processes to make products that are of use to humans. For thousands of years people have been using yeasts to make bread and alcohol, and bacteria to make cheese and yoghurt.

Modern biotechnology has dramatically expanded the range of techniques and products that can be used to improve human welfare. Improvements in the treatment and prevention of disease, food production, production of clean energy and enhanced efficiency of manufacturing processes are all resulting from advances in biotechnology.

The definition of biotechnology has more recently been expanded to include genetic testing, gene manipulation, cell replacement therapies and tissue engineering. Some of the methods and outcomes of modern biotechnology are described in this chapter.

The human genome

Rapid advances in mapping the location of genes in chromosomes led to the establishment of the Human Genome Project in 1990. This was an international research effort aimed at mapping the location of the genes in all 46 chromosomes in the human genome. A **genome** is the complete set of genetic information of an organism. For humans this is the complete sequence of the nucleotides that make up the approximately 21 000 genes in our chromosomes. Although the project was completed in 2003, analysis of the data will continue for many years. When all the information is available, scientists will know the location of the genes involved in human diseases and will be able to study them much more efficiently and rapidly than ever before.

To date, around 4000 genetic disorders are known and more are being discovered. Information from the Human Genome Project has identified the location of all these potentially faulty genes and replacement of those genes is now possible. Gene replacement is a major area of investigation into the treatment and cure of disease, and will be discussed in more detail later in this chapter.

Information from the project has also influenced many other lines of research. New technology is being developed to monitor the expression of the genes involved in particular diseases. For example, scientists researching colon cancer have discovered how to monitor the genes responsible for turning on the different stages of cancer development. This has enabled researchers to map out the pathways that lead to the development of such cancers. Others have used the information from the project to develop better genetic tests that enable individuals to be screened and, if relevant, warned of their disease risk. Individuals at risk can then modify their lifestyles to help prevent the disease and, if necessary, begin preventive drug treatment. For example, those people found to have a genetic tendency to develop high cholesterol would be in a position to modify their diet and take drugs to lower their cholesterol.

For more details on the Human Genome Project

Biotechnology and DNA

DNA

DNA (deoxyribonucleic acid) is found in the cells of all organisms, usually in the nucleus, but there is also some in the mitochondria (the organelles in a cell where the aerobic phase of cellular respiration occurs) and, in some organisms, in the cytosol. All DNA molecules consist of two strands of alternating sugars (deoxyribose) and phosphates with pairs of nitrogen bases forming cross-links between the sugar molecules in the two strands. The molecule is twisted into a spiral known as a double helix (see Figure 13.1 on page 178).

There are four different nitrogen bases in a DNA molecule: **adenine (A)**, **thymine (T)**, **cytosine (C)** and **guanine (G)**. To form the cross-links between the two strands of the DNA molecule, the bases will only pair in a certain way. Adenine will pair only with thymine and cytosine will pair only with guanine. The order in which the nitrogen bases occur in the DNA molecule is the genetic information that determines the structure of the cell and the way it functions.

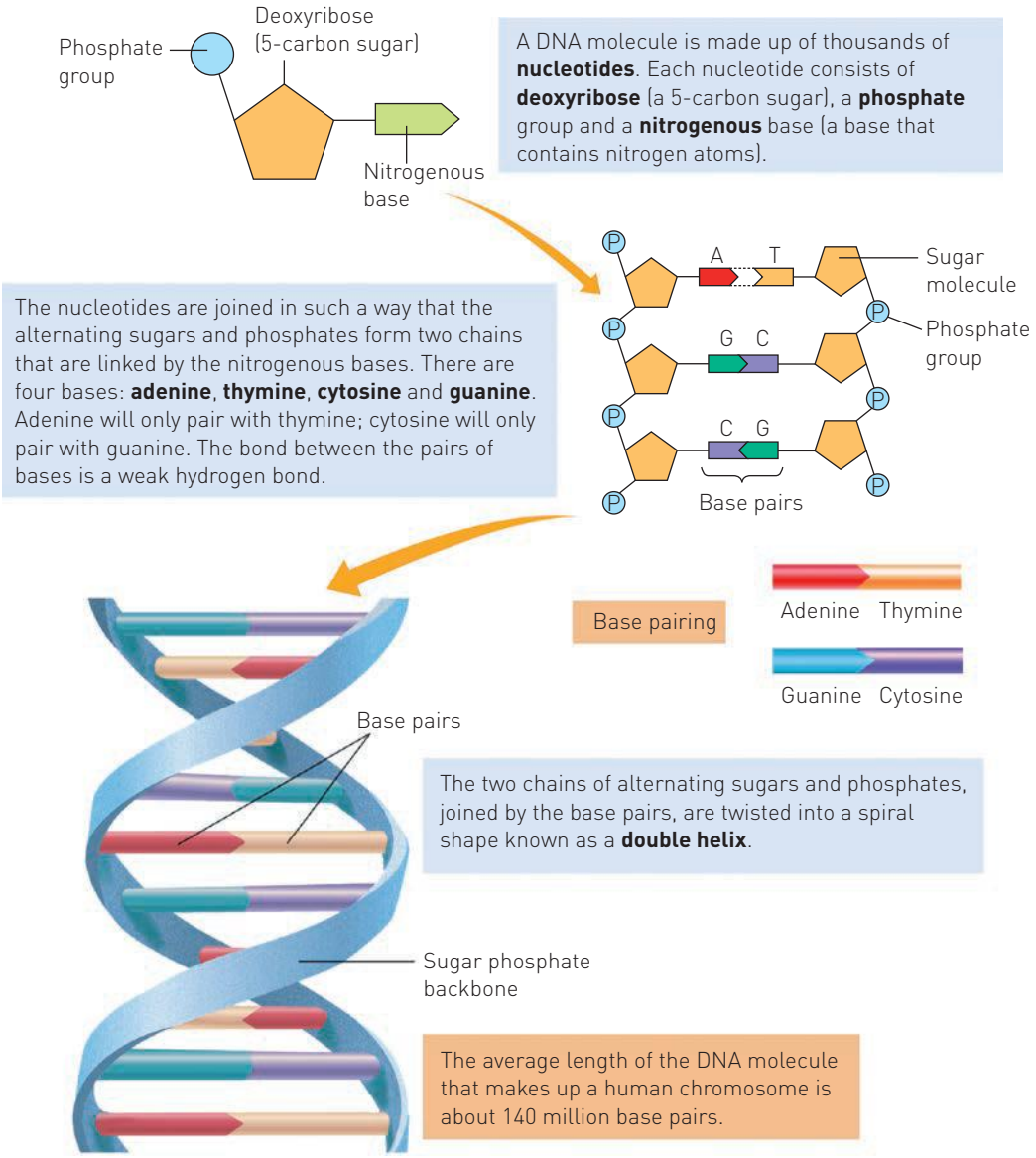


Figure 13.1 DNA consists of two strands of alternating sugars and phosphates with pairs of nitrogen bases forming cross-links between the chains. The two strands are twisted into a double helix.

DNA sequencing

Each phosphate group and sugar molecule with a nitrogen base attached is called a **nucleotide**. **DNA sequencing** is the determination of the precise order of nucleotides in a sample of DNA. The method most frequently used to determine such a sequence was invented by Frederick Sanger, who was awarded his second Nobel Prize in Chemistry in 1980 for this accomplishment.

DNA is synthesised from four nucleotides, more correctly called deoxynucleotide triphosphates, as each nucleotide consists of three phosphate groups joined to the sugar deoxyribose. Each nucleotide has a different base – adenine, cytosine, guanine or thymine. In building a sequence, each new nucleotide is bonded to the hydroxyl group (OH) of the previous nucleotide (Figure 13.2). In Sanger's method of determining a DNA sequence, synthetic nucleotides that lack this OH group are added to the growing strand (see red arrow in bottom formula of Figure 13.2). The synthetic nucleotide stops the elongation of the sequence because there is no OH group for the next nucleotide to attach to. This technique then allows the strands to be compared.

DNA sequencing can be used to show whether a person will develop an inherited disease. By comparing DNA sequences, changed alleles can be detected. Point mutations, as well as small insertions or deletions, are readily identified by DNA sequencing. An example is hereditary spastic paraplegia, an inherited disorder that causes progressive limb weakness and stiffness, often resulting in paralysis. People with the disorder typically begin to show symptoms during their mid-20s to mid-50s, the symptoms growing progressively more debilitating. There is currently no cure, so treatment involves physical therapy to try to improve muscle strength and safeguard muscular movements. Researchers searched for the genes associated with the disease by studying two families whose members had hereditary spastic paraplegia. They searched a segment of chromosome 2 and, by painstakingly examining the DNA sequence of a number of genes, located mutations that were present in the affected people but not in their unaffected relatives. Knowing the location of the allele that may have mutated allows people who are concerned that they may have inherited spastic paraplegia to undergo screening before symptoms of the disorder become apparent.

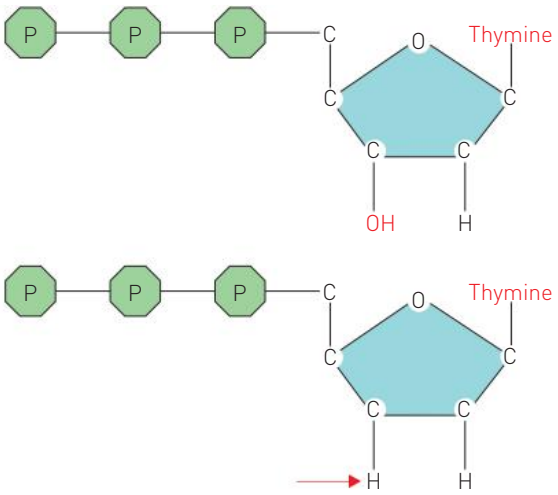


Figure 13.2 DNA is synthesised from four deoxynucleotide triphosphates. One of them, deoxythymidine triphosphate (dTTP), is shown in the top formula. Shown below is the synthetic nucleotide dideoxythymidine triphosphate (ddTTP).

Many other diseases can be determined by DNA sequencing, such as sickle-cell anaemia, cystic fibrosis and some forms of cancer. Knowing that they have inherited a faulty allele, people are able to seek effective treatment, and possibly prevent the disease or at least reduce its effects. DNA sequencing has also been used for maternity and paternity tests, in cases where the identity of the father or mother of a child is in dispute.

Getty Images/Alfred Pasieka

Figure 13.3 A DNA sequence displayed on a computer screen

Sanger sequencing
This website shows an animation of the Sanger method of DNA sequencing.

DNA sequencing
This website provides a series of annotated slides on DNA sequencing.

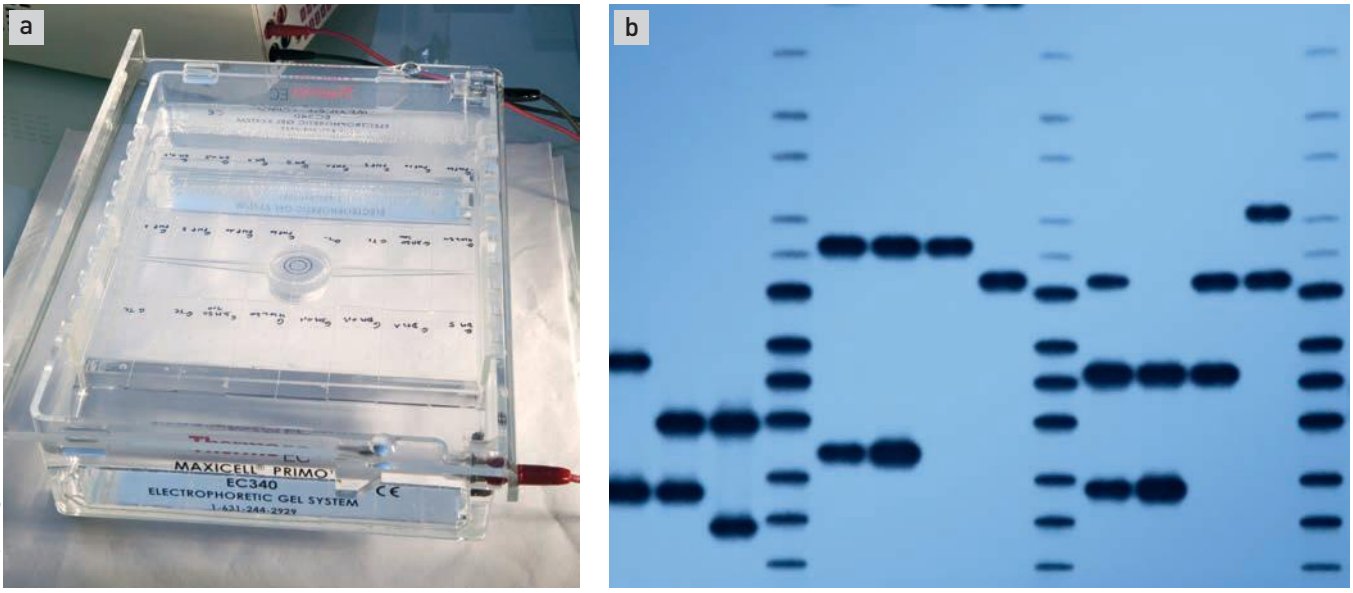
Profiling techniques

A person's DNA is so distinctive that it can be used as a means of identification. In the late 1960s, scientists developed techniques using special enzymes to cut the DNA at specific base sequences, leaving pieces of various lengths. The length of these pieces varies distinctively from one person to another. However, it was not until 1984 that a breakthrough enabled the technique to be refined. The DNA pieces were placed on a bed of semi-solid gel and an electric current was passed through electrodes at either end, a technique called **electrophoresis** (Figure 13.4a). The DNA, which is negatively charged, moves through the gel toward the positive electrode. The smaller DNA pieces move faster than the larger ones, resulting in a pattern of bands that looks similar to the barcodes on products sold in supermarkets. This banding pattern is an individual's **DNA profile**, often called a **DNA fingerprint** (Figure 13.4b).

DNA fingerprints are frequently used in tracing ancestry and in forensic science. They are also useful in the identification of hereditary diseases. Using gel electrophoresis, a person who carries a gene that causes a hereditary disease, such as cystic fibrosis or Huntington's disease, can be identified, as can a newborn baby who will develop the disease. In some cases, the fact that a person has a particular gene does not automatically mean that they will have the disease, or even develop the disease. A recently discovered allele has been shown to increase an individual's risk of colon cancer. DNA profiling enables this allele to be identified and a person with it can then have regular medical examinations, even though colon cancer may never develop.

DNA profiling
This BBC website has a brief article about the discovery of DNA profiling.

DNA profiling enables many genetically inherited diseases to be detected at an early age. Early diagnosis provides a greater chance that the condition can be effectively treated and possibly cured. People with a history of an inherited disease in the family can use a DNA profile to determine the risk of having an affected child.



Getty Images/Science Photo Library

Getty Images/Martin Shields

Figure 13.4 a A tray of electrophoresis gel. The wires can be seen that supply the electric current that runs through the gel. **b** A DNA fingerprint

Polymerase chain reaction

The **polymerase chain reaction (PCR)** is a technique widely used in molecular biology. Segments of DNA are artificially multiplied through a series of repeated cycles of duplication using an enzyme called DNA polymerase. To initiate duplication, a **primer** is required. The primer is a segment of DNA, complementary to the targeted sequence of DNA, which initiates replication by the DNA polymerase (Figure 13.5). Kary Mullis was awarded the Nobel Prize in Chemistry in 1993 in recognition of his development of the PCR technique.

Nobel prizes
This website provides the press release for the 1993 Nobel Prize in Chemistry.

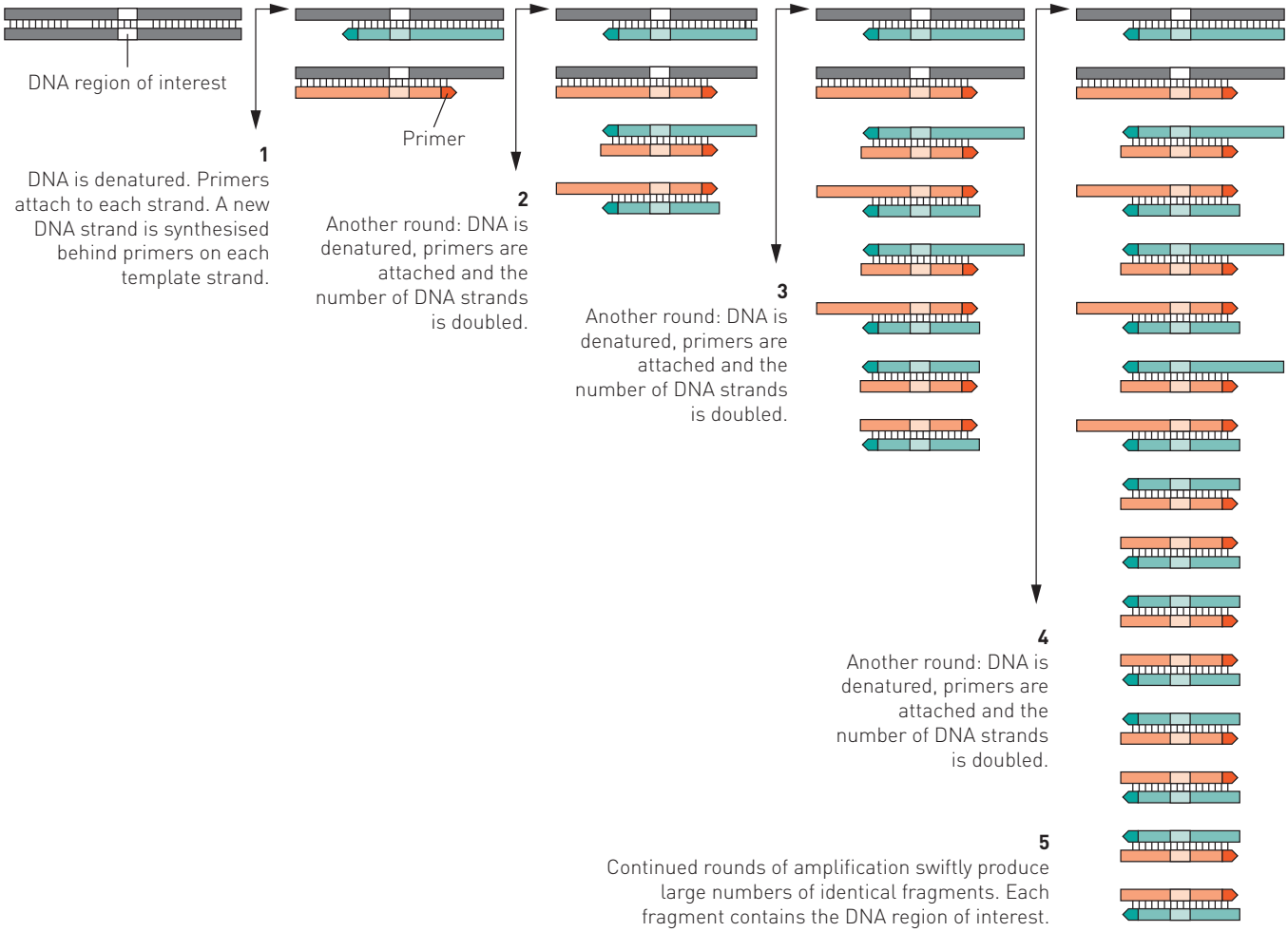


Figure 13.5 A diagrammatic representation of the polymerase chain reaction

By using DNA polymerase, the original molecule of DNA is replicated, doubling the number of DNA molecules. Each molecule is then replicated in a second sequence of replication, resulting in four times the number of the original molecule. A third sequence of replication occurs, again doubling the number of molecules of DNA, and so on. By using PCR, an original DNA template can be amplified over many sequences to generate millions of copies of the original DNA molecule. Such compounding amplification of the original molecule has resulted in the process being called a **chain reaction** (Figure 13.5).

DNA polymerase occurs naturally in living organisms, where its role is to duplicate DNA when cells divide. It is able to bind to a single DNA strand and then create the complementary strand. In the original PCR process, the double-stranded DNA was separated into two single strands by heating it to 96°C. However, at this temperature, the DNA polymerase was destroyed. That meant that more of the enzyme had to be added after the heating stage of each sequence. This was very time consuming and used large amounts of DNA polymerase. Almost all PCR applications now employ a heat-stable DNA polymerase. One such enzyme, taken from a heat-loving bacterium called *Thermus aquaticus*, is called Taq polymerase. This does not break down when heated and it has allowed the procedure to be simplified and automated, permitting the PCR sample to be alternately heated and cooled. Such steps are necessary, as heat is required to separate the strands of DNA but cool conditions are essential for the synthesis of the DNA by the enzyme.

PCR is used to significantly shorten the time it takes to detect hereditary diseases in a particular genome. Each gene of interest can be easily amplified by PCR and then sequenced to detect the mutation in question, such as sickle-cell anaemia, phenylketonuria (PKU) or cystic

PCR
This website provides an animated sequence on PCR.

PCR virtual laboratory
This website provides a PCR virtual laboratory.

fibrosis. Viral diseases can also be detected by the use of PCR. Amplification of viral DNA is possible immediately after infection. Under normal circumstances, days or even months may pass before symptoms of the virus become evident, eventually leading to testing and treatment. With early detection of infection, a medical practitioner has a significant advantage in appropriately managing the disease.

In forensic science, PCR has been most valuable. It can be used to amplify the DNA from a single drop of blood or semen, or a strand of hair, thus allowing sequencing to take place and a DNA fingerprint to be produced. It is also used to determine relationships between human ancestors. Where small amounts of DNA can be extracted from fossils, they can be amplified and the genomes of our fossil ancestors compared.

EXTENSION

There are a number of steps in each cycle of the polymerase chain reaction. Find out what occurs at each of the following stages.

- Denaturing
- Annealing
- Elongation

Recombinant DNA technology

Recombinant DNA technology, frequently referred to as **genetic engineering**, involves the introduction of DNA into cells, where the DNA is foreign to that organism or has been modified in some way. It can be used to take genes from one organism and place them into the chromosomes of another. This has huge potential for replacing faulty genes with healthy ones. It could be used for the benefit of patients suffering from cystic fibrosis, rheumatoid arthritis and certain cancers. The same technology is another way of identifying mutations and determining whether a person is affected by, or is a carrier for, hereditary diseases.

Stanley Norman Cohen and Herbert Boyer invented the recombinant DNA technique in 1973. Their technique was to isolate and amplify genes or DNA segments and insert them into a bacterial cell, creating a transgenic bacterium. **Transgenic organisms** are those whose genome has been altered by the transfer of a gene or genes from another organism. The introduced genes become part of the transgenic organism's DNA and can be passed on from one generation to the next (Figure 13.6).

GloFish

Figure 13.6 GloFish®, the first commercially available transgenic organism, are a type of zebra fish that have been modified through the insertion of a gene that codes for the production of a protein that glows with a green fluorescence.

Viruses that infect bacterial cells are called **bacteriophages**, or **phages**. A key breakthrough that led to recombinant DNA technology was the discovery that certain enzymes in bacteria are able to restrict the duplication of infecting viruses by cutting up the viral DNA. Scientists discovered that such an enzyme always cuts the DNA at a point where there is a specific sequence of bases. This is known as a **recognition site**, and the enzyme that cuts the DNA is a **restriction enzyme** because it restricts the duplication of bacteriophages.

Some of the restriction enzymes produce a straight cut at the sequence, while others produce a staggered cut. A **straight cut** is when the restriction enzyme makes a clean break across the two strands of DNA to produce a blunt end. A **blunt end** is when both strands terminate in a base pair (Figure 13.7). On the other hand, some restriction enzymes produce a **staggered cut** resulting in fragments with sticky ends. A **sticky end** is a stretch of unpaired nucleotides in the DNA molecule that overhang at the break in the strands (Figure 13.7). Sticky ends, so called because of their ability to combine with sections of DNA that have a complementary ending, are very useful in recombinant DNA technology. A single-stranded overhang from one fragment can be paired with any other fragment of DNA that has a corresponding sequence, including one from a different organism.

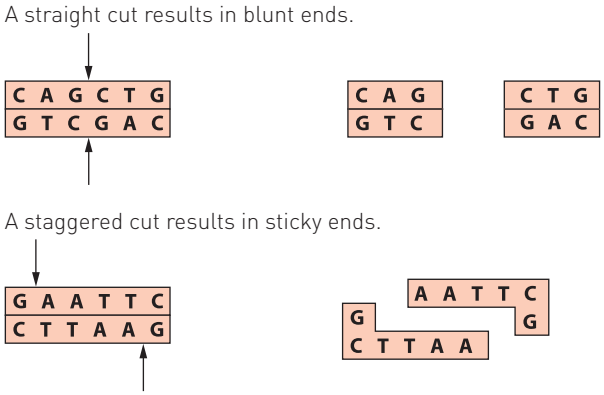


Figure 13.7 Cuts in DNA strands produced by restriction enzymes

Look carefully at Table 13.1. The name of each restriction enzyme reflects its origin. The first letter of the name comes from the genus of the bacterium from which it was isolated, while the second two letters come from the species. For example, EcoRI comes from the RY13 strain of the bacterium *Escherichia coli*, while HindIII comes from the R(d) strain of the *Haemophilus influenzae* bacterium. The numbers listed after the name indicate the order in which the enzymes were isolated from the single strains of bacteria.

Table 13.1 Examples of restriction enzymes

Enzyme	Recognition site	Bacterial origin
*Bam*HI	G|G A T C C C C T A G|G	*Bacillus amyloliquefaciens*
*Eco*RI	G|A A T T C C T T A A|G	*Escherichia coli*
*Hin*dIII	A|A G C T T T T C G A|A	*Haemophilus influenzae*
*Taq*I	T|C G A A G C|T	*Thermus aquaticus*

Another major breakthrough in being able to modify genes was the discovery of an enzyme that was able to join, or recombine, separate pieces of DNA. This enzyme, found in the bacterium *Escherichia coli* (*E. coli*), was originally called a 'DNA-joining enzyme', but is now known as **DNA ligase**. Some version of DNA ligase is used by every living cell to 'glue' together short strands of DNA during replication, a process called **ligation**.

Researchers found that it was only in the presence of ligase that single-stranded breaks in phage DNA could be repaired. They demonstrated that ligase was able to form a bond between a particular end of the last nucleotide on one DNA fragment with a complementary end of the last nucleotide on an adjacent fragment. This discovery enabled scientists to attempt their own recombination experiments (Figure 13.8). Such experiments involved not just recombining the DNA of a single organism but recombining DNA from different organisms, including different species.

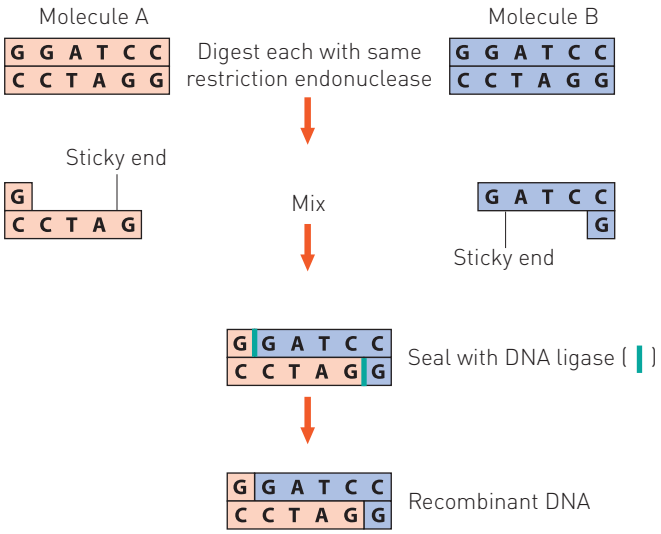


Figure 13.8 Making a recombinant DNA molecule

Recombinant DNA
This website provides an animated sequence explaining the technique of recombinant DNA technology.

Video on recombinant DNA
This website has a video showing how DNA recombination can be used in the manufacture of certain proteins.

The first step in producing an organism with recombinant DNA is to isolate the gene of interest. This gene is then inserted into a vector and cloned. The **vector** now has a segment of DNA that is capable of replicating on its own. In recombinant DNA technology, commonly used vectors are bacterial plasmids and phage viruses. **Plasmids** are usually circular, double-stranded units of cytoplasmic DNA, frequently found in bacteria, that are capable of replicating within a cell independently of the chromosomal DNA. The gene of interest (alien DNA to the vector) is integrated into the plasmid or phage, and is referred to as recombinant DNA. Cloning of the vector then occurs so that numerous copies of the DNA are available to insert into the host cells. Once large quantities of the vector have been produced, they can be introduced into the selected host cells such as special bacterial, yeast or mammalian cells. These host cells will then produce the foreign protein using instructions in the gene in the recombinant DNA. Bacteria into which the gene for insulin production has been introduced are now used in the manufacture of insulin for treatment of diabetes (Figure 13.9).

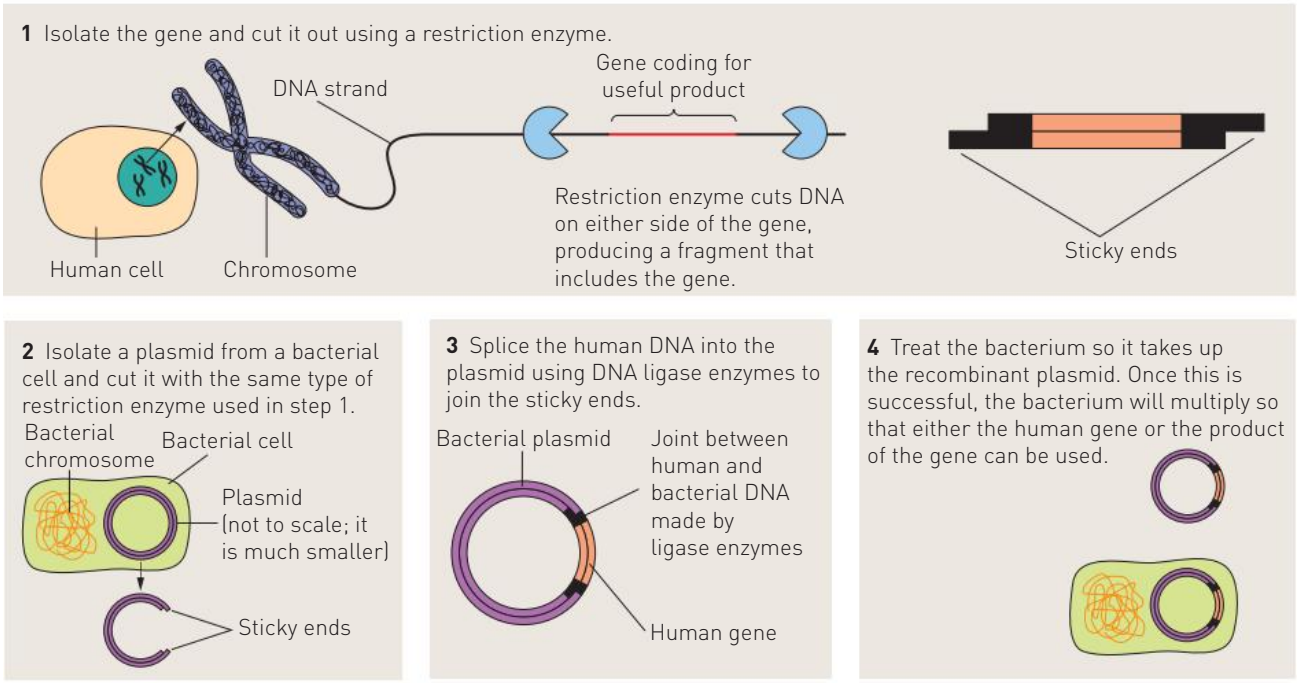


Figure 13.9 A simplified diagrammatic representation of recombinant DNA technology

Table 13.2 Terminology for recombinant DNA technology

Term	Definition
Blunt ends	The ends produced by a straight cut of a sequence of nucleotide bases
Ligase	An enzyme capable of combining two small components of single-strand DNA into one single structure
Phage	Or bacteriophage; a virus that infects bacteria
Plasmid	Small circular strand of DNA distinct from the main bacterial genome; it is composed of only a few genes and is able to replicate independently within a cell
Restriction enzyme	Enzyme that cuts a strand of DNA at a specific sequence of nucleotides
Staggered cut	Produced when a restriction enzyme creates fragments of DNA with unpaired nucleotides that overhang at the break in the strands; called sticky ends
Straight cut	Produced when a restriction enzyme makes a clean break across the two strands of DNA so that the ends terminate in a base pair; called blunt ends
Sticky ends	The overhanging ends produced by a staggered cut of a sequence of nucleotide bases; can be called cohesive ends
Vector	A bacterial plasmid, viral phage or other such agent used to transfer genetic material from one cell to another

Examples of the use of recombinant DNA technology

Recombinant DNA technology has had an enormous impact on the diagnosis and treatment of diseases and genetic disorders. It has also enabled the manufacture of large quantities of pure protein for many medical products including insulin, growth hormone, factor VIII and follicle-stimulating hormone (FSH). In the past these substances had to be extracted from people or animals, and they were often impure and/or of variable strength. One notable example was the transmission of the human variant of Creutzfeldt-Jakob disease (vCJD) by contaminated human growth hormone. This disease, a variant of 'mad cow disease', is a rare but fatal brain infection. There is evidence that some blood products used to produce the protein factor VIII were contaminated with vCJD.

Insulin

People with type 1 diabetes have elevated blood sugar levels due to impaired insulin production by the pancreas (for more information about diabetes, see page 118). Insulin regulates the use and storage of glucose. It was identified in 1921, and patients with diabetes were treated with insulin derived from the pancreas of pigs and cattle. In 1982, insulin produced by genetically engineered bacteria was approved for diabetes treatment. Using recombinant DNA techniques, the human gene that has the code for insulin production was introduced into bacterial cells. These bacteria became insulin factories and are now cultured in vats where they produce insulin that can be used to treat diabetes (see Figure 9.6 on page 122). The insulin produced by the bacteria is identical to human insulin because the human gene was engineered into the bacteria (Figure 13.10). This procedure is now frequently performed using yeast cells as the growth medium. Insulin produced by this technology does not result in any of the side effects that were suffered by some people when insulin from cattle or pigs was used.

Insulin
This website provides a brief discussion of the manufacture of insulin, with diagrams.

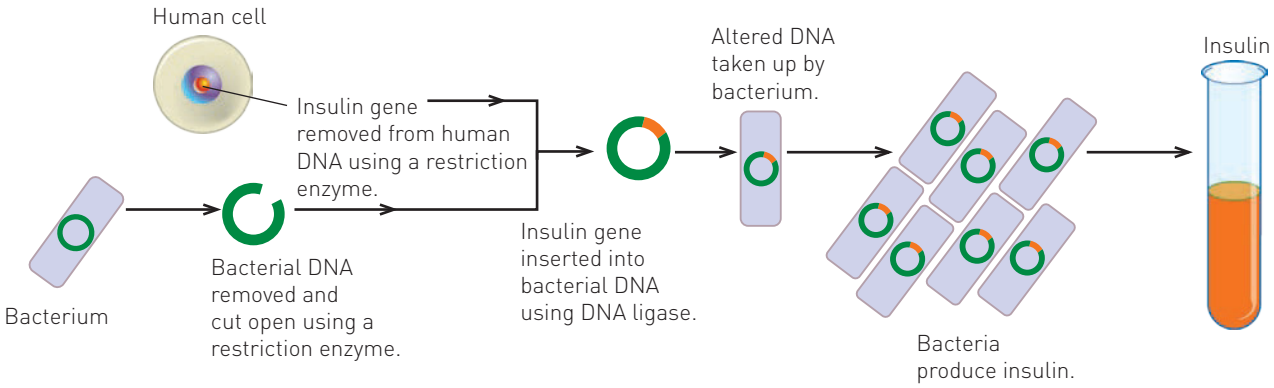


Figure 13.10 A diagrammatic representation of the production of human insulin using recombinant DNA technology

Human growth hormone

As we described in Chapter 9, production of human growth hormone (hGH) by genetically engineered *E. coli* bacteria has dramatically increased the supply of the hormone. As it is now readily available, hGH has been used to try to enhance athletic performance and to delay the physical deterioration associated with ageing. However, there is little evidence that hGH is of any benefit for either of these uses, and it can produce serious side effects.

Interestingly, this technology has resulted in the production of growth hormone for dairy cattle. Administration of the hormone has increased milk production, and research so far indicates that drinking milk from treated cattle does not pose a risk to human health.

EXTENSION

Recombinant DNA technology has resulted in the manufacture of far more human growth hormone than was available in the past. Now it is being used to overcome some of the cosmetic effects of ageing.

Find out:

- when hGH first became available for use with adults
- what evidence there is of beneficial results from anti-ageing use of this hormone
- if there are risks involved in the use of the hormone in this way
- if there are other benefits to adults in the use of this hormone.

Factor VIII

Haemophilia A, sometimes referred to as **classic haemophilia**, is an inherited disorder in which a blood-clotting protein known as factor VIII is in poor supply or missing. People with the condition are unable to form blood clots adequately and are therefore at risk of life-threatening bleeding from injuries that would be trivial in people with normal blood clotting. To treat this condition, injections of factor VIII concentrates, made from human plasma, have been used. To obtain sufficient quantities of factor VIII, plasma from thousands of donors was required. With such a large number of donors there was the constant risk of transmission of viral disease. Two viral diseases that caused the deaths of many haemophiliacs all over the world were human immunodeficiency virus (HIV) and hepatitis C. The production of factor VIII by recombinant DNA techniques overcame this problem. Factor VIII produced in this way has the added advantage that it is free of other plasma proteins that could cause an immune response or allergic reaction. Recombinant factor VIII, one of the largest molecules synthesised to date, is cultured in mammalian cells and has been found to be highly effective in the control of excessive bleeding.

Getty Images/Science Photo Library

Figure 13.11 A computer-generated model of a factor VIII molecule

Vaccines

The first vaccine for human use that was produced using recombinant DNA technology was hepatitis B vaccine, introduced in 1986. It was produced by inserting a gene from the hepatitis B virus into the cowpox virus. Development of recombinant DNA vaccines does have disadvantages. It is very expensive, as the genes for the desired antigens must be located, cloned and expressed efficiently in a new vector. Besides this financial deterrent to innovation, those involved in vaccine research must be conservative. Because vaccines are used on large numbers of healthy people, many of whom are children, the safety of the product is paramount. Therefore, if a conventional vaccine is known to be safe, there is little incentive to develop a new one using genetic engineering.

EXTENSION

Rapid advances in medical technology have resulted in new ways of manufacturing vaccines.

Find out:

- how recombinant DNA is contributing to the manufacture of new vaccines
- the difficulties involved in the use of such a technique
- which vaccines are now produced using recombinant technology.

Designer hens
This website shows how designer hens are able to lay eggs containing proteins to fight human diseases.

The identification of hereditary diseases

A **hereditary disease** is caused by defective genetic information being transmitted from parents to their children. Such diseases are often passed on within families over many generations. Just as a person may inherit features such as blue eyes or curly hair from one or both parents, a person can also inherit certain diseases.

Genes contain coded instructions that direct the development of all our inherited characteristics. Usually, genes produce normal characteristics. However, a particular gene may quite suddenly change from its original structure and produce a totally different characteristic. Characteristics occurring like this are referred to as **mutations** (see Chapter 12).

Frequently, mutant genes function improperly and cause a disorder or a change to the structure of the body. Because mutations involve a change in the genetic material, they can be passed on to future generations. Advances in biotechnology have facilitated the development of techniques to identify diseases caused by mutant genes (see Table 13.3). As with many techniques in medical science, the tremendous benefits involve risks and ethical concerns.

Table 13.3 Summary of techniques for identifying genes and alleles

Technique	Features
DNA sequencing	Determines the precise order of nucleotides in a sample of DNA Enables sequences to be compared easily
Profiling	Determines an individual's DNA profile or fingerprint as a distinct series of bands Enables the detection of many genetically inherited diseases
Polymerase chain reaction	Segments of DNA are multiplied through a series of repeated cycles using an enzyme called DNA polymerase Genes of interest can easily be amplified and then sequenced to detect the mutations

EXTENSION

Genetic probes are used to detect the presence, in a person's genome, of alleles responsible for hereditary diseases such as thalassaemia, cystic fibrosis, Duchenne muscular dystrophy and Huntington's disease.

Find out

- what a genetic probe is
- how genetic probes are used to detect disease-causing alleles.

Gene therapy

Gene therapy aims to treat or cure genetic abnormalities by replacing faulty genes with healthy ones. It is a way of using the genes themselves as the treatment. In many ways, it is the most obvious application of the Human Genome Project, which has revealed the location of around 4000 potentially faulty genes. Currently, gene therapy is concentrating on single-gene disorders such as cystic fibrosis, Huntington's disease, muscular dystrophy and sickle-cell anaemia. Unlike most conventional medicines, which treat the symptoms of a disease, gene therapy has the potential to correct the underlying cause by replacing the faulty gene with a healthy one.

Gene therapy
This website has the transcript of an ABC interview with an American gene therapy researcher.

Cystic fibrosis

Cystic fibrosis (CF) is the most common life-threatening genetic disorder among Australians of European descent. It mainly affects the lungs and pancreas but sometimes the liver and reproductive organs. CF is characterised by thick sticky mucus secreted by the mucous glands. In the lungs, this mucus may clog the tiny air passages and trap bacteria, making a person with CF susceptible to infection. Repeated infections and continual blockage of the airways may cause irreversible lung damage and shorten life expectancy. The pancreas is also affected, preventing secretion of enzymes required for digestion. Therefore, people with CF frequently have problems with nutrition and need to take care with their diet.

CF results when an individual inherits the recessive allele for the condition from each parent. In most Australian states, a blood sample is usually taken from a baby's heel within two to three days after birth. If the blood test reveals that a child has the disease, a special low-fat, high-carbohydrate and high-protein diet is advised.

The identification of the Cystic Fibrosis Transmembrane Regulator (CFTR) gene in 1989 was a major step forward in developing a treatment for CF. Mutations in this single gene result in the disease and since its discovery more than 900 mutations have been identified. In 1991, scientists successfully corrected faulty CFTR genes in cultured cells by adding normal copies of the gene to the culture. This was the first step toward gene therapy for CF.

CF was a logical choice for treatment using gene therapy. It is a single-gene disorder, and the most severely affected organ, the lung, is relatively easy to access to provide treatment. In addition, the disease is slow to progress, with the lungs of a newborn being virtually normal. This would enable gene therapy to begin before significant lung damage started to occur. The first experimental gene therapy treatment was given to a patient with CF in 1993. Researchers modified a common cold virus to act as the vector to carry normal genes to the CFTR cells in the airways of the lung. This first study was mainly concerned with the safety issues of the treatment. The amount of gene transfer was probably too small to have any real therapeutic benefit and any benefit was short-lived. Trials with alternative methods of gene transfer are continuing.

Huntington's disease

Another single-gene disorder is Huntington's disease and researchers believe that gene therapy could be used to slow down or prevent its development. It is caused by a mutation in a single gene on chromosome 4 called IT15. The symptoms of this incurable genetic disorder seldom appear before the age of 40. The mutated form of a protein called huntingtin results in nerve cells in the brain being damaged, causing physical, mental and emotional changes. The disease is characterised by occasional unintentional flailing movements of the arms and legs, and difficulty making voluntary movements of the limbs. The affected person also suffers from progressive dementia, the loss of ability to think clearly.

Research in the United States on mice has indicated that gene therapy for Huntington's disease could be effective in humans. In other research, French scientists experimented with a modified virus to deliver a corrective gene into brain cells that boosts a natural shield against the effects of the defective huntingtin protein. This research has been conducted on rats and primates, and the positive results have encouraged movement towards a clinical trial on humans.

Sickle-cell anaemia
This website provides information about recent progress with gene therapy for sickle-cell anaemia.

Cell replacement therapy and tissue engineering

Stem cells are undifferentiated cells that are capable of repeated mitotic divisions for long periods of time and, given the right conditions, can differentiate into specialised cells. These characteristics make them ideal for producing replacement tissues. In *Human Perspectives Units 1 & 2 ATAR* (Chapter 17) the types of stem cells and their sources were discussed.

Any disorder involving loss of, or injury to, normal cells is a potential candidate for stem **cell replacement therapy**. However, cell replacement therapy for the nervous system has generated the most interest, due to the debilitating nature and widespread occurrence of neurodegenerative disorders such as Parkinson's and Alzheimer's diseases. The most attractive method for restoring brain function in, say, Parkinson's disease is the replacement of dying neurons with healthy neuronal tissue. Pilot studies using embryonic stem cells have been carried out in humans with some success. The transplanted cells not only survived but also grew and established connections with adjacent neurons. However, the use of human embryonic stem cells is controversial and raises a number of ethical questions. Researchers into Parkinson's disease are currently exploring other sources of cells to help restore patients' brain function.

Stem cells are increasingly being used for tissue engineering. The primary objective of **tissue engineering** is to restore healthy tissues or organs for patients and thus eliminate the need for tissue or organ transplants, or artificial implants. Early research in this area used cells from the intended recipient, but in many cases, such as genetic diseases, this was not practicable. In other situations, the organ from which cells were to be harvested was diseased, and so not enough normal cells were present to enable a successful culture. The use of stem cells overcomes both problems.

Tissue engineering requires an abundant supply of disease-free cells of specific types. These cells then need to be induced to grow on a scaffold of natural or synthetic material to produce a three-dimensional tissue. Tissue engineering **scaffolds** serve as a template for tissue growth, and need to have high pore sizes that enable the cells to grow while at the same time allowing the diffusion of nutrients throughout the whole structure. They frequently need to be biodegradable so that they can be absorbed by the surrounding tissues without having to be removed surgically. This needs to be carefully established, as the rate at which the scaffold degrades needs to match, as far as possible, the rate of tissue formation. That is, while the new cells are manufacturing their own natural matrix structure around themselves, the scaffold is providing a support structure that will eventually break down, leaving newly formed tissue.

Once a scaffold has been devised, suitable stem cells need to be cultured. These cells are seeded onto the scaffold, which then enables further cell growth and proliferation. This cell-covered scaffold is then implanted into the patient at the site where new tissue is required. As the new cells continue to grow and divide, the material making up the scaffold begins to degrade or, in some cases, to be absorbed. Such tissue engineering techniques are being used to develop a wide range of tissues, including bone, skin, cartilage and adipose tissues.

Tissue engineering
This website provides an interesting account of how tissue engineering is being used to manufacture artificial skin.

Biotechnology

Science inquiry

ACTIVITY 13.1 Electrophoresis simulation

Electrophoresis simulation

Go to the weblink and work through the electrophoresis simulation. As you go, or after you have finished, answer the following questions.

1. What ingredients are used to make the gel?
2. Describe how the gel is made using the ingredients that you have listed.
3. DNA samples are placed in wells in the gel. Explain how the wells are made.
4. What is the purpose of the DNA size standard?
5. What electrical charge does a DNA molecule have?
6. Which electrical charge is applied to the well end of the gel?
7. Is it possible to tell whether an electric current is running through the gel?
8. What makes the DNA migrate through the gel?
9. Describe the technique that is used to make the DNA visible in the gel.
10. Why do shorter DNA strands move further through the gel than longer strands?

ACTIVITY 13.2 Restriction enzymes

Recombinant DNA technology, or genetic engineering as it is frequently called, involves the introduction into cells of fragments of DNA that are foreign to the organism. To do so, the strands of DNA under investigation need to be cut into useful fragments. The 'scissors' that cut the DNA are called restriction enzymes. The fragments can then be inserted into a suitable vector and joined with DNA ligase.

In this activity we will investigate how a sequence of DNA can be cut into suitable fragments using an appropriate restriction enzyme.

WHAT TO DO

Answer the questions below. As you answer the questions, refer to the relevant parts of this chapter where necessary.

1. Explain the following terms by describing their role in recombinant DNA technology.
   - **a** Restriction enzymes
   - **b** Recognition sites
   - **c** Blunt ends
   - **d** Sticky ends
2. Look at Figure 13.12 and, using Table 13.1 (on page 183), identify the restriction enzyme that is being used and the organism from which it was first isolated. What is the base sequence for this restriction enzyme's recognition site?

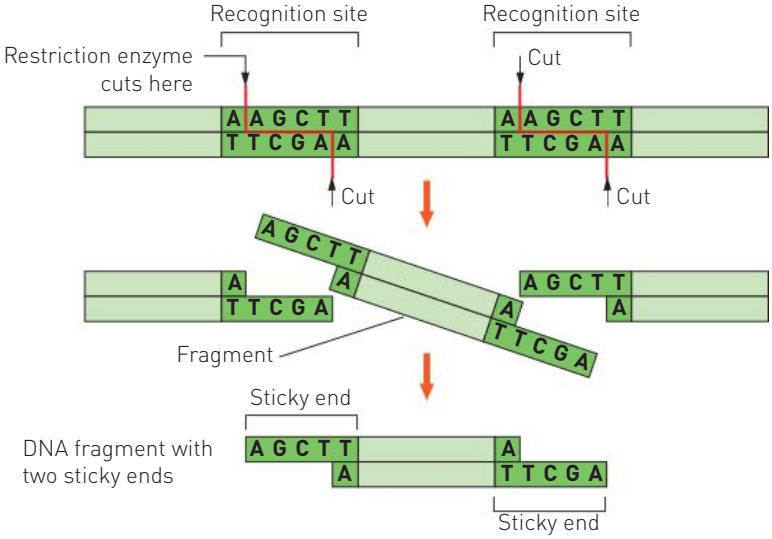


Figure 13.12 A restriction enzyme cuts a double-stranded DNA molecule at the recognition site.

3 Imagine that you are a genetic engineer and need to cut the DNA sequence shown below. Using the four restriction enzymes listed in Table 13.1 (page 183), study the sequence carefully and circle every recognition site that could be cut by each of the enzymes in turn. You may wish to use pens or pencils of four different colours.

- **a** Which of the enzymes produced the most fragments of DNA?
- **b** Write down the recognition site for this enzyme.
- **c** How many fragments of DNA have you created?
- **d** Was any other enzyme useful in cutting the strand of DNA? If so, how many fragments did it produce?

```
                10                  20                  30                  40                  50                  60
CATGGGTACG'CACAGTGGAT'CCACGTAGTA'TGCGATGCGT'AGTGTTTATG'GAGAGAAGAT'

                70                  80                  90                  100                 110                 120
CACGCGTCGC'CTTTTATCGA'TGCTGTACGG'ATGCGGAAGT'GGCGATGAGG'ATCCATGCAT'

                130                 140                 150                 160                 170                 180
ACGCGGCCGA'TCGAGTAATA'TATCGTGGCT'GCGTTTATTA'TCGTGACTAG'TAGCAGTATG'

                190                 200                 210                 220                 230                 240
CGATGTGACT' GATGCTATGC' TGACTATGCT'ATGTTTTTAT'GCTGGATCCA'GCGTAAGCAT'

                250                 260                 270                 280                 290                 300
ATCGCTGCGT' GGATCCCATA' TCCTTATATG' CATATATTCT'TATACGGATC'GAGCACGTTA'
```

4 A process called ligation is used to reassemble the fragments. Name the enzyme involved in this process.

5 Explain why the process of ligation can be viewed as the reverse of the restriction enzyme procedure.

6 In a short summarising statement explain why the discovery of restriction enzymes and DNA ligase has been so important for the advancement of genetic engineering.

ACTIVITY 13.3 Investigating biotechnological techniques

Throughout this course in Human Biology you have had the opportunity to do many activities that have enabled you to inquire scientifically. This activity will allow you to apply some of those skills to investigate a particular biotechnological technique and create your own model of the process.

WHAT TO DO

Working with a partner, or as part of a small group, select either the polymerase chain reaction or DNA sequencing for further investigation. Both techniques have a number of stages that provide logical steps to allow models to be created.

1 Use a variety of references to establish the exact sequence of steps in the technique being investigated.

2 Draw a diagram to clearly illustrate all the steps in the process.

3 A scientific model is a simplified representation of an idea or a process. Using different shapes cut out of cardboard to represent the different parts of the process, build a simple model to demonstrate how the technique you are investigating takes place. Depending on the technique being investigated, your shapes may represent various nucleotides or segments of the DNA molecule. There will be many different ways of presenting the model, so do not be surprised if yours is quite different from others.

4 Present and explain your model to the other members of the class.

Review questions

1 **a** Why was the Human Genome Project set up?
b What have been some of the major outcomes to date?
c Give two examples of other lines of research that have benefited from the Human Genome Project.
2 **a** What is DNA sequencing and what is it used for?
b Briefly outline the steps in building a DNA sequence.
c Name three diseases for which DNA sequencing is a useful technique.
3 **a** What is a 'DNA profile'?
b List two practical applications of DNA profiling.
4 **a** Outline the steps in the polymerase chain reaction.
b Giving an example, explain what the term 'heat stable DNA polymerase' means.
c What are some of the practical applications of the polymerase chain reaction?
5 What is recombinant DNA technology and what is the potential for the technique?
6 Explain, with an example, what a transgenic organism is.
7 **a** What are restriction enzymes?
b List examples of restriction enzymes. For each, give their bacterial origin.
c Differentiate between 'sticky' and 'blunt' ends in relation to restriction enzymes.
8 What is DNA ligase and what is it used for?
9 **a** What are vectors and how are they used in recombinant DNA technology?
b List two different types of vectors that are used in this technology.
10 How has treatment of the following diseases been assisted by recombinant DNA technology?
a Diabetes
b Deficiency of human growth hormone
c Haemophilia A
11 **a** What is a hereditary disease?
b How are mutations associated with hereditary disease?
12 **a** What is gene therapy?
b How is gene therapy likely to advance the treatment of cystic fibrosis and Huntington's disease?
13 **a** Define 'cell replacement therapy'.
b How could cell replacement therapy aid the treatment of diseases such as Parkinson's and Alzheimer's?
14 **a** What is the primary objective of tissue engineering?
b How are scaffolds used in tissue engineering?

Apply your knowledge

1 When the Human Genome Project was launched in 1990 it was expected to take until 2005 for complete mapping to be achieved. However, the results of the project were published in 2001, four years ahead of schedule. Find out what enabled the project to advance much faster than originally anticipated.
2 The Human Genome Project is continuing to make information available about the human genome. Use an Internet search engine to investigate the latest discoveries.
3 How do mutant genes contribute to disease? Discuss the techniques available to detect the presence of a mutant gene.
4 One of the most frequently used ways to sequence DNA is to take advantage of the way DNA replicates. Explain how, if the sequence of bases on one side of a fragment of DNA is known, the sequence on the other side is known as well.
5 With DNA profiling, genetically inherited diseases can be detected at an early age. Discuss the advantages of the early detection of a particular genetic disease.

6 The polymerase chain reaction is a method of amplifying a small amount of DNA into a much larger amount. What are the advantages of being able to do this?

7 The use of blood products sourced from living donors and human growth hormone from cadavers resulted in products that were devised to improve quality of life but which also had life-threatening side effects. Using the Internet, find out the types of diseases that were involved with these contaminated products and how they affected the recipients of those products. How has recombinant DNA technology overcome these life-threatening side effects?

8 One researcher in the United States stated:

> Tissue engineering holds out promise of truly healing the heart after congestive heart failure. … Through tissue engineering we could actually restore the function of the heart by replacing large portions of the damaged heart muscle by a bioartificial one.

This same researcher has been working for a long time on developing the ideal scaffolding to support the injected cells and the architecture of the heart. Use an Internet search engine to find out the type of scaffolding material that is being used in such research and the success that has been achieved to date.

9 In January 2009 it was announced that a woman in Britain gave birth to a baby that had grown from an embryo that had been genetically screened to ensure it was free of the BRCA1 gene. Any girl born with this gene has an 80% risk of developing breast cancer, and the mother was particularly concerned as several of her husband's close female relatives had developed the disease. Discuss the risks and ethical concerns relating to such genetic screening.

10 The impact of biotechnology on our daily lives is growing. Much is being said and written about developments in the use of stem cells to aid the treatment of disease. Hold a class debate to canvas both sides of the question: 'Should the Australian federal government support embryonic stem cell research?' Remember to keep an open mind and respect the opinions of others.

11 Population projections by the Australian Bureau of Statistics indicate that by the year 2051 the proportion of the total Australian population that is aged 65 years or more will almost double. Discuss how the impact of this shift in the age structure of the population will affect diseases of ageing such as Parkinson's and Alzheimer's, with particular reference to the stress it will create for health systems and resources.

CHAPTER

14

EVOLUTIONARY MECHANISMS

UNIT 4 CONTENT

SCIENCE INQUIRY SKILLS

- represent data in meaningful and useful ways; organise and analyse data to identify trends, patterns and relationships; discuss the ways in which measurement error, instrumental accuracy, the nature of the procedure and the sample size may influence uncertainty and limitations in data; and select, synthesise and use evidence to make and justify conclusions

SCIENCE UNDERSTANDING

Mutations

- different genotypes produce a variety of phenotypes, which are acted on differently by factors in the environment, producing different rates of survival
- mutations are the ultimate source of variation introducing new alleles into a population: new alleles may be favourable or unfavourable to survival

Gene pools

- populations can be represented as gene pools that reflect the frequency of alleles of a particular gene; gene pools can be used to compare populations at different times or locations
- gene pools are dynamic, with changes in allele frequency caused by
  - mutations
  - differing selection pressures
  - random genetic drift, including the founder effect
  - changes in gene flow between adjoining groups
- the incidence of genetic disease in particular populations illustrates the effects of different factors on the dynamics of gene pools, including the incidence of Tay-Sachs disease, thalassemia and sickle-cell anaemia
- natural selection occurs when factors in the environment confer a selective advantage on specific phenotypes to enhance survival and reproduction
- the mechanisms underpinning the theory of evolution by natural selection include inherited variation, struggle for existence, isolation and differential selection, producing changes to gene pools to such an extent that speciation occurs

Each individual human is unique. We vary in physical characteristics, as you can see in Figure 14.1, but we also vary in countless ways that cannot be observed, such as blood grouping, resistance to disease, tolerance of heat, cold or pain, and thought processes.

Figure 14.1 Variation in humans

As we saw in Unit 2 of this Human Biology course, variations between individuals of a species are caused by a number of processes, all of which contribute to the inherited characteristics of the individual.

- **Random assortment** of chromosomes during meiosis results in gametes that have a huge number of possible combinations of the chromosomes that originally came from the male parent and the female parent.
- **Crossing over** of chromatids during meiosis may result in pieces of chromatid being broken off and attaching to a different chromatid. This results in a changed sequence, or recombination, of the alleles along the resulting chromosome.
- **Non-disjunction** is where one or more members of a chromosome pair fail to separate during meiosis. This results in gametes that have more or less than the correct number of chromosomes. If such gametes are involved in fertilisation, the resulting embryo will have the incorrect number of chromosomes.
- **Random fertilisation** means that, because each person will produce a huge number of different sperm or eggs with respect to the alleles each contains, and because any sperm can fertilise any egg, there is an almost infinite number of possible combinations of alleles in the offspring.
- **Mutations**, as discussed in Chapter 12, are permanent changes in the DNA of a chromosome and may result in totally new characteristics in an individual. If the mutation occurs in a gamete, it can be passed on from generation to generation.

With respect to evolution, or gradual change of a species' characteristics, mutations are the most important source of variation in individuals. Mutations introduce new and different alleles into the gene pool. If the new allele helps the individual to survive, the allele composition of the gene pool may change.

Changes to allele frequencies in gene pools

Natural selection

In general, the proportion of alleles occurring in a large population is very much the same from one generation to the next. Consider the alleles controlling hair form. If 45% of these alleles in a population were for straight hair and 55% were for curly hair, after a few generations the proportion of these alleles would still be 45% straight and 55% curly. If natural selection is operating on some characteristics at the expense of others, then, over time, the allele frequencies for that characteristic will change. Suppose straight-haired people had a survival advantage over those with curly hair. Over a number of generations the proportion of alleles for straight hair would increase, while the proportion of alleles for curly hair would decrease.

When such a situation occurs, nature is favouring one set of alleles at the expense of others. This selection of favourable alleles is referred to as **natural selection**, which will be discussed in much greater detail later in the chapter. Natural selection is a major cause of changes to allele frequencies in a gene pool.

Random genetic drift

Natural selection is not random. Alleles are not passed on randomly to the next generation. The alleles passed on tend to be the ones that enhance survival and reproduction of the individual and therefore of the species.

In small populations, however, there is often a random, non-directional variation in allele frequencies. This phenomenon is called **random genetic drift** or, sometimes, the **Sewall Wright effect**, after the man who first recognised its significance in causing changes to allele frequencies. It is a purely chance occurrence, a change in allele frequencies that may occur in a very small population. It is much the same as if you had 50 red balls and 50 black ones, with each ball able to reproduce itself periodically. If these 100 balls were placed in a bag and 50 balls selected at random from it, the expected result would be 25 balls of each colour. It would not be surprising, though, to find that your sample contained 30 black balls and only 20 red ones. In this case, after reproducing, your new population would have 60 black balls and 40 red ones. If 50 balls were again selected at random, you would now expect the black ones to be favoured (Figure 14.2). This is how random genetic drift works in small human populations. An allele that is rare in large populations may, purely by chance, become frequent in a small population (Figure 14.3).

Studies have been done on isolated groups to demonstrate this effect. One early and well-known study was by Bentley Glass and his co-workers in the 1950s on an isolated population in the United States. This group, known as the 'Dunkers', lives in Pennsylvania but originally came from Hesse, Germany. They descend from Old German Baptist Brethren who came to the United States in the early eighteenth century. Their religion does not allow them to marry outside their group, and thus they constitute an isolated breeding population within the total population of the United States. The study investigated a number of easily measured physical traits, including the frequency of the ABO, Rh and MN blood groups, mid-digital hair, left- or right-handedness, and attached or free earlobes (Figure 14.4). For most of the traits studied, the Dunkers varied in allele frequency from the present-day population of Hesse and also from the surrounding American population. The environment for both the Dunkers and the surrounding American population is essentially the same, so there would not have been any natural selection to account for the differences in allele frequencies. Therefore, Bentley Glass concluded that genetic drift was responsible for this variation as the small size of the Dunker population allowed certain characteristics to become more common purely by chance.

Genetic drift
This website provides more information about the Dunkers and random genetic drift.

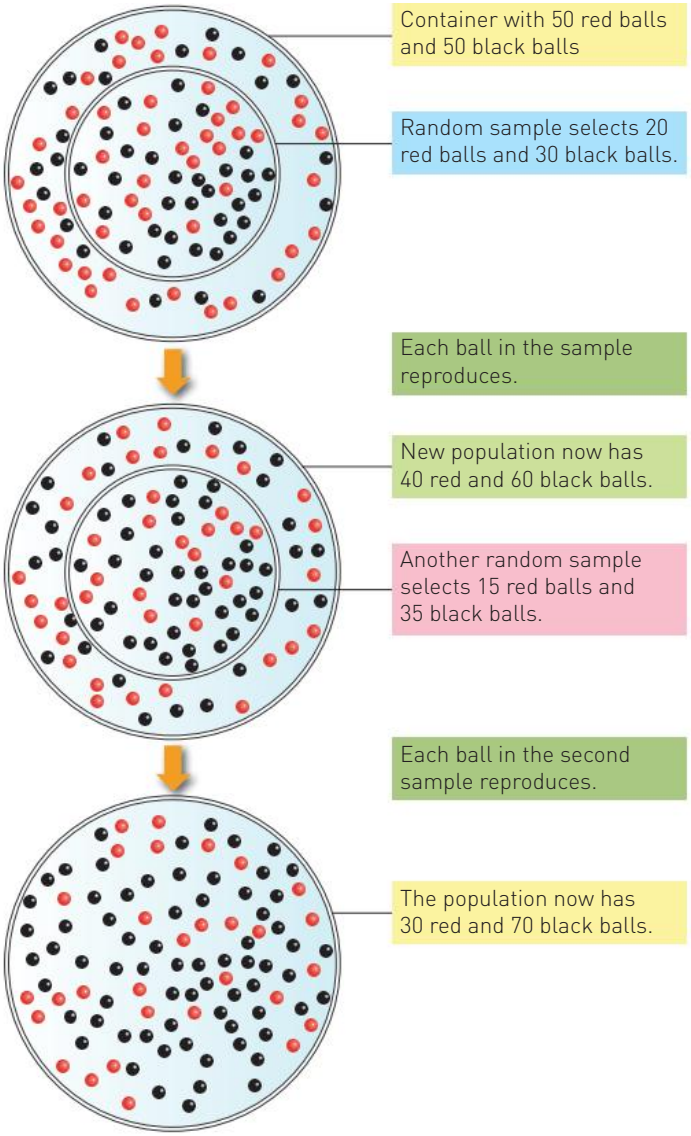


Figure 14.2 A model showing how random sampling of a pair of alleles can, by chance, increase the frequency of one allele and decrease the frequency of the other

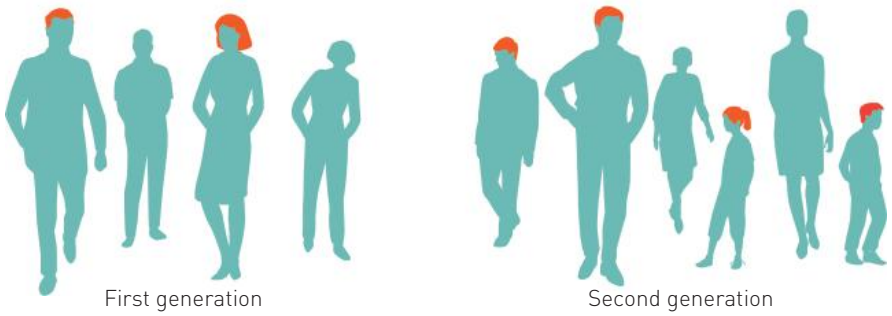


Figure 14.3 Simplified representation of genetic drift in a very small population. If the two red-haired individuals in the first generation mated and had four children, and the other two individuals mated and had only two children, the proportion of red-haired individuals in the population would increase.

iStockphotos/Craft Vision

Figure 14.4 Left-handedness was one of the physical traits observed by Bentley Glass in his study of the Dunkers.

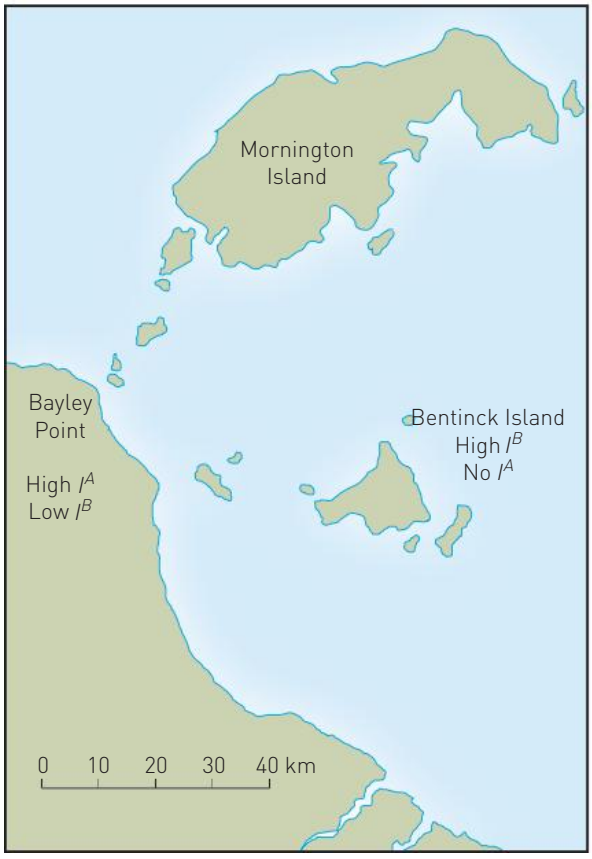


Figure 14.5 Mornington and Bentinck islands in the south-eastern corner of the Gulf of Carpentaria

Similar studies have been carried out on isolated populations of Australian Aborigines. One study investigated the isolated populations of the islands of Bentinck and Mornington in the Gulf of Carpentaria (Figure 14.5). Originally these islands were part of the mainland, but rising sea levels cut them off and the populations they contained became isolated. However, the Mornington Islanders maintained some contact with the mainland by using the smaller islands in between as 'stepping stones'. The blood group frequencies of the islanders have been studied and compared with those of the population occupying Bayley Point on the mainland. The occupants of Bentinck Island show allele frequency values for blood groups that fall outside the range for Aborigines in the rest of Australia. They show a very high proportion of the I^B allele and a complete absence of the I^A allele, unlike the mainland population, which has a low proportion of the I^B allele and a relatively high proportion of the I^A allele.

These examples illustrate the effects of random genetic drift and how it can contribute to changes in the frequencies of alleles in a gene pool. Using allele frequency data alone does not always provide sufficient evidence for the determination of the relationships between populations. Two populations could be closely related, but due to genetic drift in one or both populations, their gene pools could be quite different.

The founder effect

A phenomenon similar to genetic drift is called the **founder effect**. This effect occurs when a small group moves away from its homeland to a totally new area and establishes a community, which later expands. The migrant group, being such a small sample of the original population, is usually not genetically representative of them. This new community, therefore, generally shows features that are not typical of the original homeland population. This is the case with the inhabitants of Pitcairn Island, a small island in the Pacific, populated in 1790 by the descendants of nine mutineers from the *Bounty*, together with six men and twelve women Polynesians from Tahiti. Because of isolation there have been few newcomers to the population and so few alleles have been introduced from outside. The descendants of the original Pitcairn islanders show less genetic diversity than the original parent populations because they are all descended from the small number of original settlers.

Other examples of the founder effect include the island population of Tristan da Cunha and the population of Finland. Tristan da Cunha is an isolated group of islands in the South Atlantic Ocean between South Africa and South America. The current population of the islands can be traced to 15 British immigrants who formed the first permanent settlement in 1816. There have been few migrations since, and there are only seven surnames on these islands, which have about 250 inhabitants. The small founding population and subsequent isolation has produced a gene pool that is quite different from the British population today.

Founder effect
This website provides more information about the founder effect.

In the case of Finland, the current population is believed to have come from a small group of individuals who settled in the south-western part of the country about 2000 years ago. Since that initial migration, the population has remained relatively isolated, with little immigration. Consequently, the gene pool of the Finns is quite different from the gene pools of neighbouring European populations.

In 1775, a typhoon reduced the population of Pingelap, an island in Micronesia, to only 20. These survivors formed the founding population for the current inhabitants. Interestingly, among the survivors was a person heterozygous for achromatopsia. **Achromatopsia** is an inherited form of total colour blindness. The allele for achromatopsia is recessive. Today, after a number of generations, the incidence of achromatopsia on Pingelap is 5% of the population. In other parts of the world it is 0.0033%. Furthermore, 30% of the Pingelap population are carriers; they are not colourblind but they do have the affected allele. This is another example of how allele frequencies can change in small, atypical populations.

The founder effect is illustrated in Figure 14.6.

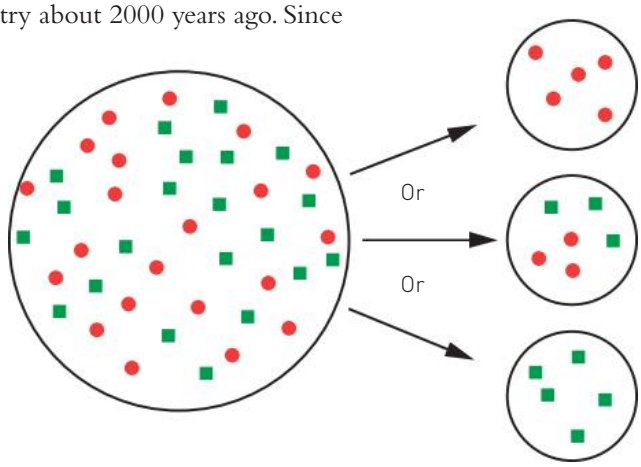


Figure 14.6 A model illustrating the founder effect. The original population is on the left and three different possible founding populations are on the right. It is possible for the founders to be quite unrepresentative of the original population. The chance selection of the founders will have a marked effect on the gene pool of later populations.

Migration

Changes in allele frequencies in a gene pool can also be due to migration. Geneticists describe migration as **gene flow** from one population to another. Therefore, if immigrants to a certain country bring alleles that are not already in the population, the frequencies for the alleles of that gene will be altered. This has occurred in China, for example. In the past, the Chinese population all had the Rh-positive blood group. The Rh, or Rhesus factor, is an antigen found on the surface of red blood cells. People with this antigen are referred to as Rh+; those who do not have the antigen are Rh–. When European countries began trading with China in the sixteenth century, European immigrants and sailors introduced the Rh– allele into the Chinese population. However, the frequency of the allele is still very low in China compared to other countries.

An example of how the distribution of ABO blood groups has been influenced by migration is the change in the frequency of the I^B allele across Europe and Asia. The inhabitants of East Asia, the Mongols, have a proportionately higher frequency of the allele I^B than those living to their west in Europe. In fact, it is thought that most Western Europeans originally did not have the I^B allele at all. In the twelfth and thirteenth centuries, the Mongols invaded Europe on a number of occasions, spreading not only their culture but their genes as well. Today, there is a steady decrease in the I^B allele from Central Asia to Western Europe. Interestingly, the lowest concentrations of the I^B allele are now in the Pyrenees mountains and a few isolated locations in Scandinavia (Figure 14.7).

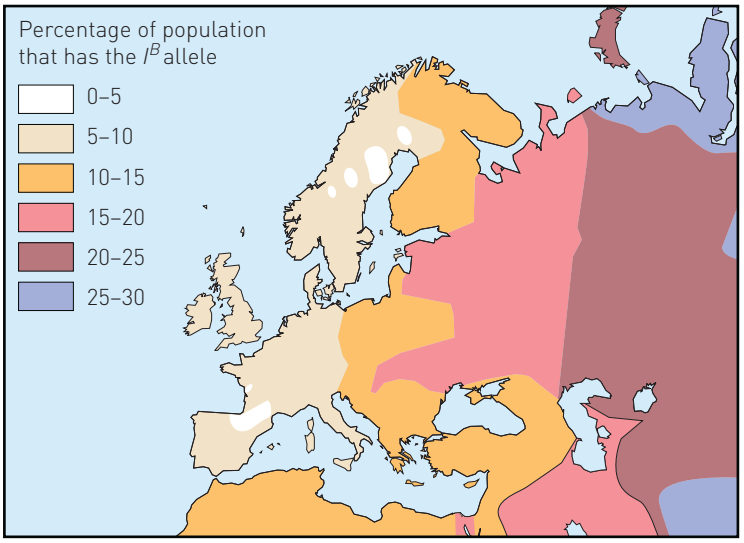


Figure 14.7 Distribution of the allele for the B blood group in Europe

Another situation in which migration has had an enormous influence on the gene pool of a population was the arrival of Europeans in Australia. Prior to colonisation by the British in 1788, the indigenous population of Australia had no contact with European disease and very little of the genetic resistance that Europeans had developed over time. Diseases such as chickenpox, smallpox, influenza and measles spread rapidly throughout the Aboriginal population. It has been estimated that about 90% of the decline in the Aboriginal population was the result of disease. As is frequently the case with infectious diseases, the worst-hit communities were those with the greatest population densities. People living in close proximity to one another facilitates the spread of such diseases. The effect of these diseases not only reduced the size of the Aboriginal population, but also changed the allele frequencies in the population that survived. Survivors were likely to have had some genetic resistance and this would have been passed on to their offspring. Thus, natural selection was occurring, but at the same time interbreeding between Aboriginal people and colonists would have introduced new alleles into the Aboriginal population.

Barriers to gene flow

Populations are often kept apart by barriers that inhibit the amount of interbreeding between them. As no two environments are exactly the same, the environmental pressures on one population will be different from the pressures on the other. This results in slightly different characteristics being favoured in one population compared to the other. In other words, over time the allele frequencies of each gene pool will change, depending on which characteristics are favoured for survival. These changes in each population over many generations result in the populations becoming less alike as they develop characteristics better suited to their respective environments. Isolation results in the development of separate gene pools.

For early human populations the most common barriers to interbreeding would have been geographical ones. **Geographical barriers** include oceans, mountain ranges, large lake systems, deserts and expansive ice sheets. For example, the original inhabitants of Australia were isolated for thousands of years by ocean barriers that formed as sea levels rose.

As human populations developed and became culturally more complex, other types of barriers to interbreeding began to form. Members of different religious groups tended not to interbreed. The same held true for members of groups that spoke different languages. These **sociocultural barriers** are just as effective in isolating groups as geographical ones. Even today such things as economic status, educational background and social position are barriers to interbreeding. For example, statistics indicate that Australians tend to marry people of similar educational background, and members of particular religious groups favour partners who have the same faith.

The Basque people of the Pyrenees in France and Spain have a language that appears unrelated to any other. This has served to unite them and to preserve their cultural identity, even though they share the same religion and occupations as their neighbours. They are characterised by such features as broad foreheads, narrow jaws and distinctive patterns within their blood groups. Thirty-five per cent of Basque people are Rh–, while in the surrounding European population only 16% of people are Rh–.

Genetic diseases

Genetic diseases result in changes to allele frequencies in a gene pool. An allele causing an inherited, fatal disease would be expected to be gradually eliminated from a population because people with the allele would die and would not pass it on to the next generation. This has probably happened many times in the past but sometimes alleles that cause serious disease do persist in certain populations.

The allele that causes Tay-Sachs disease is an example. **Tay-Sachs disease (TSD)** is a hereditary disorder of lipid metabolism that occurs most frequently in individuals of Jewish descent from Eastern Europe (the so-called Ashkenazi Jewish population). Tay-Sachs is caused by a missing enzyme that results in the accumulation of a fatty substance in the nervous system. Death usually occurs by the age of four or five.

As you would expect from a fatal disease, its frequency worldwide is very low, affecting approximately 1 in 500 000 births. However, for the Ashkenazi Jews the incidence is much higher: around 1 in every 2500 births. Scientists have speculated on what could be responsible for such a high frequency of the allele in this population. One suggestion was genetic drift. Jewish populations have tended to be small and isolated, factors that increase the chances of genetic drift. Another explanation is based on the observation that individuals with one Tay-Sachs allele, those who are heterozygous, appear to have increased resistance to tuberculosis (TB). If this is the case, then the heterozygotes would have an advantage in situations where TB is prevalent: individuals with two normal alleles would be more susceptible to TB, and would possibly die, while individuals with two Tay-Sachs alleles would die early in life. Heterozygotes, on the other hand, would have a survival advantage and would be more likely to reproduce and pass their alleles on to the next generation. Due to discrimination, the Ashkenazi Jews often found themselves isolated in overcrowded ghettos under conditions that would increase the threat of TB. In such situations, the frequency of the allele for Tay-Sachs could be maintained in the population.

It is interesting to note that the same mutation that causes Tay-Sachs in Ashkenazi Jews also occurs in the Cajun population of southern Louisiana in the United States. Cajuns are an ethnic group who have been reproductively isolated for several hundred years because of language differences. It has been suggested that the mutation may have entered the Cajun population when a Jewish family assimilated into Cajun society. If this was the case, this is another example of how migration can change the frequency of alleles in a population.

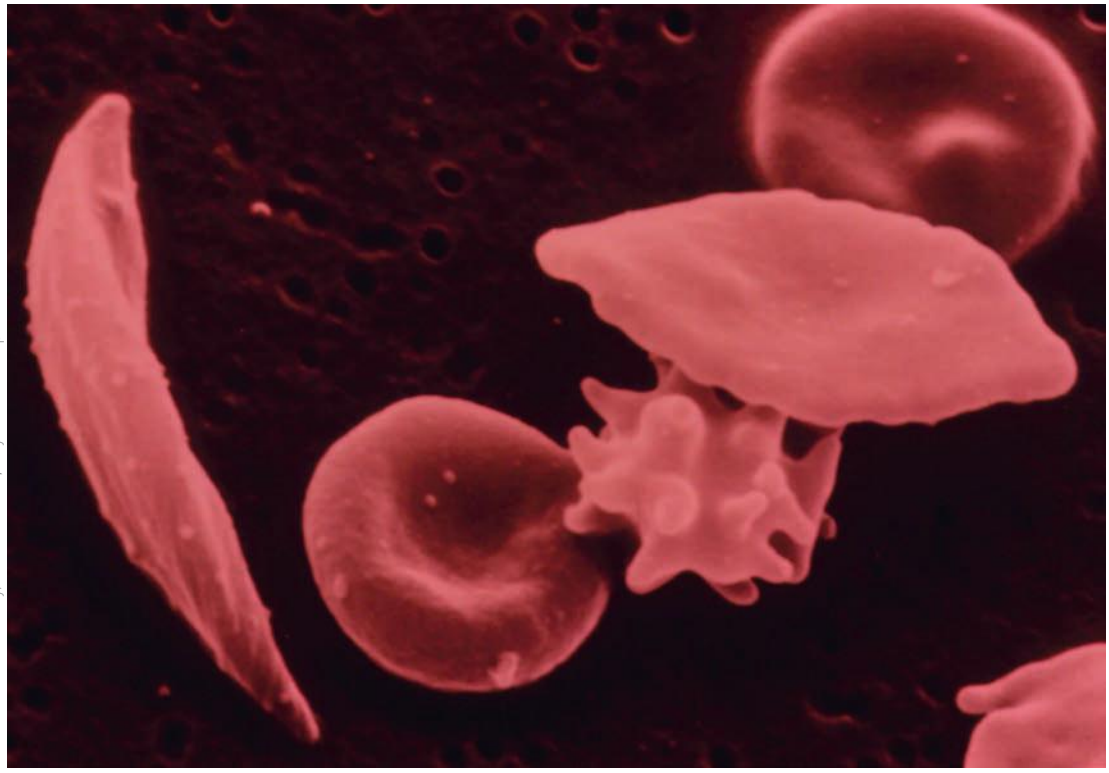
In some regions of the world where populations have been geographically or culturally isolated, marriages between close relatives are common. The probability of having a child with a genetic disease caused by a recessive allele then increases. The related parents have received some of their genes from a common ancestor and, therefore, have a greater chance of being carriers of an allele for the same abnormal condition.

Marriages between cousins were once common among the people inhabiting the countries around the Mediterranean. In these populations, the incidence of **thalassaemia**, a recessive disease in which anaemia results from defects in the formation of haemoglobin, is relatively high. As thalassaemia is most frequent in countries along the Mediterranean coast, in Australia it occurs in people of Mediterranean origin, especially immigrants from Italy and Greece, or their children. People with thalassaemia require frequent blood transfusions throughout their life and special drugs to remove the excess iron that tends to build up in the body.

Tay-Sachs
This website provides more information about Tay-Sachs disease.

Tay-Sachs mutation
This website provides further in-depth information, including about the mutation that causes Tay-Sachs disease.

Another inherited disease is **sickle-cell anaemia**. It occurs mainly in black Africans, or in people of black African ancestry. In the tropical zone of Africa, up to 40% of some populations carry the allele for sickle-cell anaemia. The disease occurs when a person inherits the allele from both parents. It results in the red blood cells being a crescent (or sickle) shape (Figure 14.8). The disease is usually fatal, as the sickle-shaped cells do not carry as much oxygen as normal red blood cells and they also stick together and block small blood vessels. Individuals with only one allele for sickle-shaped cells show no ill effects unless oxygen is in short supply. When this occurs, their red blood cells show mild sickling. These individuals suffer from **sickle-cell trait**. Sickle-cell trait gives certain advantages to those who have it. It provides a degree of immunity to malaria, a disease prevalent in parts of the world where the sickle-cell allele is found. For this reason, the allele is maintained in areas where malaria is present. The way this has occurred will be discussed in greater detail later in this chapter.



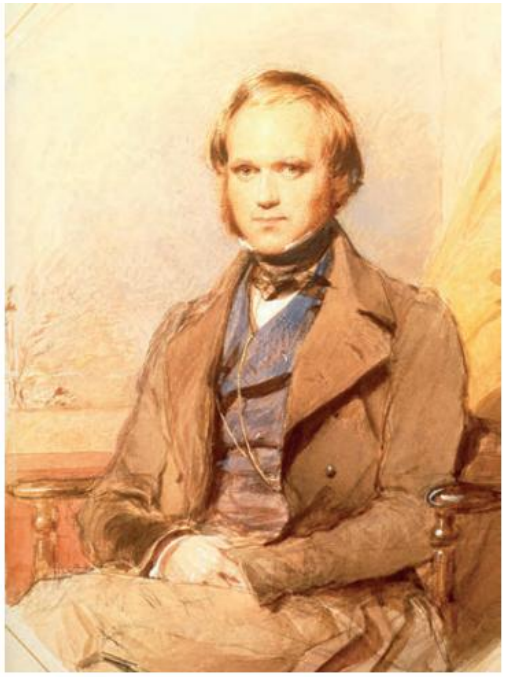
Science Photo Library/Jackie Lewin, Royal Free Hospital

Figure 14.8 Blood of a person with sickle-cell disease. Notice how the red blood cells are distorted and are frequently shaped like sickles.

The theory of evolution through natural selection

There are countless millions of species of plants, animals and micro-organisms living on Earth today. How has this multitude of species come into existence? Until the 1800s it was widely believed that God had individually created each species. This is known as **special creation** and it is still the belief of members of some religious groups. **Evolution** is a gradual change in the characteristics of a species. The theory of evolution through natural selection was put forward independently by Charles Darwin (Figure 14.9) and Alfred Russel Wallace in 1858. However, it is Darwin's name that is usually associated with this theory because of the massive amount of supporting evidence he collected.

Darwin was a keen amateur naturalist and as a young man he joined a surveying expedition as its biologist. He voyaged on HMS *Beagle*, visiting, among other places, the Galapagos Islands, New Zealand and Australia (Figure 14.10). This voyage, and the material Darwin collected, was to be the preparation for all his later work. The Galapagos Islands were especially important for his research. On these islands he was able to observe the differences and similarities between geographically separated animals – those living on the mainland of South America and those on the various islands – and between animals separated by time – animals recently extinct and species still alive. These observations led Darwin to question the commonly held belief that living species had always been exactly the same as they then appeared. He became convinced that species did change. But how did the changes take place?



Getty Images/Science Source

Figure 14.9 Charles Darwin. Together with Alfred Russel Wallace, Darwin put forward the theory of evolution through natural selection in 1858.

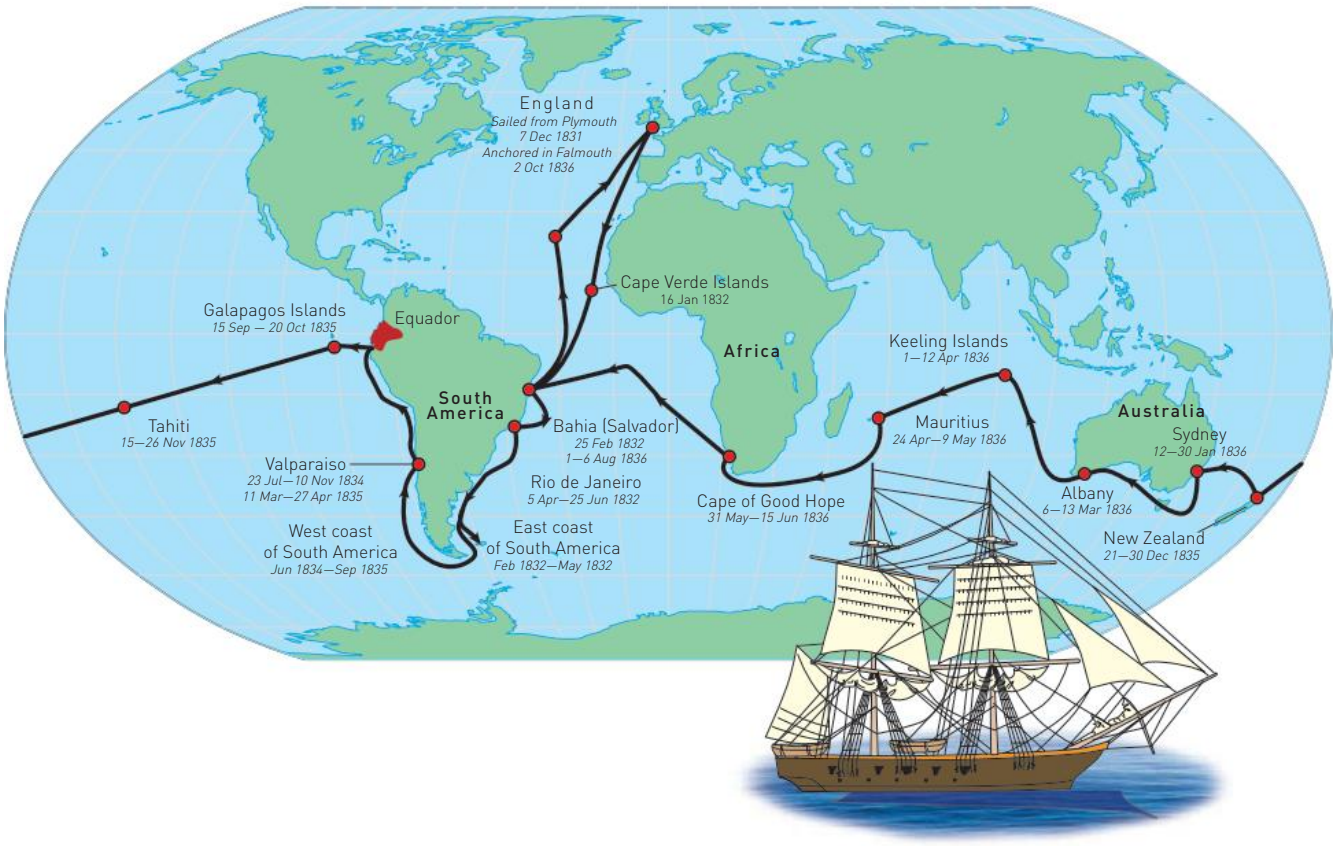


Figure 14.10 The route taken by HMS *Beagle* from December 1831 to October 1836. Darwin's observations on this journey were crucial to his later ideas on natural selection.

Darwin was greatly influenced by the works of other people. Carolus Linnaeus (1707–78) established the basis of our present system of classification and the **binomial system** of naming organisms using the generic (genus) and specific (species) names. This system was important to Darwin as it enabled him to classify and organise the material he collected.

Another major influence on Darwin was a book, *The Principles of Geology*, written by his friend Charles Lyell. Lyell hypothesised that the natural forces existing in the past were much the same as those existing in his own time. This hypothesis implied that the Earth's surface had been gradually moulded over a very long period of time, by such simple forces as changes in temperature, running water and earth movements. Lyell's ideas provided Darwin with a concept of constant change against which he could view his own work.

Thomas Malthus, a British clergyman and political economist, provided the idea for the foundation of Darwin's theory of natural selection. Malthus, in *An Essay on the Principle of Population*, pointed out that the human population was increasing at a rate far exceeding the rate of food production. Drawing on examples from natural populations of plants and animals, he demonstrated that natural reproduction rates exceeded the available resources; that is, more plants and animals are produced than can possibly survive. Darwin realised that under these circumstances a struggle for existence would occur, with favourable variations being preserved and unfavourable ones being gradually lost from the population.

In 1858, Darwin received a copy of an essay by Alfred Russel Wallace, a naturalist then on the island of Fernate in Indonesia (then the Dutch East Indies). Wallace's essay, *On the Tendency of Varieties to Depart Indefinitely from the Original Type*, covered the same ideas that Darwin had been working on. Darwin had been collecting evidence and refining his ideas for 20 years but Wallace's essay was the stimulus for him to publish his views. A joint essay was prepared by Darwin and Wallace and read before the Linnean Society in 1858.

A year later Darwin published his first book, *On the Origin of Species*. This book – the first edition of 1250 copies was sold out on the first day – created a storm of controversy, but with the support of other scientists Darwin's ideas became firmly established.

Darwin's theory of natural selection was based on three observations.

1. *Variation*: Darwin noted that all members of a species vary. He made no attempt to explain the source of this variation. However, he did point out that these variations were passed on from one generation to the next, characteristics displayed by the parents being passed on to their offspring.
2. *Birth rate*: inspired by Malthus, Darwin realised that all living organisms reproduce at a rate far greater than that at which their food supply and other resources increase. This would normally result in overcrowding.
3. *Nature's balance*: Darwin observed that, although the birth rate of organisms was very high, each species' numbers tended to remain at a relatively constant level.

From these three observations, Darwin made a number of interpretations. First, he realised that, because of the excessive birth rate and limited resources, there must be a **struggle for existence**; and, second, because there was a range of variations in any species, those with characteristics best suited to their environment were more likely to survive. This second point became known as the **survival of the fittest**: more organisms with favourable characteristics survived, while many of those with unfavourable characteristics died before they had an opportunity to reproduce and pass on the unfavourable characteristics.

Survival of the fittest is possible because there is **variation** within any species. That is, the members of a species differ from one another in their physical characteristics, body functioning and behaviour. Many of these variations are inherited but Darwin was unable to explain the origin of the variations he observed in species. We now know that much of the variation that can be seen in a population is due to the effects of meiosis and fertilisation, and the simple principles first proposed by Mendel. Mendel studied characteristics that were determined by one pair of alleles.

Many characteristics of organisms are controlled by more than one pair of alleles and this leads to a huge range of variation.

New variations, showing no resemblance to either parent, may occur quite suddenly and purely by chance. Characteristics occurring like this are referred to as mutations. As mentioned in Chapter 12, there are relatively few mutations present in human populations, but those that do occur sometimes generate characteristics better suited to a particular environment, and so contribute to survival of the human species.

With knowledge of the mechanisms of inheritance, scientists building on the work of Darwin were able to explain the process of natural selection far more satisfactorily. Today natural selection can be viewed as the selection of those alleles in a population that give an organism a greater survival advantage. Those organisms that survive will pass on favourable alleles to their offspring. Gradually, over a period of time, the characteristics of a population change so that it becomes better suited to its environment. In addition, where the environment is gradually changing, characteristics that enhance survival enable succeeding generations to gradually adapt to it. An important point to note is that individual organisms do not adapt. The species adapts to its environment by natural selection, and the process of adaptation takes many generations.

We can now look at the process of natural selection in terms of the frequencies of alleles in the gene pool of a population. If the environment tends to favour a particular characteristic, more of the alleles for that trait will be passed on to the next generation. This will result in a change in the frequency of that allele in the gene pool. Over time, that characteristic becomes more frequent in the population.

Charles Darwin
This website provides an interesting perspective on Charles Darwin and the impact of his work.

A summary of the principles of evolution through natural selection

1. There is variation of characteristics within a species.
2. More offspring of a species are produced than can possibly survive to maturity.
3. Because of excessive birth rate and limited resources, there is a struggle for existence – competition for survival.
4. Individuals with characteristics best suited to the environment have more chance of surviving and reproducing – survival of the fittest.
5. Favourable characteristics (those with survival value) are passed on to the next generation.
6. In the gene pool, the proportion of alleles that produce favourable characteristics gradually increases.

Examples of natural selection in humans

The environment of early humans must have had a profound effect upon the characteristics that were selected as the most suitable for survival in the region where they lived. As a result, there are features of the human body that appear to correlate well with the environments in which they occur. Human body shape or stature, for example, can be correlated with resistance to the cold.

Body stature

Initially, the human gene pool would have contained alleles for a whole range of statures, from the short-bodied, long-limbed physique of present-day black Africans, to the long-bodied, short-limbed stature of the Inuit (Eskimos) of today (see Figure 14.11 on page 206). Individuals with long bodies and short limbs have a smaller surface area in relation to body volume than those with short bodies and long limbs. Such individuals lose less heat in very cold environments and

Getty Images/George Holton

Getty Images/Mitch Kezar

Figure 14.11 Differences in body stature between **a** Inuit (Eskimos) and **b** Africans. Body stature appears to correlate well with resistance to the cold.

would therefore have a survival advantage. When individuals of this type reproduced, they would have passed on the alleles for long bodies and short limbs to their children. They too would have had a survival advantage and would pass on the favourable alleles to their offspring. As fewer of the short-bodied, long-limbed individuals would survive in the extreme cold, fewer of the alleles for these characteristics would have been passed on. Many individuals with less-favourable characteristics would have died before reproductive age, so the frequency of unfavourable alleles in the gene pool would gradually decrease. Over time those alleles would have decreased to such an extent that the unfavourable characteristics would no longer occur in the population. In this way, the frequency of alleles controlling body stature in the population would have changed. Those controlling long bodies and short limbs would have increased, while those for short bodies and long limbs would have decreased. Thus, evolution or genetic change has taken place. Within a particular gene pool, the frequencies of the alleles have changed over time.

Similarly, long limbs and short bodies would have evolved in very hot climates. Individuals with a larger ratio of surface area to body volume would have had a survival advantage.

Sickle-cell anaemia

The incidence of sickle-cell anaemia in different parts of the world is another example of natural selection operating in human populations. The *Anopheles* mosquito, which transmits the malarial parasite, is not normally an inhabitant of tropical forests. It needs quiet, stagnant pools of water for breeding sites. This habitat is more often found in open areas. As humans began to clear the forests of Africa for agriculture, they changed the environment in a manner that created additional breeding areas for *Anopheles* mosquitoes. The increased food supply from agricultural production allowed the human population to increase, providing more bodies on which the mosquito could feed. Thus the incidence of malaria increased. Figure 14.12 shows the distribution of malaria throughout the world.

In 1910, a young West Indian student living in Chicago visited his doctor with a variety of symptoms, including clogged blood vessels, pneumonia, rheumatism, heart disease, inflammation of the hands and feet, and anaemia. His doctor took a blood sample and observed it under a microscope. When air was excluded from the sample, the red blood cells showed a dramatic change in their shape from round to a crescent-like, or sickle, shape (see Figure 14.8). Subsequent investigation showed that sickle-cell disease, or sickle-cell anaemia, results when a person is homozygous for a particular recessive allele. As discussed earlier (page 202), heterozygotes normally show no ill effects unless oxygen is in short supply. When this occurs, their red blood cells show mild sickling. These individuals are carriers and are said to have sickle-cell trait. Individuals homozygous for the normal dominant allele have blood that shows no signs of the sickling phenomenon.

Sickle-cell anaemia
This website provides more information on the changes to haemoglobin with sickle-cell anaemia.

It is now known that sickle cells are formed because of a mutation of the gene responsible for the production of normal haemoglobin. Haemoglobin, the pigment found in red blood cells, is a protein that contains iron. The mutant allele responsible for the sickle shape of the affected red blood cells causes the substitution of one amino acid (valine) for another (glutamic acid) during the formation of the haemoglobin protein. The mutation affects only one of the 287 amino acids in the haemoglobin molecule, but this change is enough to affect the functioning of the red blood cell. The affected haemoglobin is often referred to as haemoglobin S, and cells that contain it collapse into sickle shapes at low oxygen concentration. Individuals homozygous for this mutant allele suffer from sickle-cell anaemia, a disease that is usually fatal.

If a person with sickle-cell anaemia dies before reproducing, the allele that causes the disease is not passed on to the next generation. Therefore, you would expect that over many generations the frequency of the sickle-cell allele would gradually decrease until it was eliminated from the population altogether. On the other hand, if the rate of mutation of normal alleles to sickle-cell alleles was great enough, it could cancel out the loss of alleles through the death of affected individuals. However, this is not the case: investigations have shown that the rate of alleles being lost from the population is about 100 times greater than the average rate of mutation at any point along a human chromosome. Some other mechanism must be at work to maintain the sickle-cell allele in the population. Figure 14.13 shows places in the world where the sickle-cell allele occurs in the population. Compare this with Figure 14.12. Notice how the sickle-cell allele occurs only in areas where malaria is prevalent.

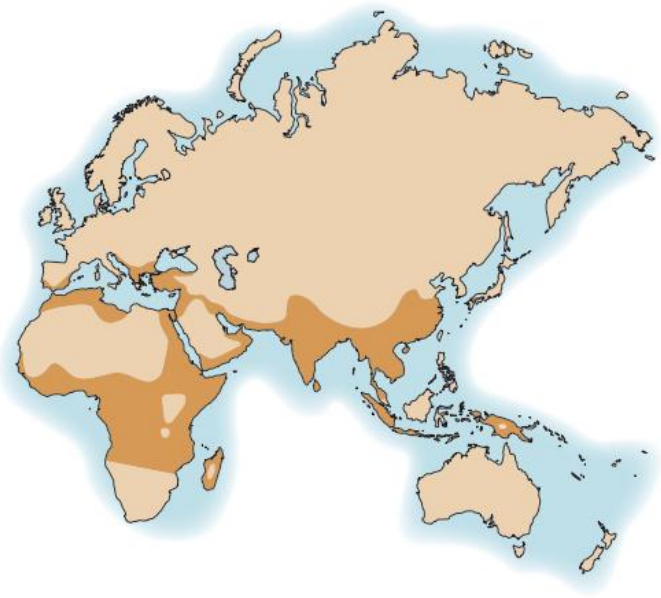


Figure 14.12 The distribution of malaria

Figure 14.13 The distribution of sickle-cell anaemia

Anthony Allison was one of the first to notice the relationship between sickle-cell anaemia and malaria. He reported his observations in the *British Medical Journal* in 1954, noting that the sickling allele tended to have its highest frequency in areas where the risk from malarial parasites was greatest. He suggested that individuals with one sickle-cell allele were more resistant to malaria than those with normal haemoglobin in their red blood cells. This conclusion was based on Allison's observations that malarial patients who were also 'sicklers' had fewer malarial parasites than did malarial patients who were 'non-sicklers'. To gather evidence in support of these observations, Allison conducted a number of experiments. He inoculated both sicklers and non-sicklers with malaria and then treated those individuals in whom the disease developed. His results confirmed that the heterozygotes were less susceptible to infection from malaria than individuals homozygous for normal haemoglobin. Further studies since Allison's pioneering experiments have supported his findings. It is now generally accepted that individuals heterozygous for the sickle-cell allele have a survival advantage in areas where malaria is prevalent.

Genetic diseases
This website provides more information about sickle-cell anaemia and other genetic diseases that appear to aid survival.

The sickle-cell example shows how natural selection occurs in human populations. A favourable mutation established a new allele in the population. Having one of these alleles gave individuals living in malarial-prone areas a survival advantage. Individuals with two sickle-cell alleles, those with sickle-cell anaemia, usually die. Those who are homozygous for normal haemoglobin are more susceptible to malaria. So the presence of malaria acted as a **selective agent** for the sickle-cell allele.

EXTENSION

One of the best researched investigations into natural selection is the work of a British geneticist, Henry Bernard Davis Kettlewell, on the peppered moth, *Biston betularia*.

The peppered moth gets its name from the scattered dark markings on its otherwise pale wings and body. The moth flies at night and rests by day on tree trunks. These trunks are usually encrusted with lichens and the pale-coloured moth is practically invisible against this background.

However, in 1849, a coal-black mutant form of the moth was found near Manchester in England. Within a century, this black form had increased to 90% of the population in this region.

The change in allele frequency that occurred in this example is a good model of how natural selection takes place.

Find out:

- how the black form of the moth became the more prevalent variant
- which form is the most prevalent today.

Speciation

Earlier in this chapter, isolation was mentioned as a barrier to gene flow. Reproductive isolation may lead to the development of separate gene pools. No two environments are exactly the same, so it would be expected that different alleles would be favoured in one environment more than another. Therefore, over time the allele frequencies of each gene pool will change, depending on which characteristics are favoured for survival. Over many generations, the populations will become less and less alike as they develop characteristics that better suit them to their respective environments (Figure 14.14).

If two populations are isolated for a very long period of time, and the environmental influences on each are different enough, major changes in the allele frequencies within each population could occur. In such a situation, the members of those populations may become so different that, even if the barriers to reproduction were removed, interbreeding would no longer be possible. If this

occurred, the two populations would be regarded as separate species. The process of producing two species in this way is referred to as **speciation**.

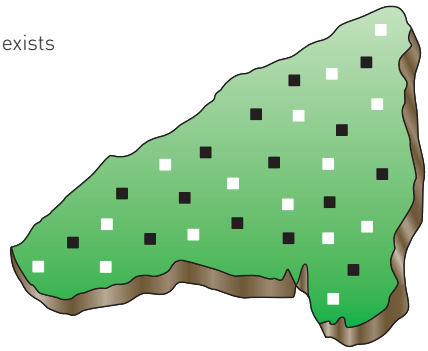
Humans are all the one species, but in the past there have been various species on the pathway to modern humans. These species are known only from the fossils that have been found and there is conjecture over their classification (see Chapter 19). However, the groups of humans with differing physical characteristics observable today have all formed through the processes described above.

Speciation
This website provides an animation about the mechanisms of speciation.

WS

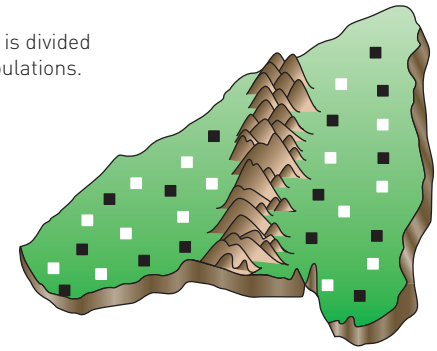
Evolutionary mechanisms

a Variation
A population exists on an island.



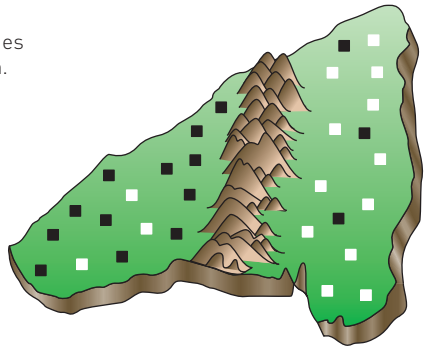
A range of **variations** exists within the population, which shares a **common gene pool**.

b Isolation
The species is divided into two populations.



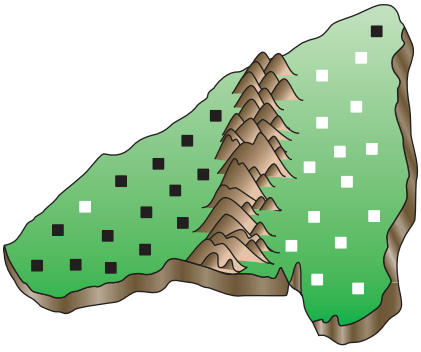
A **barrier** has formed, dividing the population into two. No interbreeding occurs between the two populations. Each population has a **separate gene pool**.

c Selection
Two subspecies begin to form.



Different **selection pressures** act on each of the two populations over a number of generations. This brings about a change in the **gene frequencies** of each gene pool. Such changes lead to the evolution of separate **subspecies**.

d Speciation
Two species now exist.



Over a long period of time the changes in the gene frequencies may be great enough to prevent the production of fertile offspring by interbreeding between the two populations from ever occurring again. When this happens, *two* **species** exist.

Figure 14.14 A diagrammatic representation of variation, isolation, selection and speciation

Science inquiry

ACTIVITY 14.1 A model of genetic drift

Genetic drift occurs only in small populations, so take as the starting point of our model the smallest possible breeding population: two individuals, a male and a female. Both happen to be albinos and both are therefore homozygous for the allele *a*. Thus, the hypothetical population has only the *a* allele. This activity will investigate how genetic drift may change this allele frequency over time.

YOU WILL NEED (FOR EACH PAIR)

8 beads, cards or counters of one colour (such as black); 8 beads, cards or counters of a second colour (such as white)

WHAT TO DO

1. Place two white beads on the table to represent the two alleles possessed by the female, and two more white beads to represent those possessed by the male.
2. If a mutation were to occur in one of the alleles of the male, he would become heterozygous. For our model, one of his *a* alleles is replaced by *A*. Simulate the mutation by replacing one of the white beads of the male with a black bead.
3. During meiosis, the chromosomes separate and therefore the genes in that chromosome separate as well. These separated chromosomes duplicate and separate to form four gametes. Separate your pairs of beads and duplicate them so that you have eight gametes, four for the female (all white – *a* alleles) and four for the male (two white – *a* alleles and two black – *A* alleles).
4. If mating occurs and one offspring is produced, calculate the probability that it will have the mutant *A* allele.
5. Calculate the probability that if two offspring are produced, that they will both have the mutant *A* allele.
6. Now consider the situation where a large number of offspring are produced. What proportion would you expect to be albino (*aa*) and what proportion normal pigmentation (*Aa*)?
7. To continue with our model, we will assume only two offspring were produced, one of each sex, and they both had normal pigmentation. Put two pairs of beads in front of you to represent these individuals – each pair should have one white bead and one black bead.
8. Simulate meiosis again by separating the beads, duplicating them and separating them again to form the gametes.
9. Calculate the probability of getting an individual homozygous for normal pigmentation (*AA*) if offspring of the parental generation were to mate.
10. Determine the probability that an offspring could be heterozygous for normal pigmentation (*Aa*).
11. Work out the probability that an individual in this generation from the offspring of the original survivors will have at least one *A* allele.

STUDYING YOUR DATA

1. If we assume that the original parents and their children died soon after producing their offspring, what is the frequency of the *A* allele in the third generation?
2. How does this compare with its frequency in the original generation?
3. Explain how, in this model of genetic drift, a further generation could be produced in which the *a* allele could be entirely eliminated.

IN SUMMARY

Our model has been based on a number of assumptions, and so the effects of genetic drift have been exaggerated. However, you have seen how by certain chance events (hence the term 'random genetic drift') a mutant allele can become established in a small population regardless of natural selection.

4 Explain why genetic drift can only occur in a very small population.
5 What barriers exist in the world today that might isolate small groups of humans and hence promote conditions in which drift can occur?

ACTIVITY 14.2 Sickle-cell haemoglobin

In an article published in the *British Medical Journal* in 1954, A. C. Allison first put forward the hypothesis that the possession of the sickle-cell allele may have a selective advantage in areas where malaria is prevalent. In investigating this proposition, Allison inoculated 30 African adult male volunteers with malaria and then observed them for 40 days. At the end of the period of observation he treated all the participants with a prolonged course of antimalarial chemotherapy.

Allison's volunteers were of similar age and none had been in an area where malaria occurred for at least 18 months. They all appeared to be comparable except for the presence or absence of the sickle-cell allele. His results are shown in Table 14.1.

Table 14.1 Allison's results from the inoculation of Africans with malaria

	Number of participants	Developed malaria	Did not develop malaria
With a sickle-cell allele	15	2	13
Lacking a sickle-cell allele	15	14	1

INTERPRETING THE RESULTS

1 What was Allison's dependent variable? What was his independent or experimental variable?
2 What factors did Allison appear to control in his experiment?
3 Which group of subjects was the control group, and which the experimental?
4 Did Allison's results support his hypothesis? Explain why you think so.
5 Do the results Allison obtained suggest a reason why the sickle-cell allele has survived in Africa?
6 Refer to Figures 14.12 and 14.13. Does the information provided in these figures support your answer to Question 5? Give reasons for your answer.
7 Explain how the high incidence of the sickle-cell allele in parts of Africa could be considered an example of natural selection.
8 Would a university ethics committee today be likely to approve an experiment such as the one that Allison performed? Give reasons for your answer.

Allison's article describing his investigation

ACTIVITY 14.3 Modelling natural selection

In this activity you will model the effects of natural selection on a hypothetical population of frogs. The frogs are naturally green, yellow or orange in colour, and are preyed upon by water birds. You will simulate the different predation rates on the three variations of frog colour over a number of generations by throwing a die.

YOU WILL NEED (FOR EACH GROUP)

Coloured cards or counters – 30 green, 30 yellow and 30 orange; a die

WHAT TO DO

1 Draw up a table similar to Table 14.2 to record your results.

Table 14.2 Data sheet

Generation number	Green frogs	Yellow frogs	Orange frogs
1	10	10	10
2			
3			
4			
5			
6			
7			
8			
9			
10			

2 From the pool of coloured cards, select 10 of each colour. These will be your first generation of frogs. Shuffle the cards so that they are well sorted, and then deal them out in pairs. You should have 15 pairs of cards representing 15 pairs of frogs.

3 We will assume that each pair of frogs consists of a male and a female, and that each pair produces only one offspring. The pairs produce offspring according to the following rules.

- Two green frogs produce a green offspring.
- Two yellow frogs produce a yellow offspring.
- A green frog and a yellow frog produce an orange offspring.
- Two orange frogs produce a colour that can be decided by the throw of a die.
  1 = a green offspring
  2 = a yellow offspring
  3 or 4 = an orange offspring
  5 or 6 – throw the die again until you get a 1, 2, 3 or 4.
- A green frog and an orange frog produce a colour that can be decided by the throw of a die.
  1, 2 or 3 = a green offspring
  4, 5 or 6 = an orange offspring.
- A yellow frog and an orange frog produce a colour that can be decided by the throw of a die.
  1, 2 or 3 = yellow
  4, 5 or 6 = orange.

4 Because their colours do not blend into the background so easily, yellow and orange frogs are more likely to be preyed upon by birds than are the green frogs. Simulate predation in your population of 45 frogs. Fifteen of the frogs are to be taken as prey. Throw a die 15 times and for each throw remove one frog according to the following rules.

- If 1, 2, 3 is thrown, remove a yellow frog.
- If 4 or 5, remove an orange frog.
- If 6, remove a green frog.

5 You should have 30 cards remaining. This is your second generation of frogs. Count the cards and record the number of each colour in the table.

6 Shuffle the cards well and repeat steps 3, 4 and 5 to get the third generation. Record your results in the table.

7 Continue the process until all the frogs are the one colour, or until you have completed 10 generations.

STUDYING YOUR RESULTS

1 Which colour frog became the most frequent in the population? Why do you think this was the case?
2 Which colour frog was eliminated first? Explain why this occurred.
3 Compare your results with other groups in the class. Have all groups obtained similar results? How much variation was there in the results between the different groups?

INTERPRETING YOUR RESULTS

1 How has this activity modelled the process of natural selection? In your answer describe what was creating the selection pressure on the population of frogs.
2 Explain why there was variability, if any, between the groups in your class.
3 What changes would you have to make to predation by the water birds to achieve a completely orange population of frogs? Repeat the activity with your changed parameters. Was your prediction correct?
4 Over several generations, what would happen to the composition of the frog population if water birds preyed equally on the three frog colours?
5 Write a summarising paragraph, using the principles of natural selection, to link the breeding patterns of the frogs and predation by water birds.

Review questions

1. How do new variations arise in a population? Give a brief description of the ways in which this may occur and the genetic structures involved.
2. **a** Explain what 'random genetic drift' is.
   b Select a modern population in which genetic drift is thought to have had an effect and describe why this might be the case.
3. Briefly describe the significance of the founder effect in human evolution.
4. Explain why geneticists think of migration as gene flow from one population to another.
5. List the common barriers that may lead to the isolation of one gene pool from another, and give examples of each type.
6. **a** List five different kinds of sociocultural barriers to gene flow, and describe how each is thought to act.
   b Outline the importance of gene flow for human evolution.
7. Using the example of Tay-Sachs disease, explain how genetic diseases can lead to changes in allele frequencies in a population.
8. Outline the main points of Darwin's theory of natural selection. Include an explanation of the terms 'struggle for existence' and 'survival of the fittest'.
9. Explain how the following people contributed to Darwin's theory of natural selection.
   a Linnaeus
   b Malthus
   c Lyell
10. Once the mechanisms of inheritance were understood, the theory of natural selection was modified to account for this new knowledge. Outline briefly the way natural selection is now thought to operate.
11. People of short stature tend to live in cold climates, and people with long limbs and short trunks tend to live in hot climates. Explain how these adaptations to cold and hot environments could have come about.
12. **a** What is sickle-cell anaemia? Explain why it is usually lethal.
    b List the advantages and disadvantages of having the sickle-cell trait in an area where malaria is prevalent.
13. Explain what 'a selectively advantageous mutation' means.
14. How could isolation lead to selection and speciation?

Apply your knowledge

1. Malthus claimed that species of organisms always produce more offspring than the existing resources can support. Is this true of the human species in the past or at present? Is it likely to be true of the human species in the future?
2. During the fourteenth century, plague epidemics drastically reduced the human population of Europe. Use this as an example to describe the way natural selection operates so that only the fittest tend to survive.
3. Using the concepts of natural selection and of gene pools, describe how a new variation could arise in a population and then become frequent within that population.
4. According to a recent report, 13% of Scotland's population are redheads. Two out of every five Scots carry the allele for red hair. However, only 2% of the world's population are estimated to be natural redheads.
   a Suggest a reason for the high frequency of the allele for red hair in the gene pool of the Scots.
   b In the population of Scotland, what do you think will happen to the frequency of the allele for red hair over time? Give reasons for your answer.

5 Today, humans adapt culturally to environmental change. Does natural selection affect cultural characteristics?

6 A team of American scientists has been trying to develop a vaccine to give permanent immunity against malaria. What do you think will happen to the frequency of the sickle-cell gene within a population if this vaccine is effective? In writing your answer, ensure that you explain the adaptive value of the various genotypes and the selection pressures on each.

7 Describe the barriers to gene flow that exist for the following populations.
- **a** Groups in South Africa
- **b** Groups in the islands of Polynesia, such as New Zealand, Tahiti and Hawaii
- **c** The Jewish people

8 Using analysis of mitochondrial DNA, researchers have determined that all humans are descended from a woman who lived in Africa 200 000 years ago – the so-called mitochondrial Eve. If we are all descended from a common ancestor, how is it that there are so many different types of humans today? Describe the processes that must have taken place to produce the differences between present-day groups of humans.

9 Consider the population of the city in which you live, or the nearest large city to you. Do you think there are isolated breeding groups within that population? If there are, describe the mechanisms that tend to isolate them, and say whether you think they will continue to operate in the future.

10 Speculate on what might be the long-term effect on allele frequencies if a mutation suddenly produced a favourable allele that gave a natural resistance to all forms of heart disease.

11 Describe the process involved in producing two separate species from a common gene pool.

CHAPTER

15

EVIDENCE FOR EVOLUTION

UNIT 4 CONTENT

SCIENCE INQUIRY SKILLS

- conduct investigations, including the use of virtual or real biotechnological techniques of polymerase chain reaction (PCR), gel electrophoresis for deoxyribonucleic acid (DNA) sequencing, and techniques for absolute and relative dating, safely, competently and methodically for valid and reliable collection of data

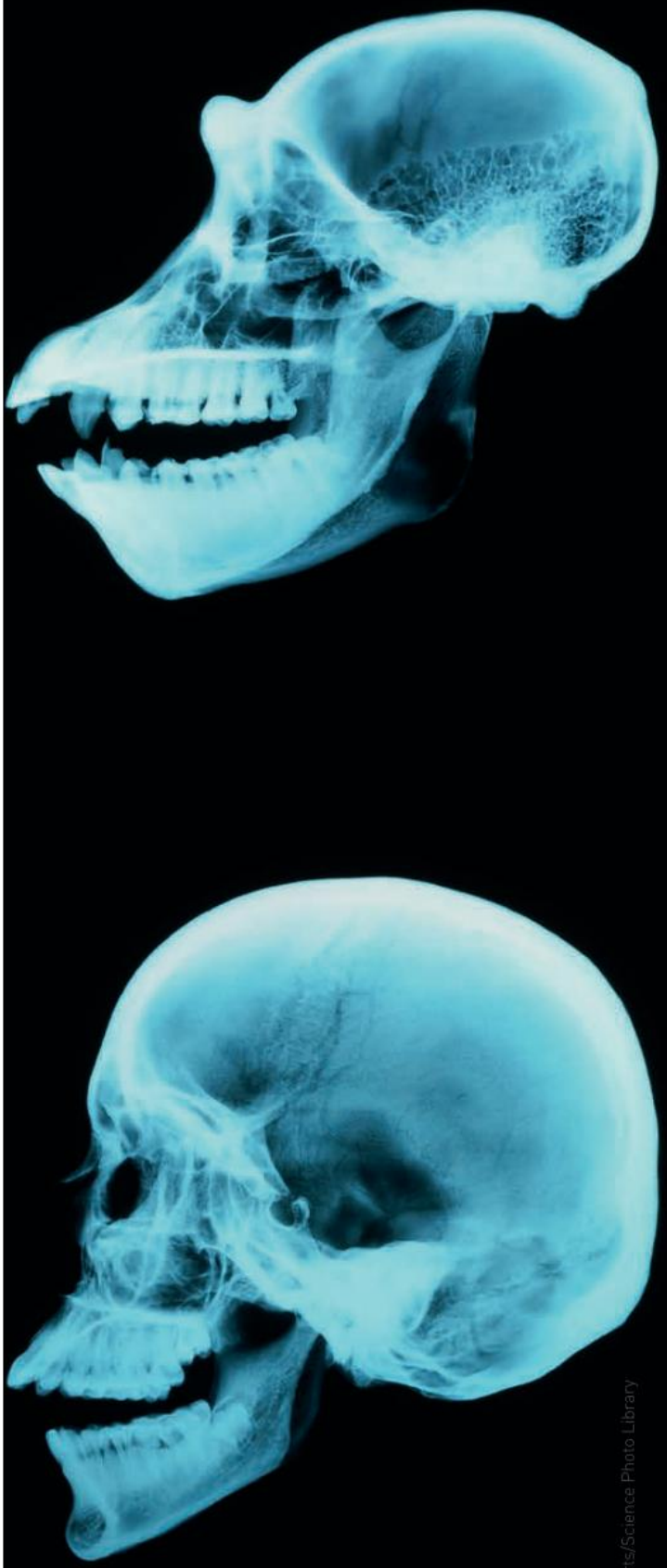
SCIENCE AS A HUMAN ENDEAVOUR

- developments in biotechnology have increased access to genetic information of species, populations and individuals, existing now or in the past, the interpretation and use of which may be open to ethical considerations
- developments in the fields of comparative genomics, comparative biochemistry and bioinformatics have enabled identification of further evidence for evolutionary relationships, which help refine existing models and theories

SCIENCE UNDERSTANDING

Evidence for evolution

- biotechnological techniques provide evidence for evolution by using PCR (to amplify minute samples of DNA to testable amounts), bacterial enzymes and gel electrophoresis to facilitate DNA sequencing of genomes
- comparative studies of DNA (genomic and mitochondrial), proteins and anatomy, provide additional evidence for evolution; genomic information enables the construction of phylogenetic trees showing evolutionary relationships between groups



X-rays comparing a chimpanzee skull (top) with a human skull (bottom)

The great majority of scientists accept the general idea of evolution – the gradual change in the characteristics of a species over many generations. However, this idea has always been controversial and there are still many people who, for a variety of reasons, do not accept the idea that species evolve. It is important, therefore, to look at the sorts of evidence available to support the theory of evolution. Besides the study of fossils, much of the evidence for evolution has come from comparative studies. Traditionally, the focus for comparative studies has been on anatomy and embryology, but the development of technology in more recent times now allows comparative studies to be conducted on both proteins and DNA.

The same evidence that demonstrates that evolution of living things does occur can also be used to chart the course of evolution. In this chapter we look at anatomical and biochemical evidence that can be used in both ways – to demonstrate that evolution has, and is, occurring, and to show the pathway that evolution has taken. In the next chapter we look at fossil evidence that can be used in similar ways.

Comparative studies in biochemistry

DNA

DNA (deoxyribonucleic acid) is the chemical compound that makes up the genes and it is DNA that determines the type of proteins a cell can make. The DNA molecule contains hundreds of nitrogen bases, which are of four types – adenine, cytosine, guanine and thymine. A sequence of three of these bases in the DNA molecule is the code for one particular amino acid in a protein. Scientists have determined that all living things use the same DNA code, adding weight to the hypothesis that all living things are related to each other and have evolved from a common ancestor.

Although all species of organism have DNA, the sequence of bases in the DNA varies. New genes are gained by mutation; others are lost by natural selection, genetic drift or some other process. Despite the common ancestor, the code in the DNA is different for different species.

When speciation occurs (an ancestral species giving rise to two or more new species), the new species would have very similar DNA. However, as the new species gradually change through the processes described in Chapter 14, they accumulate more and more differences in their DNA. Species that are more distantly related have more differences in their DNA, whereas species that are more closely related share a greater portion of their DNA.

The complete set of DNA in each cell of an organism is called the **genome**. Examination of the genome of our closest living relatives, the chimpanzees, shows that they share more than 98% of our DNA (Table 15.1). Scientists quote slightly higher or lower figures depending on what exactly is being compared. Interestingly, humans have 23 pairs of chromosomes while chimpanzees have 24 pairs. Scientists believe that this can be explained by two small chromosomes found in chimpanzees having fused to form one of the human chromosomes at some time in the past.

DNA and evolution
This website provides a light-hearted account of using DNA sequencing.

Table 15.1 Relationship between humans and great apes using DNA differences

Primates being compared	DNA difference (%)
Human – chimpanzee	1.2
Chimpanzee – gorilla	1.2
Human – gorilla	1.6
Chimpanzee – orang-utan	1.8
Human – orang-utan	2.4
Gorilla – orang-utan	2.4

Chromosomes also contain some non-coding sequences of bases in the DNA. These sequences are sometimes referred to as 'junk DNA' as they have no apparent function and appear to serve no purpose. Comparisons of junk DNA provide similar results as those for other parts of the genome – more closely related species have more junk sequences in common. This observation only makes sense if related species have evolved from a common ancestor.

Good examples of stretches of apparently non-functional DNA are **endogenous retroviruses (ERVs)**. An ERV is a viral sequence that has become part of an organism's genome. Retroviruses store their genetic information as RNA, not DNA. Upon entering a cell, a retrovirus copies its RNA genome into DNA – a process known as reverse transcription. The DNA then becomes inserted into one of the host cell's chromosomes. A retrovirus only becomes endogenous if it inserts into a cell whose chromosomes will be inherited by the next generation – that is, an ovum or a sperm cell. The offspring of the infected individual will then have a copy of the ERV in the same place, in the same chromosome, in every single one of their cells. All subsequent generations will also have a copy of the ERV at the same location. What scientists have found is that ERVs make up 8% of the human genome, and that other primates also possess some of the same ERVs in exactly the same locations in their genomes.

For example, when comparing the chromosomes of humans and chimpanzees, it has been discovered that the same ERVs are located in the short arm of chromosome 10, the short arm of chromosome 1, the long arm of chromosome 9 and the short arm of chromosome 6 for both species. In all, scientists have found 16 instances of human ERVs matching exactly with chimpanzee ERVs. This is compelling evidence that humans and chimpanzees share a common ancestor. Any retrovirus that became inserted into the genome of a common ancestor would be inherited by both chimpanzees and humans at exactly the same location in the chromosome.

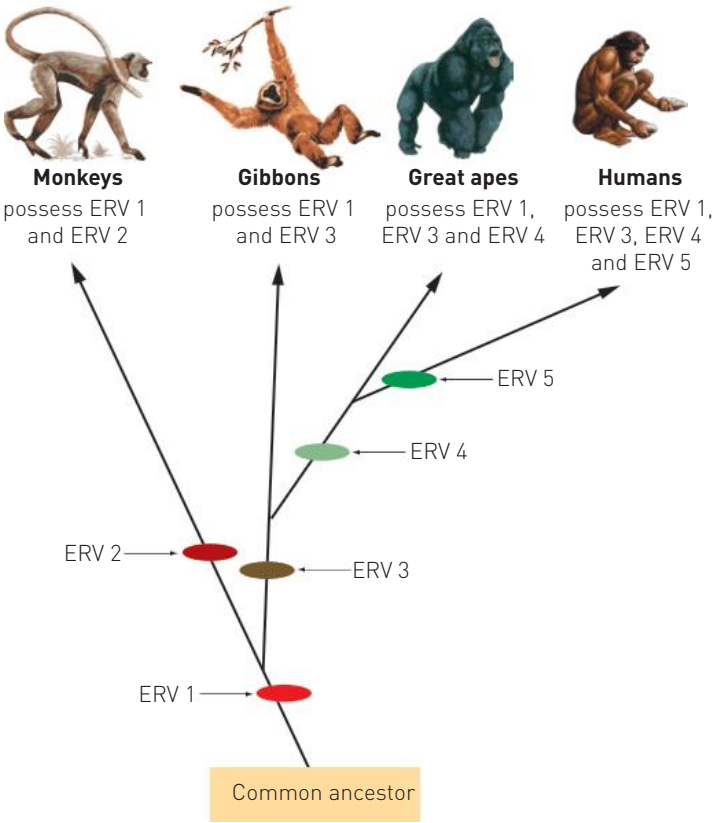


Figure 15.1 A simplified example of how endogenous retroviruses could be used to trace common ancestry: the great apes and humans have a more recent common ancestor as they share more endogenous retroviruses.

Experimentation with the DNA strands from different species suggests an increasing genetic distance between humans and the other primate groups as one progresses from chimpanzees, to gorillas, to orang-utans, to gibbons and to Old World monkeys. This is a very strong indication that all these animals shared a common ancestor, diverging at differing periods.

The polymerase chain reaction (PCR) can be used to amplify minute amounts of DNA so that it can be used to facilitate the sequencing of the genome. In Chapter 13 the PCR technique was described (see Figure 13.5 on page 181). Because significant amounts of a sample of DNA are necessary for molecular and genetic analyses, studies of isolated pieces of DNA are nearly impossible without PCR amplification. This is particularly important when dealing with fossil evidence as, generally speaking, only very small amounts of DNA may be available.

DNA sequencing is also facilitated by gel electrophoresis and bacterial enzymes. The technique of electrophoresis was discussed in Chapter 13 (see page 180). It is used to establish a DNA profile, which is invaluable in tracing ancestry and relationships between individuals and groups.

In order to be able to sequence DNA, it is first necessary to cut it into smaller fragments. Many DNA-digesting enzymes can do this, but most of them are of no use in sequencing as they cut each molecule randomly. What is required is a way to slice the DNA molecule at a few precisely located sites so that a small set of homogeneous fragments are produced. Restriction enzymes derived from bacteria (see pages 182–4) are used to do this task.

Mitochondrial DNA

Mitochondria are the organelles in the cell where the aerobic phase of respiration occurs to release energy for use by the cell. Most of a cell's DNA is located in the nucleus but a small amount is in the mitochondria. This is called **mitochondrial DNA** or **mtDNA**.

Unlike the DNA in the nucleus, which is in the form of very long strands, mitochondrial DNA is in the form of small circular molecules (Figure 15.2). There are about five to ten of these molecules in each mitochondrion. Mitochondrial DNA has 37 genes, all of which are essential for the mitochondrion to function normally. Twenty-four of the genes contain the code for making transfer RNA molecules, which are involved in protein synthesis. The other 13 genes have instructions for making some of the enzymes necessary for the reactions of cellular respiration. Some rare diseases may be caused by mutations in mitochondrial DNA.

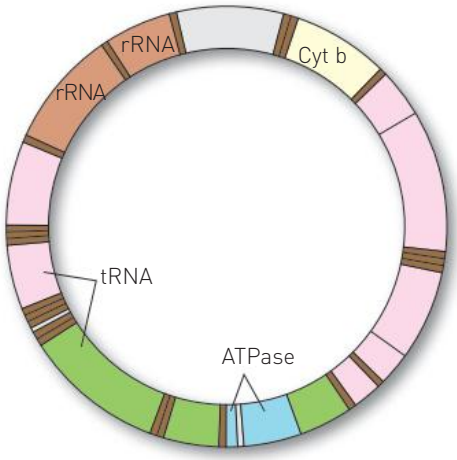


Figure 15.2 A model of a molecule of mtDNA showing the location of some of the genes

Most cells contain large numbers of mitochondria and therefore usually have between 500 and 1000 copies of the mtDNA molecule. This makes it a lot easier to find and extract than the DNA in the nucleus, and so smaller samples can be used. In humans the mtDNA genome consists of about 16 500 base pairs, representing only a fraction of the total amount of DNA in a cell.

Inheritance of mitochondrial DNA

Human eggs and sperm both have mitochondria, but while an egg has many hundreds, a sperm has only about 100 – just enough to provide the energy for the sperm to swim to the egg. After a sperm has penetrated the egg at fertilisation, the mitochondria in the sperm are rapidly destroyed. This means that our nuclear DNA comes from the nucleus of the egg and the sperm, but our mitochondrial DNA comes only from the egg. In other words, we inherit nuclear DNA from both parents but we inherit mitochondrial DNA only from our mothers. You got your mitochondrial DNA from your mother; she got it from her mother, who got it from hers, and so on.

DNA found in the mitochondria has a higher rate of mutation than nuclear DNA. Because of these mutations, human mtDNA has been slowly diverging from the mtDNA of our original female ancestor, and the amount of mutation is roughly proportional to the amount of time that

has passed. Scientists are able to use the similarity between the mtDNA of any two individuals to provide an estimate of the closeness of their relationship through their maternal ancestors. If their mtDNA is identical they will be closely related, perhaps even siblings. On the other hand, if the mtDNA is very different, their last common maternal ancestor lived long ago. The use of mtDNA has been found to be of most value when comparing individuals within a species and for species that are closely related. In this way it has allowed scientists to track the ancestry of many species back hundreds of generations. For example, through studying mitochondrial DNA it has been possible to trace the migration routes of ancient peoples. Such studies have shown that most Europeans are descended from hunter-gatherers who migrated into Europe during the last Ice Age, rather than from farmers coming from the Middle East. It has also been used to demonstrate the evolutionary relationships between humans and closely related species.

mtDNA and Neanderthals
This website provides information about the identification of the genes in mitochondrial DNA of Neanderthals.

Analysis of mtDNA has become an important tool in mapping the relationships between species. Using such analysis scientists can verify evidence of evolution gained from other sources. For example, examination of mtDNA has shown that the last common ancestor of modern humans and Neanderthals lived around 600 000 years ago. Nuclear DNA analysis shows that Neanderthals are likely to have interbred with *Homo sapiens*.

EXTENSION

Mitochondrial Eve is a name that has been given to the woman who, when traced through the female line, is the most recent common ancestor for all living humans. The mitochondrial DNA in all humans alive today is derived from her.

Find out:

- how the matrilineal line is traced back to Mitochondrial Eve
- how long ago Mitochondrial Eve is believed to have lived
- in what part of the world she lived
- whether the fact that the mitochondrial DNA of all humans is derived from Mitochondrial Eve means that she was the only human female alive at the time
- how it is possible that one woman could be the matrilineal ancestor of us all.

Table 15.2 Types of nucleic acids

Deoxyribonucleic acid (DNA)	Very large molecule made of two strands of nucleotides that are joined by bonds between the nucleotide bases. The two strands are twisted into a double helix. Found in the nucleus and mitochondria of cells.
Nuclear DNA (nDNA)	DNA found in the nucleus of cells.
Mitochondrial DNA (mtDNA)	DNA found in the mitochondria.
Ribonucleic acid (RNA)	Large molecule composed of a single strand of nucleotides.
Messenger RNA (mRNA)	RNA molecule that carries the code for protein synthesis from the DNA in the nucleus to the ribosomes where the protein is made.
Transfer RNA (tRNA)	A small RNA molecule that transfers the correct amino acid to the ribosome for inclusion in the protein molecule being made.

Protein sequences

Comparative protein studies also provide evidence for evolution. Proteins consist of long chains of amino acids – some proteins may contain as few as a hundred amino acid units, while others contain thousands. Linking together particular amino acids in a precise sequence determined by the DNA creates these proteins. There are tens of thousands of types of proteins in living things and all are fabricated from 20 kinds of amino acids.

Modern biochemical techniques enable the sequence of amino acids in a protein to be determined. By comparing the type and sequence of amino acids in similar proteins from different

species, the degree of similarity can be established. Animals of the same species have identical amino acid sequences in their proteins, and those from different species have different amino acids or they are arranged in a different order. Just like DNA analysis, the degree of difference between proteins enables an estimate of the amount of evolution that has taken place since two species developed from a common ancestor. The longer the period of time involved, the greater the number of amino acids that are different.

Usually amino acids are represented by a three-letter code, frequently the first three letters of their name (Table 15.3). To make comparison of amino acid chains easier, scientists have also adopted a system of coding whereby one letter is used to represent one particular amino acid. By listing the amino acids for a particular protein in sequence, a comparison can be made with other species. This has been done for a number of proteins that appear to be in all species and they are therefore referred to as **ubiquitous proteins**. Such proteins perform very basic but essential tasks that all organisms require for life. Ubiquitous proteins are found in all organisms from bacteria to humans and are completely independent of an organism's specific function or the environment in which it lives. Such proteins carry out the same functions no matter where they are found.

Table 15.3 The three-letter and single-letter codes used for amino acids

Amino acid	Three-letter code	Single-letter code
Alanine	Ala	A
Arginine	Arg	R
Asparagine	Asn	N
Aspartic acid	Asp	D
Cysteine	Cys	C
Glutamic acid	Glu	E
Glutamine	Gln	Q
Glycine	Gly	G
Histidine	His	H
Isoleucine	Ile	I

Amino acid	Three-letter code	Single-letter code
Leucine	Leu	L
Lysine	Lys	K
Methionine	Met	M
Phenylalanine	Phe	F
Proline	Pro	P
Serine	Ser	S
Threonine	Thr	T
Tryptophan	Trp	W
Tyrosine	Tyr	Y
Valine	Val	V

Cytochrome C is a well-researched example of a ubiquitous protein that shows how protein sequences can provide evidence for evolution. This protein performs an essential step in the production of cellular energy. It appears to have changed very little over millions of years of evolution. Human cytochrome C contains 104 amino acids (Figure 15.3). Regardless of the species tested, 37 of these have been found at the same positions in every sequenced cytochrome C molecule. This strongly suggests that these proteins have descended from an ancestral cytochrome C molecule found in a primitive microbe that existed more than 2000 million years ago.

To compare cytochrome C sequences, they need to be aligned so that the maximum number of positions containing the same amino acids can be determined. The more similarity there is between two molecules, the more recently they have evolved from a common ancestor. By doing such comparisons, scientists have determined that the cytochrome C of chimpanzees and gorillas is the same as that for humans, and for rhesus monkeys it differs by only one amino acid compared with that of humans (Table 15.4, page 222).

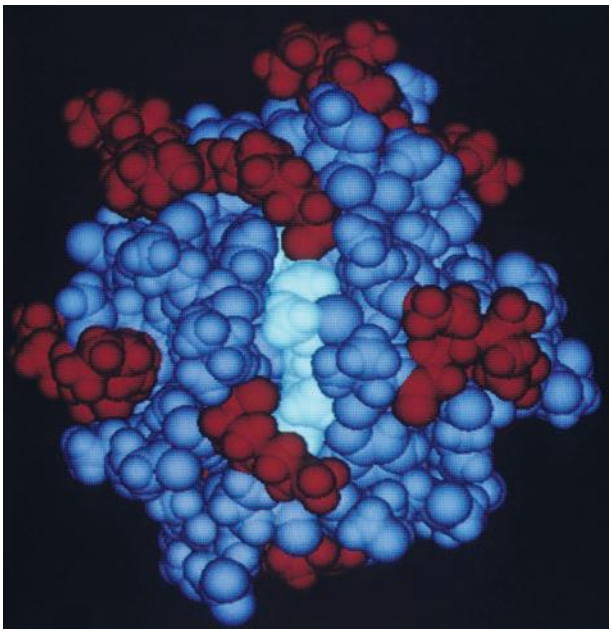


Figure 15.3 A model of cytochrome C

Table 15.4 Differences in amino acids in cytochrome C between humans and other species

Species compared with humans	Number of differences from human cytochrome C
Chimpanzee	0
Gorilla	0
Rhesus monkey	1
Patas monkey	1
Rabbit	9
Cow	10
Pigeon	12
Bullfrog	18
Tuna	21
Fruit fly	24
Yeast	44

Other protein sequences have been examined and yielded similar results. The alpha and beta chains of the blood protein haemoglobin are identical in humans and chimpanzees, but the same protein sequences in gorillas differ by one amino acid. When the same chains are examined in gibbons, there are three amino acid differences. A comparison of the delta chain indicates that humans differ from chimpanzees and gorillas by one amino acid, and from gibbons by two. Such protein studies provide more support for the evolutionary relationships between primates that have already been established by DNA comparisons.

Cytochrome C
This website provides a more detailed discussion of the evolution of cytochrome C.

EXTENSION

Haemoglobin and cytochrome C have been used to give support to the theory of evolution through natural selection. Scientists have similarly compared the biochemistry of universal blood proteins.

Find out:

- if such studies have revealed evidence for the relationships between different species
- whether such evidence implies that some species share a more recent common ancestor than other species.

Bioinformatics

Bioinformatics has become an important part of many areas of human biological science and is particularly useful in providing evidence for evolutionary relationships. It is a multidisciplinary field that combines all areas of biological science with computer science, statistics and applied mathematics to help understand biological processes. However, in practical terms, **bioinformatics** is the use of computers to describe the *molecular* components of living things. It has been particularly useful in assisting evolutionary biologists to trace the evolution of a large number of organisms by measuring changes in their DNA rather than through traditional techniques of physical taxonomy or physiological observations.

More recent developments have enabled researchers to compare entire genomes. In doing so, the genes and other biological features in a DNA sequence need to be identified, a process termed **annotation**. This process needs to be computerised as most genomes are far too large to be annotated by hand (Table 15.5). Annotation is made possible by the fact that genes have recognisable start and stop codons (see Chapter 13 of *Human Perspectives Units 1 & 2 ATAR*).

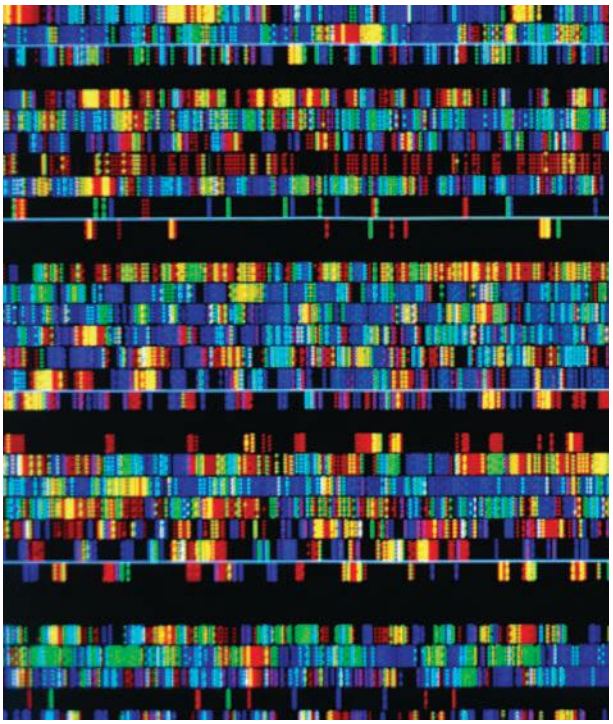
Table 15.5 Comparative genome sizes of a number of organisms

Organism	Estimated size (base pairs)	Chromosome number	Estimated gene number
Human	3.0 billion	46	21 000
Mouse	2.9 billion	40	21 000
Fruit fly	165 million	8	13 000
Roundworm	97 million	12	19 000
Yeast	12 million	31	6 000
Bacteria	4.6 million	1	3 200

Comparative genomics

Comparative genomics is a relatively new field of biological research in which the genome sequences of different species are compared. By comparing the sequence of the human genome with genomes of other organisms, researchers are able to identify regions of similarity and difference. This procedure provides an effective means of studying evolutionary changes among organisms, helping to identify genes that are preserved among species, as well as genes that give each organism its unique characteristics.

Although the different species that inhabit the world look and behave in diverse ways, all their genomes consist of DNA, the chemical chain that makes up the genes that code for the thousands of different kinds of proteins (Figure 15.4). Precisely which protein is produced by a given gene is determined by the sequence in which four chemical building blocks – adenine, thymine, cytosine and guanine – are laid out along DNA's double-helix structure. The successful completion of the Human Genome Project in 2003 demonstrated that major sequencing projects can generate high-quality data. Consequently, interest in sequencing the genomes of many other species rose significantly.



James King-Holmes/Science Photo Library

Figure 15.4 Computer screen display of the human DNA sequence. Each colour represents a specific base. The sequence of bases makes up the genetic code.

By analysing the genomic features that have been preserved in a number of species over millions of years, researchers are beginning to tease apart the often subtle differences between animal species. Comparative genomics has revealed a high level of similarity between closely related organisms such as humans and chimpanzees. It has also been used to reveal the diversity of gene composition in different evolutionary lineages. Such research may result in a rearrangement of the way we view some of the evolutionary relationships between primates.

Comparison of molecules
This website presents evidence to show that comparisons of molecules provide support for evolution.

Comparative studies in anatomy

Comparative anatomy involves comparing the structural features of related animals to ascertain the degree of similarity between them. Similarities in structure often suggest that species have a common ancestor. In discussing comparative anatomy we will focus on three areas:

- **embryology** – comparing the very early stages of the development of organisms
- **homologous organs** – organs that are similar in structure but are used in different ways
- **vestigial organs** – organs that may once have been important but have lost or changed their function.

Embryology

Comparative embryology provides evidence for evolutionary change over time by comparing the early stages in the development of organisms. Although it is relatively easy to distinguish between the adults of different species, it is frequently far more difficult to tell the difference between embryos. In vertebrates, comparing the embryonic stages reveals a remarkable similarity between different species at different times. Figure 15.5 illustrates embryos of five different vertebrates at three different developmental stages. Notice how similar they are in the early stages. The embryonic gill pouches and arches have been labelled and you can see that these appear in all the species. What is the significance of these structures when reptiles, birds and mammals have lungs for breathing air and do not even have aquatic larvae? The presence of such structures is significant if the vertebrates are viewed as an evolutionary series that began with fish hundreds of millions of years ago. Over that time, evolution resulted in their divergence into amphibians, reptiles, birds and mammals. This evolutionary line is well supported by other evidence. In humans, one of the embryonic gill slits develops into the Eustachian tube, and tissue surrounding other gill slits develops into the thyroid gland and tonsils.

Examine Figure 15.5 again. Notice that all the early embryos represented are characterised by the absence of paired appendages and the presence of a well-developed tail. Features not obvious from the diagrams, but also common to all vertebrate embryos at this stage, are a two-chambered heart and similar brain development. This all adds up to striking evidence for a common ancestry with later evolution along different pathways.

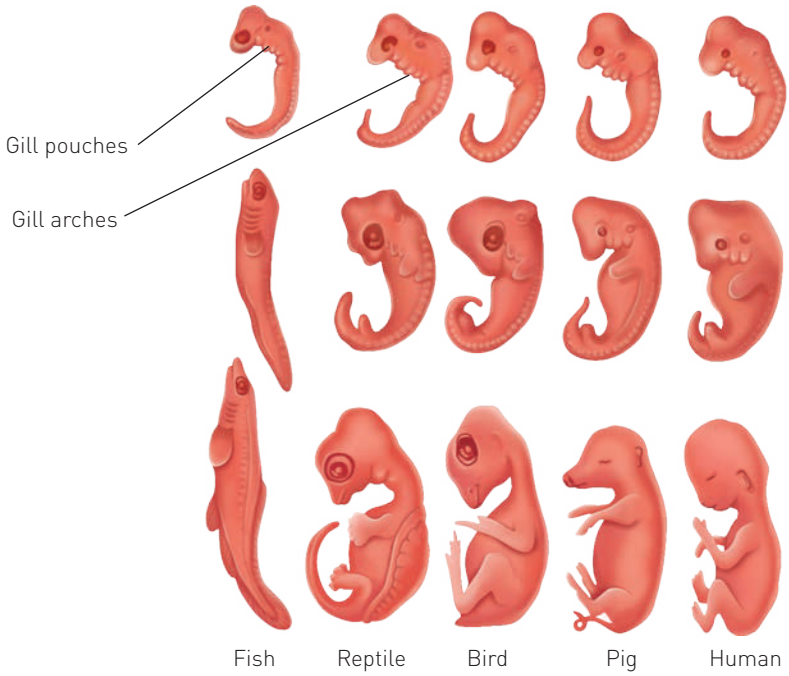


Figure 15.5 Embryos of five vertebrates at early (top), intermediate (middle) and late (bottom) stages of development

Homologous structures

One of the classic examples used to illustrate similarity in anatomy is the forelimbs of vertebrates (Figure 15.6). The same bones appear in various forms throughout the vertebrates – the feet of amphibians and reptiles, the wings of bats and birds, the leg of a horse, the flipper of a whale or seal, and the human hand. In Figure 15.6 notice the degree of similarity between the bones that have been coloured blue. In every case the bones are arranged in a similar way, even though some have developed different functions. These forelimb bones are described as **homologous organs**

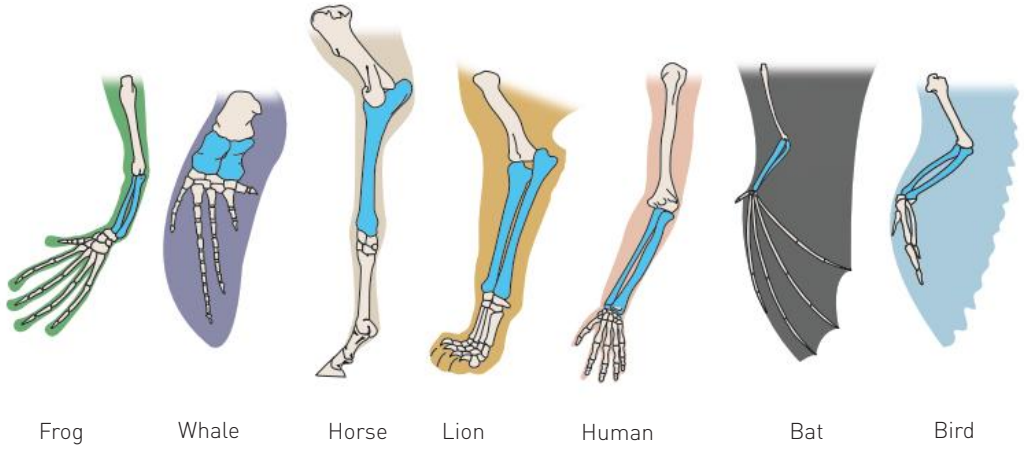


Figure 15.6 Left forelimb bones of seven vertebrates; from left to right: frog forelimb, whale flipper, horse forelimb, lion forelimb, human arm, bat wing, bird wing

because they possess a similar structure. Organisms possessing organs that are similar in structure are likely to have a common ancestor. Therefore, the arrangement of the bones of the forelimb in such a range of vertebrates is convincing evidence that they have all evolved from a common ancestor.

Anthropoids, the human-like primates, show a great many anatomical resemblances. The number of traits shared and the degree of similarity between the shared traits is remarkable, especially considering the range of habitats occupied. Figure 15.7 shows the skeletons of a human and a gorilla; Figure 15.8 on page 226 shows the arrangement of muscles in their legs. Note the high degree of similarity between them. These two species share a common ancestor and are therefore closely related. This will be discussed further in later chapters.

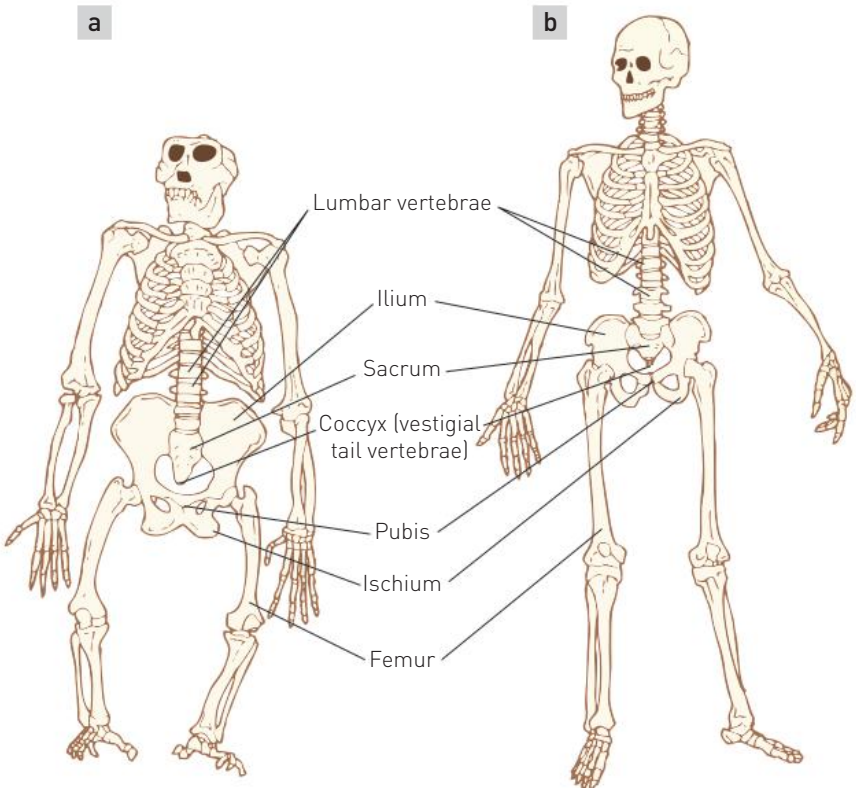


Figure 15.7 Skeleton of **a** a gorilla and **b** a human

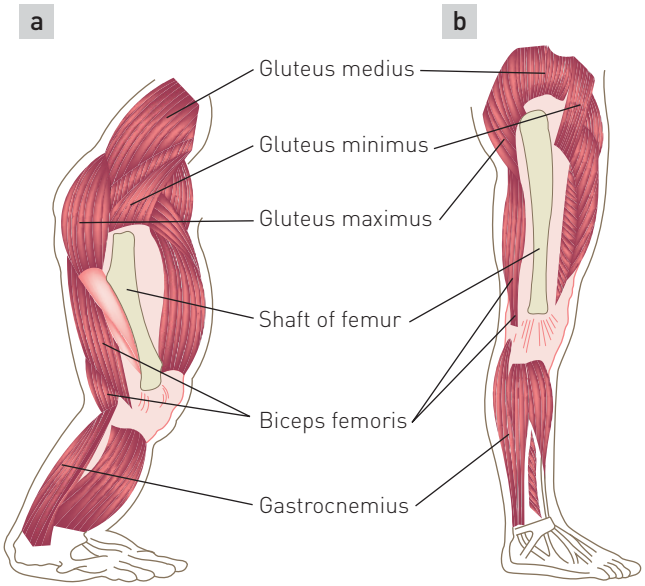


Figure 15.8 Musculature of the right leg of **a** a gorilla and **b** a human

Vestigial organs

Vestigial organs are structures of reduced size that appear to have no function. They are common in vertebrate species and form an intriguing aspect of comparative anatomy. Humans may have as many as 90 of these structures, a few of which are shown in Figure 15.9. Keep in mind that vestigial structures are largely or entirely functionless when their original role is being considered. Some may retain lesser functions or develop new ones. As such, they contribute to an understanding of how different species may be related to one another.

The **nictitating membrane**, or transparent third eyelid, found in cats, birds, frogs and other vertebrates, is only represented in humans by a pinkish membrane located at the inner corner of each eye. The muscles that move the external ears of many mammals are reduced to such an extent in humans that, in most individuals, they will not move the ears at all. In most humans the third molars, or wisdom teeth, erupt abnormally and cannot be used in mastication. Frequently, they are removed before eruption so that they do not become painful. About one-fifth of the population are spared any discomfort because the third molars do not develop at all. Likewise, about one-fifth of the population do not develop the muscles that lie above the pubic bone, the pyramidalis muscles. These muscles, if present, do not make any difference to muscular performance. In addition, humans still have the vertebrae for a tail, fused to form the coccyx, and an appendix. Males also have nipples on their chests, although some would argue that these should not be termed vestigial, as they had no function in the first place. They appear to be retained in males because all human foetuses develop from the same basic genetic form, and nipples do have an important function in females.

The muscles at the base of hairs are considered to be vestigial in humans. In mammals with fur or spines, and in birds with feathers, these tiny muscles pull the hair or feather upright, creating a layer of insulating air to protect against the cold. However, human hair is so fine that it is not capable of such a function and the contraction of the muscles is seen as goose bumps.

Evolutionary mechanisms can be used to explain the existence of many of these structures that appear to have no function. They are what remain of organs that were functional in ancestral forms. Over time, and with changing environmental conditions, such organs were no longer essential to survival and were gradually reduced to vestigial remnants. As these remnants are not harmful in any way, they have not been completely eliminated. However, natural selection has reduced the organs to non-functional remnants because it would have been a waste of the organism's energy and resources to maintain useless structures. Such organs will probably disappear altogether as there is no selection pressure to retain them.

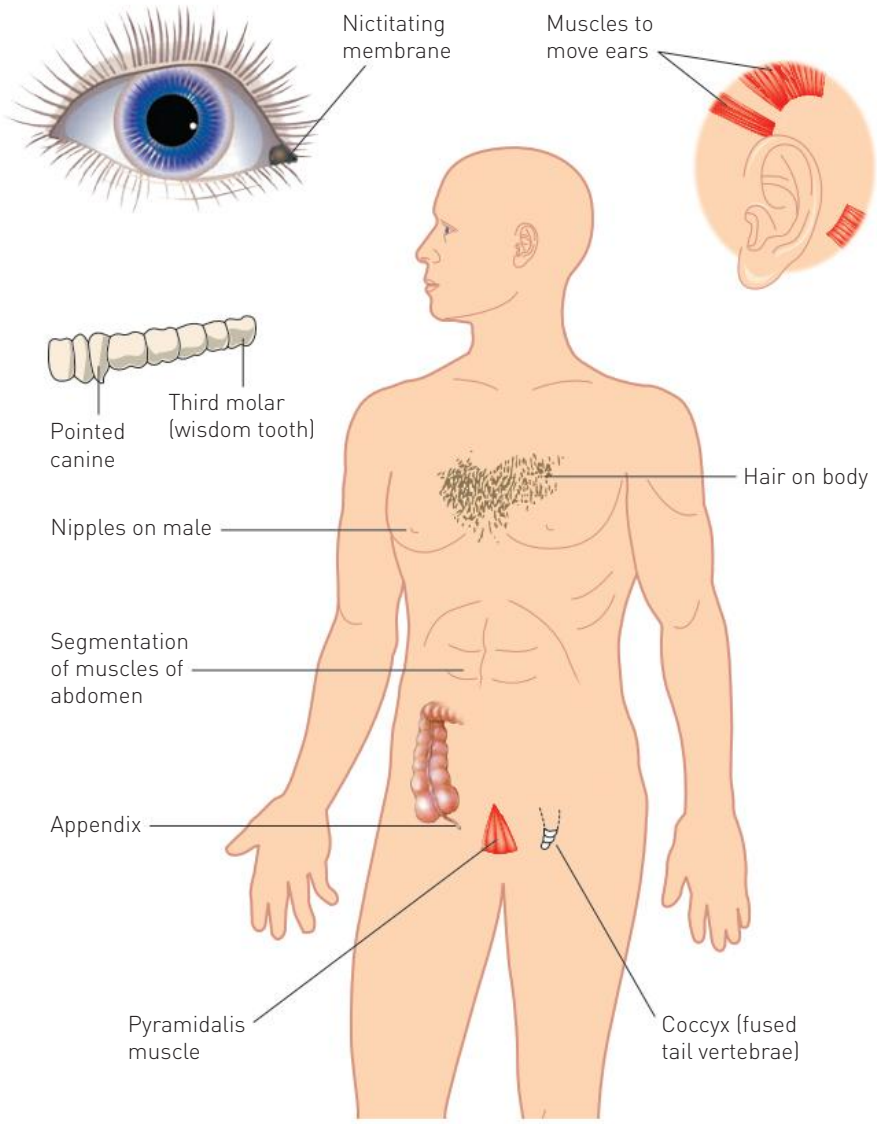


Figure 15.9 Some vestigial organs of humans

Vestigial organs
This website provides more information about vestigial organs.

EXTENSION

Some scientists now argue that the appendix should not be considered a vestigial organ. These scientists have found that the appendix may act as a haven for helpful bacteria that can grow and, if necessary, re-inoculate the gut in times of illness. Others disagree with this viewpoint.

Find out:

- what evidence there is to support the view that the appendix is far from functionless in humans and apes
- alternative explanations of why the appendix has been retained even though it no longer has a function in human digestion.

Geographical distribution

Further evidence for evolution is found in the natural geographic distribution of related species. Isolated land areas and island groups have frequently evolved their own distinctive plant and animal populations. For instance, before humans arrived in Australia, there were more than 100 species of kangaroos, koalas and other marsupials but none of the more evolutionarily advanced terrestrial placental mammals. Also, with one exception, the living representatives of the primitive egg-laying mammals, the echidna and platypus, are found only in Australia. The exception is one species of echidna that is found in New Guinea, an island very close to Australia. The most likely explanation is that the unique species found in Australia had been evolving in isolation from the rest of the world for millions of years.

During his time in South America, Darwin encountered what has become one of the classic pieces of evidence for evolution. He had observed finches on the South American mainland but when he visited the Galapagos Islands, he found the finches there quite different. For one reason or another, one species of finch had managed to fly to these islands, while many other species of birds had not. With no competition, the finches of the Galapagos Islands had evolved by taking advantage of the range of food sources on offer (Figure 15.10). In this way, their beaks had gradually changed over time to better enable the different populations to survive. Eventually they evolved into 13 separate species.

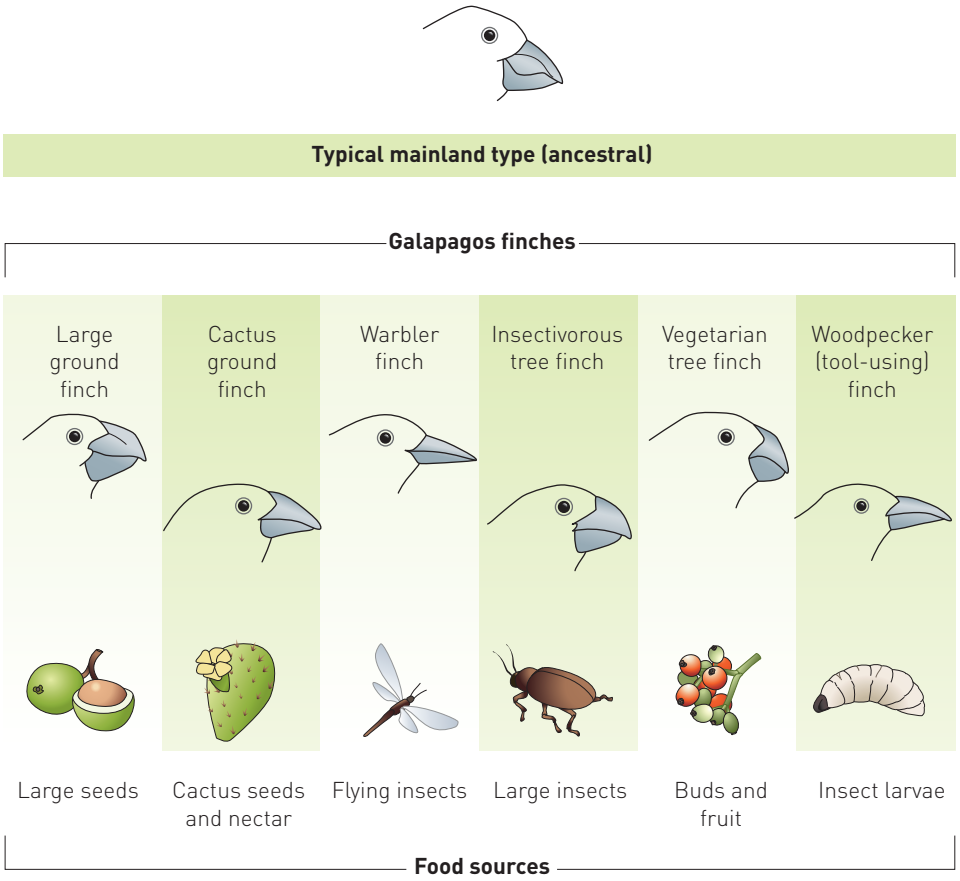


Figure 15.10 The finches of the Galapagos Islands. A common ancestor has evolved into many different species of finch as each adapted to a different food source.

Darwin's finches
This website tells more about Darwin's finches.

Speciation of Darwin's finches
This website includes a detailed discussion of the speciation process that resulted in the large number of species of Darwin's finches.

Darwin saw this as a mainland species invading different islands and then diverging into new species as natural selection adapted them to the local environment. He argued that the first finches to reach the Galapagos Islands would have shown variation in beak shapes. These would have been part of the natural variation that exists in all species. Finches of one beak shape would have

been better able to feed on, say, cactus seeds, while others would have been better able to feed on insect larvae. In this way, on islands with a lot of cacti, natural selection would have favoured one particular shape of beak. This favourable characteristic would be passed on to offspring. Beaks of other shapes would have been favoured on other islands with more insects. Over many generations, natural selection would have favoured those characteristics that aided survival on a particular island. Thus, the populations of finches on the various islands would have gradually become diverse enough to be regarded as different species.

The various species of primates living today provide evidence in support of geographical distribution. As a result of shared ancestry and geographical isolation, lemurs are limited to the island of Madagascar, New World monkeys are only found in the Americas, and Old World monkeys in Africa and Asia. Interestingly, Darwin's knowledge of geographical distribution, and the work of other scientists suggesting that humans most resemble chimpanzees and gorillas, led him, in 1871, to predict that Africa was the most likely place to find fossils of human ancestors. His prediction turned out to be correct: the earliest ancestors of modern humans have been found in Africa.

Finch experiments
This website allows you to run some experiments with Darwin's finches. Select 'Next' to get started and then click on 'Finches'.

Evidence for evolution
This website provides a good overview of the evidence for evolution.

Evolution and creation

Most of the world's religions include the concept of a god as the creator of the universe and of life on Earth. The Jewish and Christian idea of God as creator is described in the book of Genesis, the first book of the Bible, where there is a beautiful account of the creation of the Earth and its life forms.

Christians believe that the Bible is the word of God, and for some groups this has led to the belief that the Bible is literally true in every detail. For these groups the account in Genesis is a description of the actual events of creation, and thus these people do not believe in biological evolution. Other Christians see the Bible story of creation as symbolic: a story written to explain the origins of life to people lacking the scientific knowledge that we have today.

Almost all biological scientists accept the theory of evolution as fact, and you can see from the material presented in this chapter that there is a wealth of evidence to support it. There are also many scientists, including many eminent biologists, who have strong religious convictions and do not find the symbolic interpretation of the creation to be incompatible with biological evolution. Science does not have the answer to every question; it has limitations. Questions such as 'What is life?', 'When did life begin?', 'How?' and 'Where? can be investigated scientifically. However, questions relating to the meaning of life, such as 'Why?' or 'What for?', are beyond the scope of scientific investigation. It is the task of each of us to ponder and perhaps eventually arrive at our own answers to such questions. The important thing to remember is that acceptance of the theory of evolution does not preclude a belief and faith in a god.

WS

Evidence for evolution

Science inquiry

ACTIVITY 15.1 Amino acid sequencing

Haemoglobin is the protein that carries oxygen in the blood. It is found in all mammals and has the same function in each species. You would expect that it would be composed of the same sequences of amino acids. However, this is not the case. The particular protein chain we will study in this activity is composed of 146 amino acids. The numbers in Table 15.6 indicate the position of some of the amino acids in that sequence and the letters are abbreviations for the amino acids (see Table 15.3). Six different mammalian species are shown with the amino acids that are present at positions 87 to 116 in the chain.

WHAT TO DO

1. Examine Table 15.6 and count the number of differences in the amino acid sequences for the following pairings of species.
   - Human and chimpanzee
   - Human and gorilla
   - Chimpanzee and gorilla
   - Human and rhesus monkey
   - Chimpanzee and rhesus monkey
   - Gorilla and rhesus monkey
   - Human and horse
   - Human and kangaroo
2. Record your data in a table.
3. Using only the data from this section of the haemoglobin molecule, rank the species in order from the one closest to humans to the one most distant.

Table 15.6 Amino acid sequences in the haemoglobin of six mammalian species

Species	87	88	89	90	91	92	93	94	95	96	97	98	99	100	101
Human	T	L	S	E	L	H	C	D	K	L	H	V	D	P	E
Chimpanzee	T	L	S	E	L	H	C	D	K	L	H	V	D	P	E
Gorilla	T	L	S	E	L	H	C	D	K	L	H	V	D	P	E
Rhesus	Q	L	S	E	L	H	C	D	K	L	H	V	D	P	E
Horse	A	L	S	E	L	H	C	D	K	L	H	V	D	P	E
Kangaroo	K	L	S	E	L	H	C	D	K	L	H	V	D	P	E

Species	102	103	104	105	106	107	108	109	110	111	112	113	114	115	116
Human	N	F	R	L	L	Q	N	V	L	V	C	V	L	A	H
Chimpanzee	N	F	R	L	L	Q	N	V	L	V	C	V	L	A	H
Gorilla	N	F	K	L	L	Q	N	V	L	V	C	V	L	A	H
Rhesus	N	F	K	L	L	Q	N	V	L	V	C	V	L	A	H
Horse	N	F	R	L	L	Q	N	V	L	A	L	V	V	A	R
Kangaroo	N	F	K	L	L	Q	N	I	I	V	I	C	L	A	E

STUDYING YOUR DATA

1. Based on this segment of the haemoglobin molecule, which species of mammal appears to be the most closely related to humans?
2. Which animal appears to be the least closely related to humans?
3. Which of the other pairs of species show close relationships?
4. These sequences of amino acids are generally very similar but not identical. If these species were all descended from a common ancestor, how would the changes in the sequences of the different species have come about?
5. Do you think the differences in the amino acid sequences between the species would affect the function of haemoglobin?

IN SUMMARY

Using the information from this sequence of amino acids in haemoglobin, describe the evolutionary relationships between the species in terms of the evolution of humans.

Review questions

1 Using an example, explain how the study of DNA in different species has added to the evidence for evolution.

2 **a** What are endogenous retroviruses?
b How do retroviruses become endogenous?
c What is the value of endogenous retroviruses in a study of evolution?

3 Describe how each of the following has facilitated DNA sequencing.
a Polymerase chain reaction
b Gel electrophoresis
c Bacterial enzymes

4 **a** What is mitochondrial DNA (mtDNA)?
b Describe how mtDNA has been used to provide evidence for evolutionary relationships between species.
c Give an example of where mtDNA has provided information about such a relationship.

5 Describe how the sequence of amino acids in proteins can be used to determine the degree of similarity between species.

6 **a** What are ubiquitous proteins?
b Why has cytochrome C been so valuable in providing evidence for evolution? Give examples of species that contain cytochrome C.
c Besides cytochrome C, what other proteins have been used to provide evidence about relationships between species?

7 **a** How has bioinformatics assisted biologists in refining evolutionary relationships?
b What role has comparative genomics played in the study of evolutionary changes among organisms?

8 How does a study of embryology assist in supporting the theory of evolution? Give examples to illustrate your answer.

9 **a** What are homologous organs?
b Using an example, describe how homologous structures provide evidence for evolution.

10 **a** What is a vestigial organ? Describe four human vestigial organs.
b Describe the significance of vestigial organs to the theory of evolution.

11 Explain how the geographical distribution of species provides evidence for evolution.

12 Describe how Darwin explained the way different populations of finches became established as separate species on the Galapagos Islands.

Apply your knowledge

1 When ancestral species evolve into two or more separate species, those new species would exhibit considerable similarity in their DNA. What causes the DNA to change over time? How has the information from DNA been used by scientists to speculate on the relationships between species?

2 Modern technology has provided the means to compare DNA and protein sequences. How has this changed the traditional way of looking at the relationships between humans and apes?

3 Explain why mtDNA is only of use when looking at the relationships within a species or between closely related species.

4 Explain why scientists select ubiquitous proteins for their biochemical research on the relationships between species.

5 Refer to Table 15.4, which indicates the degree of difference in the amino acids in cytochrome C between humans and some other species. Using this information, construct a family tree to illustrate a possible relationship between those species.

6 Why would scientists use a comparative study of haemoglobin in different species in a search for data to support their theories of primate evolution?

7 Comparative genomics has been used effectively to examine relationships between species. There have also been successful applications of comparative genomics in other fields of biological science. Find out what these successes have been.

8 In this chapter, the forelimb was used as an example of homologous structures. What other structures found in vertebrates could be used to illustrate homology?

9 Homologous organs are so called because they have a similar structure. However, the basic structure may be modified substantially to carry out a different function. Describe the changes that have taken place to the vertebrate forelimb for it to become:

a a flipper

b a wing

c an arm.

10 In 1893 a German anatomist, Robert Weidersheim, compiled a list of 86 vestigial organs. On his list were the valves in veins, the tonsils, the pituitary gland and the thymus. Why must scientists be very careful about describing an organ as vestigial?

11 More than 135 years ago, Darwin predicted that fossils of the ancestors of modern humans would be found in Africa. What evidence would Darwin have used as the basis for making that suggestion?

CHAPTER

16

FOSSIL EVIDENCE FOR EVOLUTION

UNIT 4 CONTENT

SCIENCE INQUIRY SKILLS

- conduct investigations, including the use of virtual or real biological techniques of polymerase chain reaction (PCR), gel electrophoresis for deoxyribonucleic acid (DNA) sequencing, and techniques for relative and absolute dating, safely, competently and methodically for valid and reliable collection of data
- represent data in useful and meaningful ways; organise and analyse data to identify trends, patterns and relationships; discuss the ways in which measurement error, instrument accuracy, the nature of the procedure and sample size may influence uncertainty and limitations in data; and select, synthesise and use evidence to make and justify conclusions
- interpret a range of scientific and media texts, and evaluate models, processes, claims and conclusions by considering the quality of available evidence; and use reasoning to construct scientific arguments
- select, use and/or construct appropriate representations, including phylogenetic trees, to communicate conceptual understanding, solve problems and make predictions

SCIENCE UNDERSTANDING

Evidence for evolution

- the fossil record is incomplete and cannot represent the entire biodiversity of a time or a location due to many factors that affect fossil formation, persistence of fossils and accessibility to fossilised remains
- sequencing a fossil record requires a combination of relative and absolute dating techniques to locate fossils onto the geological time line
- both relative dating techniques, including stratigraphy and index fossils, and absolute dating techniques, including radiocarbon dating and potassium-argon dating, have limitations of application

The living things that exist on Earth today have all evolved from simpler forms that existed in the past. One of the crucial pieces of evidence for evolution, the gradual change in the characteristics of organisms over time, is the record of those changes left to us in the form of fossils. A fossil does not have to be a part of an organism. Any preserved trace left by an organism that lived long ago is a **fossil**. Fossils therefore include footprints, burrows, faeces or impressions of all or part of an animal or a plant, as well as bones, shells or teeth. In the case of human ancestors, fossil remains are usually bones, teeth or sometimes footprints. Figure 16.1 shows the fossil remains of an ancestor of modern humans, *Australopithecus afarensis*, found in the Hadar region of Ethiopia. Such fossil remains are extremely important as they allow scientists to determine exactly what extinct species were like. Other material associated with the bones, such as the rock in which they were found and fossils of other plants and animals, allows the scientist to develop a picture of life in the past – what the organisms ate, what other organisms existed at that time and, sometimes, even what the climate was like.

There are many cases where the fossil record has allowed scientists to build up a sequence of the evolution of a particular plant or animal. One of the best known is the evolution of the horse (Figure 16.2), which can be traced through fossil remains from a small creature not much bigger than a small dog to the horses that we know today.

Getty Images/Science Photo Library

Figure 16.1 The fossil hominin skeleton known as 'Lucy'

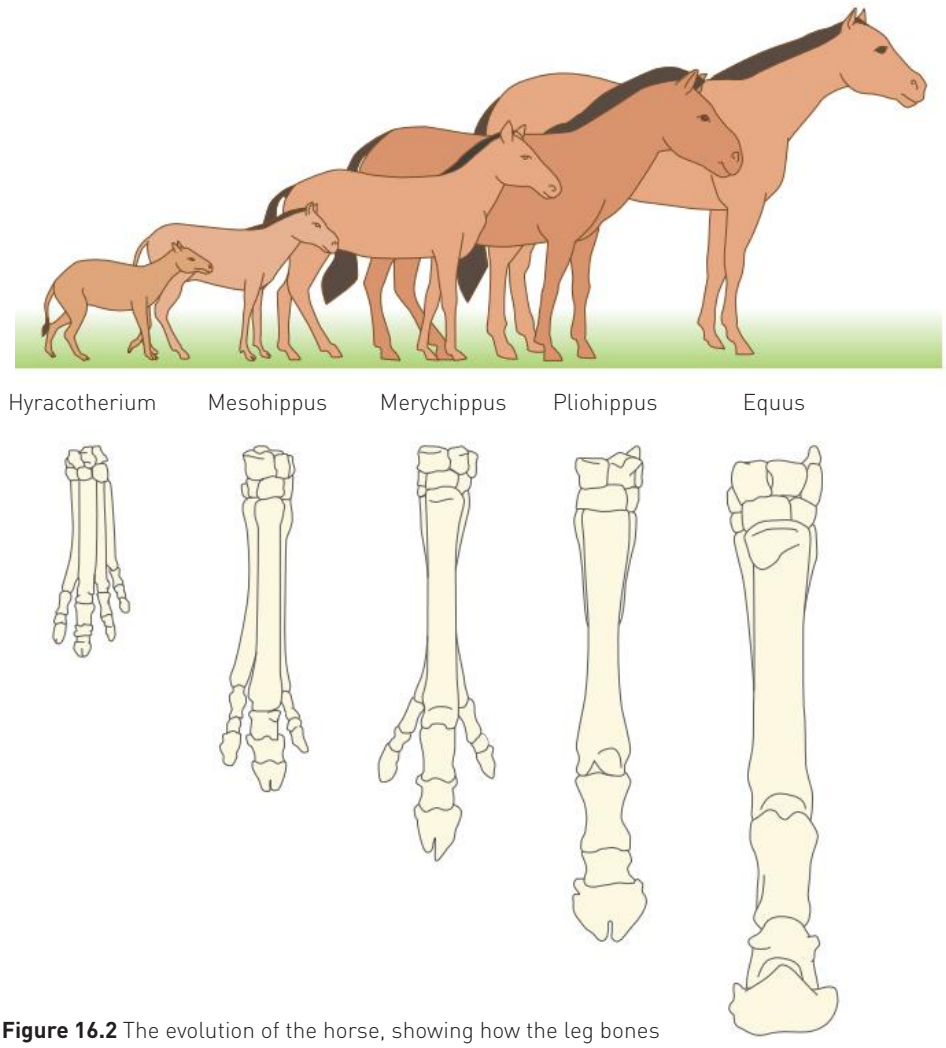


Figure 16.2 The evolution of the horse, showing how the leg bones appear to have changed as the animal increased in size

Horse evolution
This website provides more information about the evolution of the horse. Click on 'Gallery of horse fossils'.

Fossil formation

When we consider the billions of organisms that have lived on Earth, the chance that a plant or animal will be fossilised is very small. Normally, dead organisms are decayed by micro-organisms and no trace of their existence is left. Parts of organisms may become fossilised when buried by drifting sand, mud deposited by rivers, volcanic ash or, in the case of some of the more recent human ancestors, other members of the species. If buried rapidly, conditions may not be suitable for the activity of decay organisms and decomposition may be slowed or prevented.

The nature of the soil is very important for the fossilisation of bone. In wet, acid soils the minerals in the bone are dissolved and no fossilisation occurs. However, if such soil contains no oxygen, as in the case of peat, complete preservation of the soft tissues and bones of the animal may occur. Bones buried in alkaline soils produce the best fossils because the minerals in the bones are not dissolved. New minerals, often lime or iron oxide, are deposited in the pores of the bone, replacing the organic matter that makes up about 35% by weight of the bone. The bone becomes petrified (turned into rock) but the details of structure are still preserved.

Fossils of human ancestors are often found at the edges of ancient lakes and river systems, in caves or in volcanically active areas. Lakes and rivers build up sediments when flooding occurs or when the water flow slows rapidly. Many caves are in limestone, which consists of calcium carbonate. This chemical may be deposited around dead organisms, or the cave roof or walls may collapse, covering the bodies of animals. It is unusual for animals to be preserved near volcanic eruptions because heat from the volcanic material destroys the organism, but in East Africa ash falls have preserved fossils of many human ancestors.

Discovery of fossils

Fossils are sometimes found by chance at the surface of the ground where they may have been uncovered by erosion, but more often the discovery of fossils is the result of slow and painstaking excavation of likely sites. Surface discoveries such as fossil fragments, or evidence of human occupation such as that found in many caves, are indications of places where excavations may prove fruitful. Scientists refer to an excavation as a 'dig' (Figure 16.3).

Figure 16.3 Excavation of a site, showing how carefully the trenches have been dug

Alamy Images/Ken Gillespie Photography

The area to be investigated is first surveyed and marked out in sections. Small hand tools are used to remove the soil gently so as not to damage any of the material. The soil removed is usually sieved so that even very small fragments are not overlooked. In the case of fossils of human ancestors, artefacts are often found in association with the fossils. **Artefacts** are objects that have been deliberately made by humans. They include items such as stone tools, beads, carvings, charcoal from cooking fires and cave paintings.

Photographs are taken at every stage of a dig so that detailed studies of the positions of uncovered material can be carried out later. Each item is carefully labelled and catalogued for the prolonged study that follows the excavation of the site. In the laboratory, fossil bones are carefully scraped clean (Figure 16.4), broken parts are pieced together, measurements are made and plaster casts or latex moulds may be made.

Dating of fossils

One of the major tasks following the excavation of fossils or artefacts is to determine the age of the material. This is known as **dating**. Knowledge of the age is crucial in finding out the sequence of changes that have resulted in present-day humans. Various methods of dating fossils and material associated with human ancestors have been devised. Some of these methods provide **absolute dates** – that is, the actual age of the specimen in years; others give **relative dates**, which tell us whether one sample is older or younger than another. Modern technology has enabled accurate estimates to be made of the absolute age of many samples. However, when that is not possible, knowing whether one fossil is older or younger than another is very important.

Science Photo Library/Pasquale Sorrentino

Figure 16.4 Cleaning prehistoric animal bones. These bones are from the jaw of a rhinoceros dating back 600 000 years.

The age (or date) of a fossil or artefact is usually given in years before the present time. For example, a fossil may be said to date from 45 000 years BP, which is another way of saying it is 45 000 years old. BP stands for 'before present'.

Absolute dating

The **potassium-argon** technique is based on the decay of radioactive potassium to form calcium and argon. Potassium (chemical symbol K) is a mixture of three different forms with atomic weights 39, 40 and 41. Such different forms of the same element, with different numbers of neutrons in the nucleus of their atoms, are called **isotopes**. The isotope potassium-40 is radioactive and decays to form calcium-40 and argon-40. Such decay takes place at an extremely slow but constant rate, and so determining the amounts of potassium-40 and argon-40 in a rock sample enables the age of the rock to be calculated. Potassium-argon dating has limited usefulness: not all rock types are suitable for this method of dating and it can only date rocks older than 100 000 to 200 000 years. At the earlier date of 100 000 years, only 0.0053% of the potassium-40 in a rock would have decayed to argon-40. Such a small amount pushes the limits of detection devices currently in use.

Potassium-argon dating
This website provides more information about potassium-argon and some animated sequences on dating.

To determine the age of a fossil using this method, some suitable rock of the same age as the fossil must be available. This occurs, for example, when rocks produced in volcanic eruptions bury bones. Despite these limitations, potassium-argon dating is very useful in providing precise dates for those rocks for which it is suitable.

The **carbon-14** or **radiocarbon dating** method is based on the decay of the radioactive isotope of carbon, carbon-14, to nitrogen. Carbon-14 is produced in the upper atmosphere by the action of cosmic radiation on nitrogen at about the same rate at which it decays. In the atmosphere there is a ratio of one carbon-14 atom to every million million (10^{12}) atoms of the stable isotope carbon-12. (In the United States and some other countries, a million million is called a trillion.) When green plants use atmospheric carbon dioxide in photosynthesis, one atom in every million million of the carbon atoms incorporated in the plant tissues is carbon-14. Should an animal eat the plant, the carbon-14 then becomes a part of the animal's tissues. With death, an organism's intake of carbon-14 ceases, but the carbon-14 already in the tissues of the organism continues to decay at a fixed rate (Figure 16.5, page 238). By measuring the amount of radiation liberated by a sample, the ratio of carbon-14 to carbon-12 can be estimated, and from this the age of the sample can be calculated.

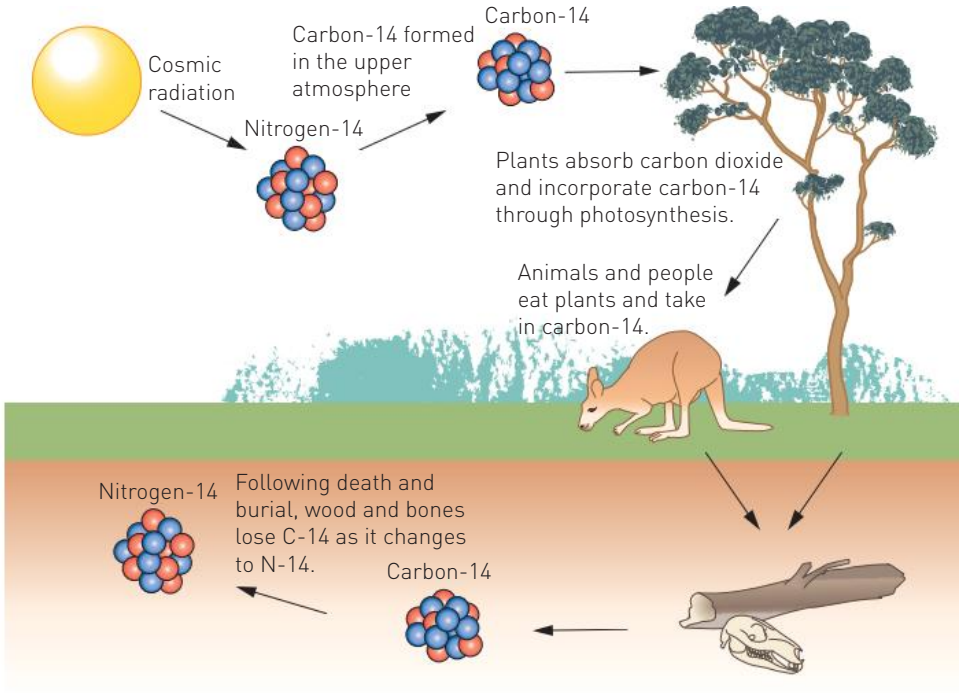


Figure 16.5 Summary showing how carbon-14 is formed, enters living things and decays

Carbon-14 dating
This website provides an animation of the use of carbon-14 dating.

How carbon-14 dating works
This website provides further explanation of the processes involved in carbon-14 dating.

Figure 16.6 shows the rate of decay of carbon-14. The ratio of radioactive carbon in the tissues of a living organism today is one carbon-14 atom to every 10^{12} carbon-12 atoms. This ratio declines to 0.5 in 10^{12} after 5730 years, to 0.25 in 10^{12} after another 5730 years, and so on. In other words, over a period of 5730 $\pm$ 40 years, half of any given quantity of carbon-14 breaks down. Therefore, this 5730 $\pm$ 40 years is known as the **half-life** of radioactive carbon.

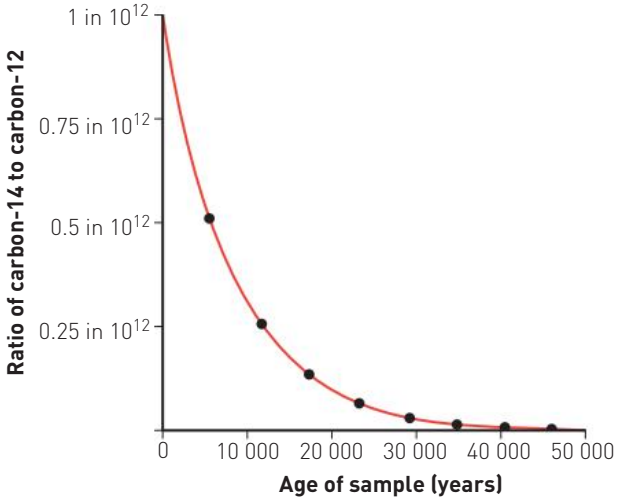


Figure 16.6 Rate of decay of carbon-14 to nitrogen. Each dot on the curve represents a period of 5730 years, the half-life of carbon-14.

The normal method of radiocarbon dating requires at least three grams of organic material so that the rate of radioactive decay of carbon-14 in the sample can be measured. A more refined technique known as **accelerator mass spectrometry (AMS) radiocarbon dating** can be used to date a sample as small as 100 micrograms. This technique involves breaking the sample up into its constituent atoms so that the number of atoms of each isotope of carbon can be counted. Using AMS radiocarbon dating, it has become possible to date cave paintings accurately from tiny samples of pigment. It has been found that such pigments often contain organic material such as charcoal, while honey, milk, blood or oil seed may have been used to bind the pigment particles.

After about 70 000 years, the quantity of carbon-14 left is negligible. For this reason the radiocarbon dating method cannot be used to date back more than about 60 000 years. A further limitation is that the material to be dated must contain **organic compounds** – that is, it must contain carbon. Radiocarbon dating is nevertheless of great value in dating fossils of more recent origin and also in dating artefacts, because these are often found in association with charcoal left from cooking fires. By dating the charcoal found in ancient hearths, the approximate age of artefacts can be deduced.

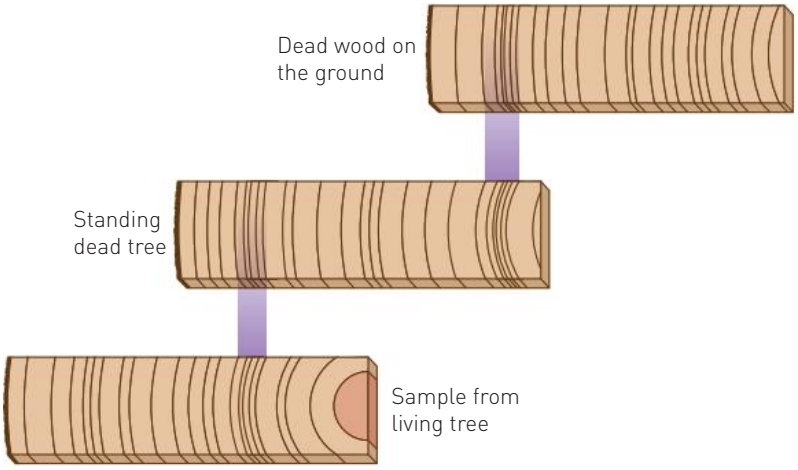


Figure 16.7 Building a tree ring chronology. Overlapped samples from living and dead trees extend the period of dating back to prehistoric times.

There is another problem with using radiocarbon dating. It was once assumed that the ratio of carbon-14 to carbon-12 in the atmosphere was constant, but it is now known that the amount of carbon-14 in the atmosphere varies. Thus, radiocarbon dates must be treated with a certain degree of caution. Corrections for the fluctuations in the carbon-14 content of the atmosphere are, however, now possible for about the past 9000 years, by reference to tree-ring dating.

Dendrochronology (or **tree-ring dating**) is another type of absolute dating that is sometimes of value in the study of human origins. You have probably seen the concentric rings on the surface of a cut tree trunk. Each ring represents one year's growth and the rings differ in width according to how favourable the growing season was. Certain rings produced in years of exceptional weather conditions can be used as marker rings. Starting with living trees, it is possible to correlate these marker rings with timber taken from ancient human structures and gradually to work back to timber thousands of years old (Figure 16.7). Living trees may be dated by drilling a small core out of the trunk wood and counting the rings. It may be noted, for example, that a particularly wide ring, indicating a year of very favourable growth, occurs near the middle of the trunk. This wide marker ring could be found near the outside of a piece of tree trunk used in an ancient structure. By such correlation of marker rings, dates for the building of the structure can be determined.

Tree-ring dating
This website provides further explanation of tree-ring dating.

Tree-ring dating simulation
This website provides a simulation of how tree-ring dating is done.

The bristle cone pine, which grows in the Sierra Nevada in the United States, has been of great value in tree-ring dating. By taking sample cores from the trunks and counting growth rings, some of the living trees have been found to be more than 4500 years old. By correlating marker rings in these trees with those of dead pines, accurate dates as far back as 8600 years ago have been established. It has been possible to use wood from these trees, accurately dated by growth rings, for radiocarbon analysis, so that the accuracy of carbon-14 dates can be verified.

A timber circle, now known as Seahenge, was discovered in the sea off the coast of England in 1998. Using a combination of tree-ring and radiocarbon dating it was found that the central stump of the circle came from a tree that had been felled in the spring of 2049 BC and was 167 years old when felled (Figure 16.8).

Figure 16.8 Seahenge

Tree-ring dating has obvious limitations. The particular conditions necessary for the use of the method do not occur often and timber is rarely preserved for more than a few thousand years, but given certain special circumstances the method can be valuable in calculating absolute ages.

Each method of absolute dating is limited in its application because each depends on the occurrence of a particular set of circumstances before it can be used. Together, however, these and other methods do give the anthropologist a number of ways of determining the actual age of ancient material. New methods are being developed all the time and there is constant improvement in the accuracy of older methods. Table 16.1 shows the approximate time span applicable to the methods described and also those of some more recently developed techniques.

Seahenge
This website provides more information about Seahenge.

Table 16.1 Useful range of common absolute dating methods

Dating method	Material used	Useful range (years BP)
Tree growth rings	wood	up to 9000
Carbon-14	carbon compounds	up to 60 000
Protactinium	sea sediments	up to 250 000
Uranium-thorium	sea sediments, coral	up to 600 000
Potassium-argon	volcanic deposits	200 000 and earlier
Electron spin resonance	calcium carbonate (in shells, coral, teeth), also quartz and flint	up to 100 000, possibly 300 000
Fission tracks	minerals and glass	100 years ago to 4550 million
Thermoluminescence	sediments, lava, ceramics	300 years ago to 100 000

EXTENSION

New techniques in establishing an absolute age for a fossil or artefact have been developed in recent years. Three of these are uranium-thorium dating, electron spin resonance and thermoluminescence.

Find out:

- the principle on which these techniques are based
- the uses to which the techniques have been put
- limitations to the use of these techniques.

Relative dating

When it is not possible to determine the actual age of a fossil or artefact, scientists can often determine whether it is older or younger than another sample, or whether it is older or younger than the rock or soil in which it is found. Such relative dating enables a sequence of events to be established.

Stratigraphy

Stratigraphy is the study of layers, or strata. There are two ways in which stratigraphy can be useful in dating fossil material. The first is the principle of superposition, which assumes that in layers of sedimentary rock the layers at the top are younger than those beneath them. Thus, any fossils or other material found in the top layers will be younger than material found lower down (Figure 16.9). This principle must be applied with care because distortions of Earth's crust do occur and a sequence of rock layers may be turned upside down. In addition, it is possible for fossils or artefacts to be buried by animals, or perhaps by early humans, some time after the deposition of sediment. In this case the specimen may be younger than some of the layers above it.

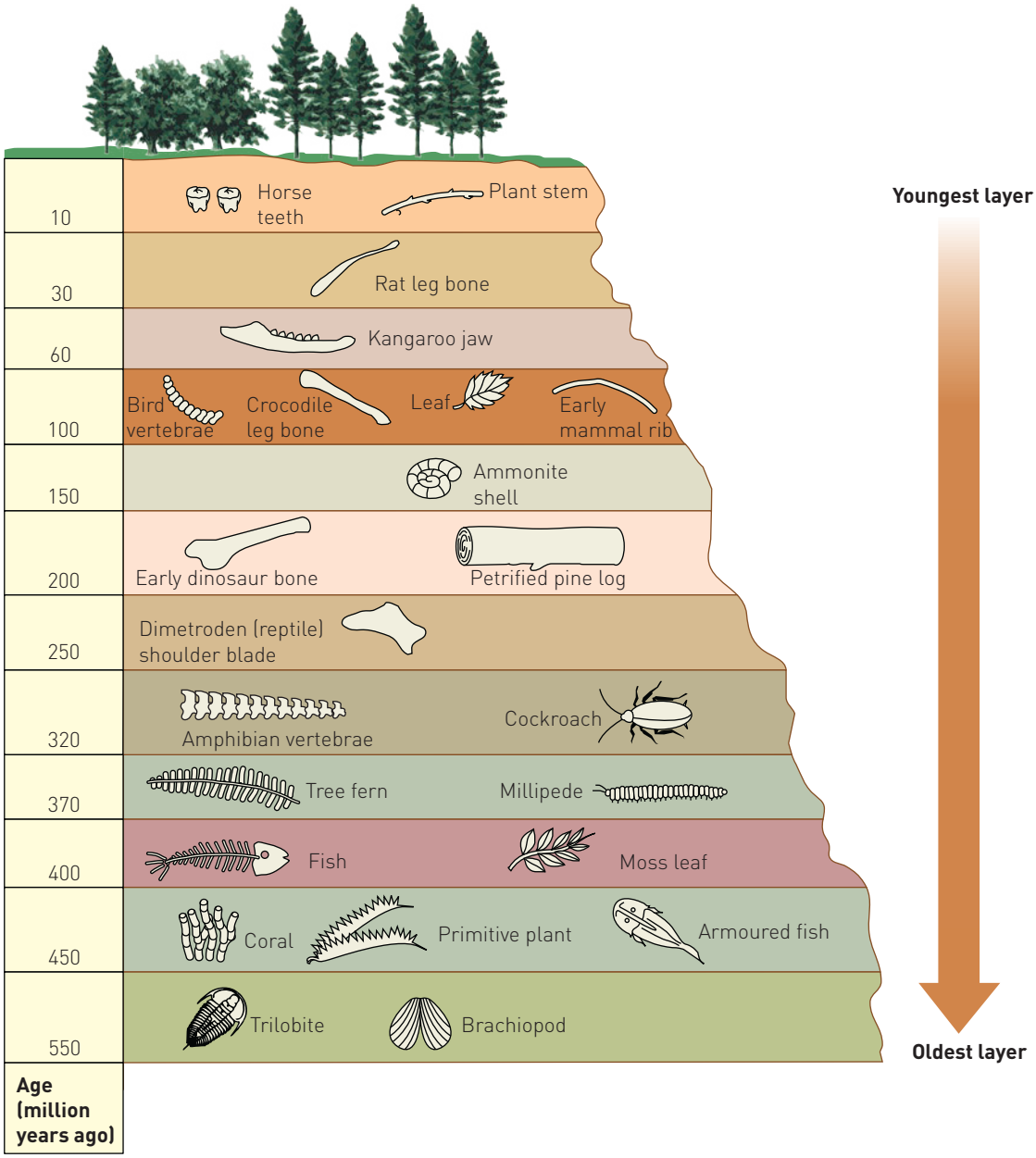


Figure 16.9 A section of rock strata containing fossils of different ages. The principle of superposition assumes that the younger strata are towards the top of the sequence.

The second use of stratigraphy is in the **correlation of rock strata**, which involves matching layers of rock from different areas. Matching of strata can be done by examining the rock itself and also by studying the fossils it contains. Rocks that contain the same fossils may be assumed to be of the same age. Certain fossils are of great value in this correlation work because they are widely distributed and were present on Earth for only a limited period of time, making the relative dating of strata more precise. Such fossils are known as **index fossils** (Figure 16.10). Figure 16.11 shows how index fossils may be used to correlate strata from different localities, often hundreds or even thousands of kilometres apart.

An analysis of **fossilised pollen grains** has developed into an important branch of science. Some fossil pollen grains are useful as index fossils, but even if they cannot be used in this way, the presence of preserved pollen grains in a soil or rock sample can enable a botanist to construct a picture of the type and amount of vegetation existing at the time the deposit was laid down. An idea of the climatic conditions prevailing at the time may then be worked out. This data can be used to confirm or refute relative dates arrived at by other methods.

Stratigraphy
This website provides more information about the problems that may arise with stratigraphy.

Getty Images/Alan Sirulnikoff

Figure 16.10 A trilobite fossil. The segmented form of the shell is clearly visible, with the head at bottom left. Trilobites make excellent index fossils as they lived between 500 and 300 million years ago before becoming extinct.

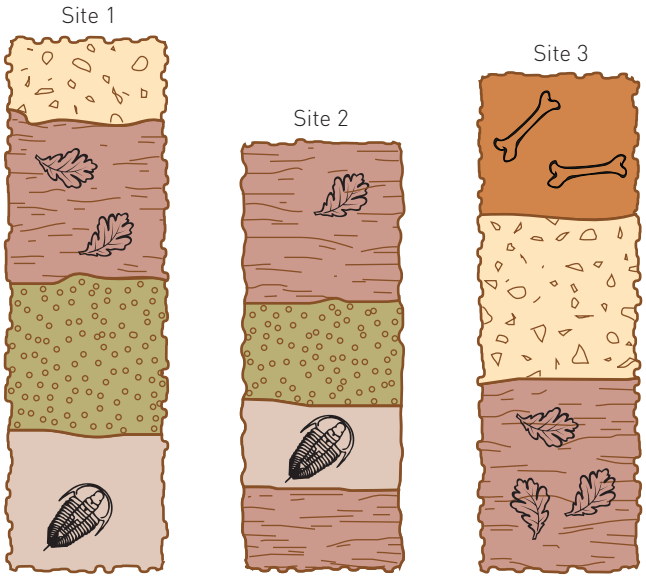


Figure 16.11 Three sets of rock strata, some containing fossils exposed in trenches at three different excavation sites. Which of the strata shown is the oldest?

Fluorine dating

Fluorine dating is another relative dating technique. It is based on the fact that when a bone is left in soil, fluoride ions, which are present in the water in the soil, replace some of the ions in the bone itself. All the fossil bones in a particular deposit should contain the same amount of fluoride, and so fossils that have been displaced can be detected. The older the fossil the more fluoride it contains, and so the relative ages can be established. It is not possible to decide absolute ages using this method, because the concentration of fluoride in ground water varies from place to place and from time to time.

Fluorine dating
This website provides additional information on relative dating, including fluorine analysis.

Piltdown Man
This website provides a more detailed account of the remarkable story of Piltdown Man.

You may have heard of the famous Piltdown skull, which was revealed as a hoax by use of the fluorine dating method. Parts of the skull and jaw bone were 'discovered' between 1912 and 1915 near Piltdown in England, and were accepted as authentic. In 1953, the 'fossils' were subjected to fluorine analysis. It was found that the fluorine content of the cranium and jaw bone did not match, so they could not possibly have come from the same sedimentary deposit. Subsequent tests showed that the cranium was indeed quite old but the jaw bone was that of a modern orang-utan. Today's sophisticated methods of dating make it unlikely that such a fake could ever again be accepted as genuine.

Phylogenetic trees

The techniques described in this and the previous chapter enable scientists to work out the likely evolutionary relationships between groups of organisms. The probable relationships can then be represented as a diagram, called a phylogenetic tree. A **phylogenetic tree**, also called a **dendrogram**, represents the evolutionary relationships between a number of organisms derived from a common ancestor. The ancestral organism forms the base of the tree, and those organisms that have arisen from it are placed on the ends of 'branches'. Relationships between the various organisms are shown by the distance between them on the tree, with closely related groups positioned on 'branches' close to one another. However, keep in mind that these are only inferred relationships; different researchers may come up with different 'trees' to fit their interpretations of the data.

Phylogenetic trees are often used to simplify more complex relationships, in order to enable them to be more easily understood. For example, in Figure 16.12 the tree on the left, labelled **a**, shows a hypothetical ancestral population that has divided to form two separate populations; each of these has divided further to produce four descendant species, A, B, C and D. Notice that the branches are thick and curving to represent the variation that may have existed in the past, and that there are side branches that have died out over the period represented. The tree on the right, labelled **b**, is a simplified representation using thin, straight lines to show the lineages of just the four descendant species A, B, C and D.

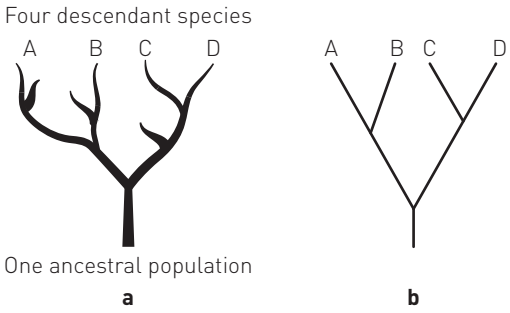


Figure 16.12 A simple phylogenetic tree representing one ancestral population and four descendant species

Phylogenetic trees are useful for representing relationships as well as organising knowledge of genetic diversity and structural classifications. They are particularly useful for showing evolutionary pathways and have been used as such since the time of Charles Darwin. Figure 15.1 (on page 218) is a phylogenetic tree. In that example, endogenous retroviruses were used to trace the common ancestry of a number of primates. The possible evolutionary pathway to *Homo sapiens* shown in Figure 19.13 (on page 295) is another example. In that case, the tree indicates one hypothetical way in which a common ancestor may have given rise to a number of hominids over an extended period of time.

Phylogenetic trees
This website provides further information on phylogenetic trees.

The geological time scale

Various methods of dating the remains of human ancestors have been discussed, but where do these dates fit into the span of time since the beginning of Earth? Because of the tremendous time span involved, Earth's geological history has been divided up into a **geological time scale**. The time scale consists of eras, which are subdivided into periods, and the periods are further subdivided into epochs (Table 16.2).

Table 16.2 The geological time scale covering the past 600 million years

Era	Period	Epoch	Millions of years BP
Cainozoic (Cenozoic)	Quaternary	Holocene (Recent)	0.012 (11 700 years)
		Pleistocene	2.6
	Tertiary	Pliocene	5.3
		Miocene	23
		Oligocene	34
		Eocene	56
		Palaeocene	65
Mesozoic	Cretaceous		145
	Jurassic		200
	Triassic		251
Palaeozoic	Permian		299
	Carboniferous		359
	Devonian		416
	Silurian		444
	Ordovician		488
	Cambrian		542
	Ediacaran		635

In studying the origins of humans we are interested in only a very small portion of Earth's history – the time covered by the Cainozoic era – because the primates, the group to which humans belong, first evolved at the beginning of this era. When a fossil is assigned a particular place in the time scale it is being given a relative age. For instance, if a fossil is said to be of Miocene origin, it means that it is younger than Oligocene fossils but older than Pliocene fossils.

Problems with the fossil record

The fossil record is very incomplete as conditions for fossilisation do not always occur, or occur at irregular periods of time. For fossils to be formed, four conditions are usually required:

- a quick burial of the material
- the presence of hard body parts
- an absence of decay organisms
- a long period of stability – the organism needs to be left undisturbed.

Fossilisation is therefore a chance occurrence and there are many gaps in the fossil record because organisms have not been preserved.

Another reason for gaps in the fossil record is that only a very small proportion of the fossils that do exist have actually been discovered. Some are buried too deep in the ground to be found, or are in inaccessible places. Others may have been inadvertently destroyed by human activity such as agriculture or industry.

Even when fossils are found, dating the fossil material can be problematic. To use carbon dating techniques, material containing carbon must be present, and the material can only be dated back to 60 000 years or so. To date material older than this, the age of the fossil is determined by the sediments in which it is found. For example, the use of potassium-argon dating relies on suitable material, such as volcanic lava, being present.

It is unusual to find a fossil of an entire organism, or the whole skeleton of an organism. This is particularly true of fossils of human ancestors. Often, from just a few fragments of bone, scientists have to reconstruct what the organism may have looked like. Figure 16.13 shows a reconstructed skull of *Homo ergaster*. Found in Kenya, the fragments were dated at around 1.8 million years old, and were pieced together like a jigsaw puzzle. Areas shown in black are parts of the skull where bones are missing. Experts have estimated the shape of the face and upper jaw in order to complete the reconstruction. Such reconstructions are only approximations based on the experience of the scientists involved. Other scientists may disagree with the interpretation and this can lead to considerable controversy. The only resolution to such disagreements is to find more fossils; but as we have seen, even if there are more fossils, the chances of finding them are often slim.

Evidence for evolution
This website provides a review of evidence for evolution that has been discussed in this chapter and the previous one.

WS

Fossil evidence for evolution

Figure 16.13 The reconstructed skull of *Homo ergaster*

Science inquiry

ACTIVITY 16.1 Radioisotope methods of dating

Radioisotopes are the basis of two of the absolute dating techniques described in this chapter. Isotopes are the different forms of an atom. Atoms are composed of particles called electrons, protons and neutrons, and the number of electrons and protons determines the type of atom.

Some isotopes are stable – the number of electrons, protons and neutrons they have does not change. Other isotopes are unstable. This results from changes in the number of particles in such a way that, over a period of time, the isotope changes into some other atom. When this occurs, radioactivity is emitted. It is for this reason that they are called radioisotopes.

Radioactive isotopes have a half-life – the time it takes for half the atoms to undergo the transition from one atom to the other. In the first half-life, half the atoms make the transition. In the second half-life, half the remaining atoms make the transition, leaving one quarter of the original material. In the third half-life, half again make the transition, leaving only one eighth of the original material, and so on.

Radioisotope methods of dating assume that the decay rate of a given isotope is constant and has always been so. Only if nuclear decay rates are constant can the method be used to reliably estimate the age.

YOU WILL NEED

Graph paper; pencils; rule; eraser

A. RADIOCARBON DATING

Radiocarbon dating is based on the decay of the radioactive isotope of carbon, carbon-14 (^{14}C), to nitrogen. When this occurs, radioactivity is released. The decay rate of ^{14}C in material from living organisms or from those that have recently died is 15.6 disintegrations per second per gram of material. After one half-life, 5730 years, the number of disintegrations will be 7.8 disintegrations per second per gram of material (abbreviated to nuclei/s/g).

WHAT TO DO

1 Draw up a table like Table 16.3 and fill in all the gaps.

Table 16.3 Decay rate of carbon-14

Half-life	Age (years)	Radioactivity (nuclei/s/g)	Half-life	Age (years)	Radioactivity (nuclei/s/g)
0	0	15.6	6		
1	5730	7.8	7		
2			8		
3			9		
4			10		
5					

2 On your sheet of graph paper, plot a decay curve for carbon-14 to show the relationship between decay rate and time, up to a maximum of 60 000 years. (Before doing this, you may wish to check page 13 on how to draw a graph.)

3 Use your graph to answer the following questions.

a Charcoal remains from a hearth in a cave occupied by Australian Aborigines were found to have a decay rate of 8.9 nuclei/s/g of charcoal. How old was the charcoal?

b A piece of wood buried in a cave in Europe was found alongside stone tools that were considered to be about 9000 years old. If the wood were the same age as the tools, what decay rate would you expect from the piece of wood?

c If the piece of wood from question **b** was found to be considerably older than 9000 years, what explanations can you offer for the fact that it was at the same level in the cave deposits as the tools?

d If the piece of wood was found to be considerably younger than 9000 years, suggest reasons to account for the fact that it was at the same level in the cave deposits as the tools.

e A fossil bone was discovered and when tested had a decay rate of 1.5 nuclei/s/g. How old was the fossil bone?

f A piece of fossilised wood was dated using the tree ring method at 4000 years old. What decay rate would you expect it to display when it was subject to carbon-14 analysis?

B. POTASSIUM-ARGON DATING

Potassium-argon dating is based on the decay of radioactive potassium (^{40}K) to form calcium (^{40}Ca) and argon (^{40}Ar). This decay is very slow as potassium-40 has a half-life of around 1300 million years, so the material to be dated must be very old, usually more than 200 000 years. Argon-40 is not normally found in rocks unless it is trapped in solid lava from volcanic eruptions. This occurs when potassium-40 decays. Because the rate at which potassium-40 breaks down into argon-40 is known, it is possible to determine the age of the lava by measuring the ratio of potassium-40 to argon-40.

WHAT TO DO

Study Figure 16.14 carefully, and then answer the following questions. Layers A, C, E and G are lava and contain trapped atoms of potassium-40 and, in most layers, argon-40.

1 Explain why there is no argon-40 in layer A.

2 Determine the ratio of potassium-40 to argon-40 in layer E.

3 Rock layers B, D and F are composed of the same material. What type of material do you think this would be? Explain how it has come to be between the alternating layers of lava.

4 Explain why there are no fossils in layers A, C, E and G.

5 Layers B, D and F all contain fossils. For this to have occurred, conditions must have been suitable for fossilisation. Describe the conditions that assist the process of fossilisation.

6 Anthropologists working at this site believe that layer B was formed around 40 to 70 thousand years ago. This date is too early to use the potassium-argon technique. Suggest at least two ways in which they could determine the age of layer B. Explain how each of these methods works.

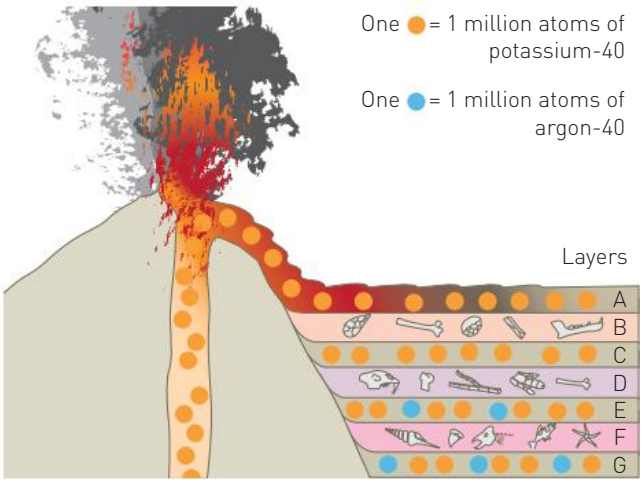


Figure 16.14 Erupting volcano. This volcano has erupted periodically for millions of years.

ACTIVITY 16.2 Stratigraphy

Observation of rock strata from various sites around the world has indicated that, in many cases, similar strata contain very similar or identical fossils. In this activity you will examine three series of hypothetical strata from two locations in Australia. The different strata are shown in three series (Figure 16.15).

WHAT TO DO

Study Figure 16.15 carefully and then answer the following questions.

1. How do you think these sediments were formed?
2. The various layers in series A and series B no longer align with each other. Explain how this may have happened.
3. Of all the strata shown in series A, B and C, which is the oldest? Explain how you arrived at your answer.
4. Of all the strata shown, which is the youngest? Explain how you arrived at your answer.
5. Layers A2 and B6, and B1 and C6, contain the same types of fossils. Would these be index fossils? List the criteria that must be met for a fossil to be considered an index fossil.
6. A fossil in layer A4 was dated at 45 000 years using carbon-14 dating. What can you infer about the relative ages of layers B6 and C8?
7. Could layer A6 be dated using the potassium-argon technique? Give reasons for your answer.
8. Do you think dendrochronology could be used to determine an absolute date for layer C2? Again, give reasons for your answer.

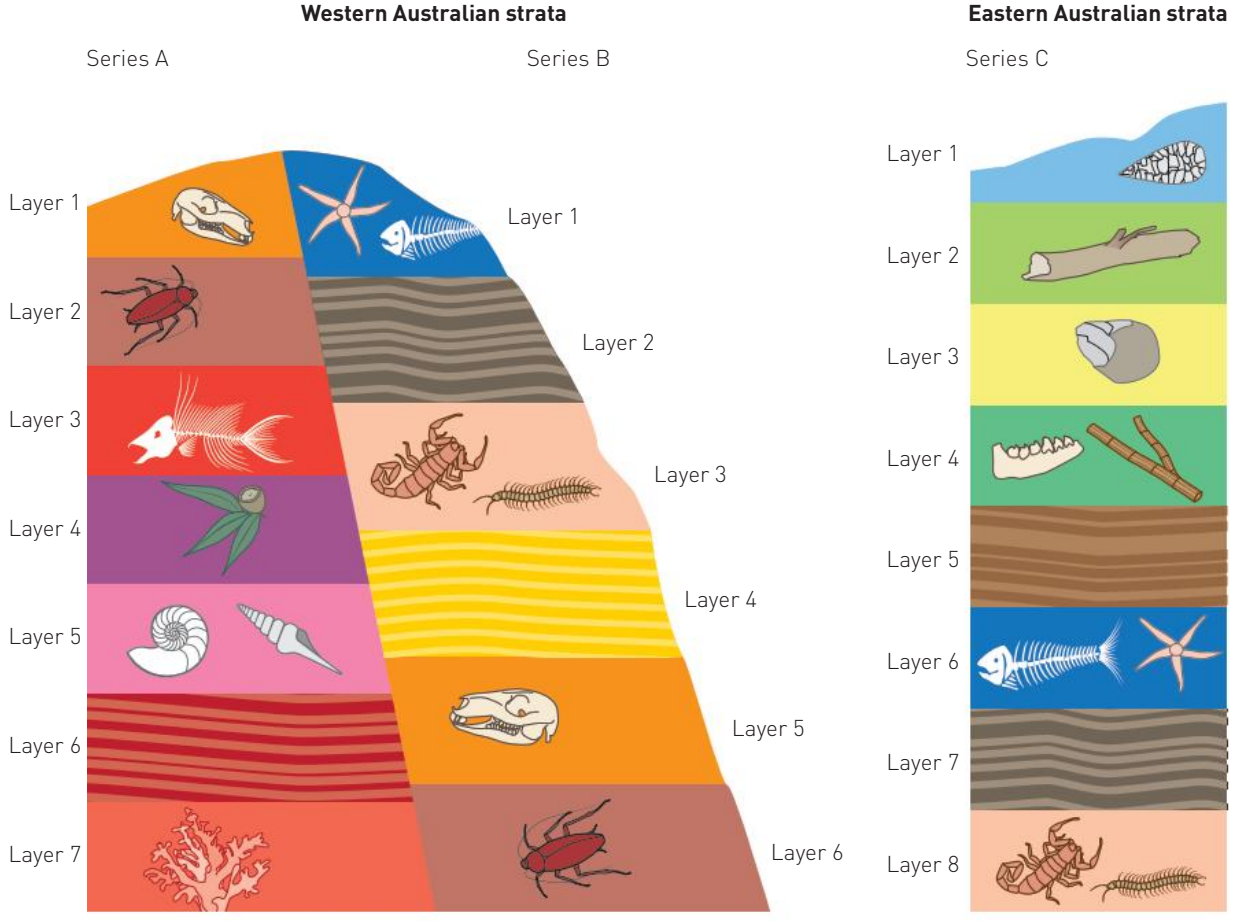


Figure 16.15 Strata from two locations in Australia

ACTIVITY 16.3 Phylogenetic trees

The increasing number of techniques in biotechnology are providing scientists with a wealth of data that can be used to examine the evolutionary relationships between species. In this activity you will use some of this data to construct phylogenetic trees.

WHAT TO DO

1. Refer to Table 15.1 on page 217, which shows the relationship between humans and great apes using DNA differences. Using this information, construct a phylogenetic tree to show diagrammatically the evolutionary relationships.
2. Refer to Table 15.4 on page 222. This table shows the differences in amino acids in cytochrome C between humans and a number of other species. The more similarity there is between two molecules, the more recently they have evolved from a common ancestor. Using this information, construct a phylogenetic tree to show the evolutionary relationships between the species listed.
3. Refer to Table 15.6 on page 230, which shows the amino acid sequences in the haemoglobin of six mammalian species. Using the data presented in the table, construct a phylogenetic tree to show the evolutionary relationships between the species shown.

STUDYING YOUR DATA

Compare the trees you have constructed with those of other members of the class and then answer the following questions.

1. How much variation was there among the phylogenetic trees constructed by different class members? Explain any similarities and differences with the ones you have created.
2. In the three trees you have drawn, does one animal appear to be more closely related to humans?
3. In which of the three trees do you have the most confidence as a good representation of evolutionary relationships? Why did you select this tree?
4. When a phylogenetic tree is constructed it can be considered a way of presenting a hypothesis. Explain why.

Review questions

1 **a** Define 'fossil'.
b Give examples of five different forms of fossils.
2 **a** Explain the difference between a fossil and an artefact.
b What is an index fossil? Could there be such things as index artefacts?
3 **a** What soil types are best for the preservation of fossils?
b Why is it that fossilised soft tissue, such as muscle, is rarely found by those searching for fossils?
4 **a** What do you understand by the terms 'relative dating' and 'absolute dating'?
b Why is relative dating used when a number of good methods of absolute dating are available?
5 Draw up a table with three columns, listing in the first column the methods of absolute dating described in this chapter. In the second and third columns, list the advantages and limitations of each method.
6 **a** Explain the principle behind radioisotope methods of dating.
b Describe why potassium-argon dating cannot be used to date fossil bones.
7 **a** How is it that the bodies of plants and animals have radioactive carbon-14 in them?
b What does it mean to say that carbon-14 has a half-life of 5730 years?
c Why is it not possible to use radioactive carbon dating on artefacts?
d What is AMS radiocarbon dating?
8 What is dendrochronology and in what situations would it be useful to a scientist dating fossil material?
9 **a** What is the principle of superposition?
b Does this principle always apply? If not, explain why.
10 **a** Explain how index fossils can be used to compare strata from different locations.
b Describe the different ways in which fossil pollen grains can be of use to the anthropologist.
11 **a** Why is it that fluorine dating cannot give the absolute age of a fossil?
b Do older fossils contain more or less fluorine than younger fossils?
c Describe a situation where fluorine analysis has shown the component parts of a fossil to be of different ages.
12 **a** What are phylogenetic trees and why are they used?
b List the techniques described in this chapter and in Chapter 15 that would provide information that could be used to draw a phylogenetic tree for human ancestors.
13 If a fossil is said to be of Oligocene age, is this an absolute date or a relative date? Explain your answer.

Apply your knowledge

1 Anthropologists excavating the floor of a cave found, at a depth of 50 centimetres, a deposit of charcoal that they concluded was the site of an ancient hearth. Next to the hearth, at the same depth, was a stone tool. Radiocarbon analysis of the charcoal showed that the ratio of carbon-14 to carbon-12 was 0.25 in 10^{12}. Further excavation uncovered, at a depth of 95 centimetres, a fragment of human jaw bone and the thigh bone of another animal. Fluorine analysis showed that the thigh bone had a much higher fluorine content than the jaw bone.
a What would be the estimated absolute age of the stone tool?
b What would be the relative ages of the stone tool, the jaw bone and the thigh bone? Explain fully how you arrived at your answer.
c Can you be certain of the relative dates? Explain why or why not.
2 The sand dunes around the Australian coast consist of alkaline soil. If an animal was buried in the dunes by drifting sand, would its bones become fossilised, provided they were left undisturbed for long enough? Explain the reasons for your answer.

3 In the peat bogs of England, Denmark and other parts of northern Europe, human bodies up to 4000 years old have been found. The hair, skin and other soft tissues have been so well preserved that the fingerprints can still be seen on the skin of the hand, and food in the alimentary canal is complete enough to indicate the nature of the last meal eaten.
   a Describe the types of conditions that must be present in peat bogs to allow preservation of these tissues for such a long period of time.
   b Would you expect the skeletons of these 'bog people' to be preserved? Why, or why not?

4 Refer to Figure 16.11 (page 242) and describe the reasoning you employed to work out which was the oldest stratum.

5 Construct a table with four columns titled 'Technique', 'Relative or Absolute', 'Time span' and 'Weaknesses'. List the various dating techniques described in this chapter in the first column, and for each indicate whether it is an absolute or relative dating technique, the period of time (in years) for which the technique is useful, and the weaknesses or problems associated with that technique.

6 Riversleigh, in north-west Queensland, is one of the world's most important and abundant fossil sites. Fossils found at Riversleigh include kangaroos, wombats, bandicoots, possums, koalas, platypuses, crocodiles, snakes, turtles, lungfish, birds, frogs, snails and insects.
   a From this list of some of the fossils found at Riversleigh, write a description of what the area must have been like when the fossil animals were alive.
   b What conditions must have occurred at Riversleigh for so many organisms to have been fossilised?

7 Some scientists found a few fragments of a fossil skull. Referring to other fossil skulls, they decided it was the skull of an early human. Using their extensive experience, they made a reconstruction of what they thought the complete skull would have looked like. When they published the results of their investigations, many other scientists disagreed with the findings and stated that the fossil fragments were from an ape. List as many possible reasons as you can for the disagreement among the scientists.

CHAPTER 17

PRIMATE EVOLUTION

UNIT 4 CONTENT

SCIENCE INQUIRY SKILLS

- represent data in useful and meaningful ways; organise and analyse data to identify trends, patterns and relationships; discuss the ways in which measurement error, instrument accuracy, the nature of the procedure and sample size may influence uncertainty and limitations in data; and select, synthesise and use evidence to make and justify conclusions

SCIENCE UNDERSTANDING

Hominid evolutionary trends

- humans as primates are classified in the same taxonomic family as the great apes. The species within the family are differentiated by DNA nucleotide sequences, which brings about differences in:
  - relative size of cerebral cortex
  - mobility of the digits
  - locomotion – adaptations to bipedalism and quadrupedalism
  - prognathism and dentition

Look carefully at the animals shown in the figure below. What characteristics do they have in common? What differences enable us to distinguish between them? Are the similarities of more significance than the differences? Do any of them have human characteristics?

All the animals shown in Figure 17.1 are classified as a group called **primates**. Humans belong to this group. This is why primates are of such great interest to us. By studying the characteristics of primates and the evolutionary trends within the group, we are studying our own evolutionary history.

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Getty Images/Anup Shah

Figure 17.1 Clockwise from top left: ring-tailed lemur, macaque (Old World monkey), tarsier, orang-utan, woolly monkey (New World monkey)

As early as the eighteenth century, scientists recognised the similarities between humans, monkeys and apes. One of these scientists was Carolus Linnaeus (1707–78). He was one of the first to consider that similarities in structure could form the basis of a systematic classification of all the known animals and plants.

It was Linnaeus who established the basis of our current system of classification and the binomial system of naming organisms. The **binomial system** uses the generic (genus) and specific (species) names for the scientific name of a species. Using this system, humans are referred to as *Homo sapiens*, chimpanzees as *Pan troglodytes*, and gorillas as *Gorilla gorilla*.

Classification
This website provides an outline of the Linnaean system of classification.

What are primates?

Humans, apes, monkeys and some other related animals are called primates because they are all classified together in the order Primates. The non-human primates are of special interest to us because they are the closest living relatives of our own species. A comparative study of primates is fundamental to any investigation of the evolution of modern humans. In trying to develop an understanding of how human characteristics evolved, a number of sources of evidence can be used:

- comparative anatomy of the primates
- comparative biochemistry

› behaviour of living primates
› fossils of primates.

In this chapter we look at the characteristics that define primates as a group. We also consider some of the evolutionary trends in primates – that is, the gradual changes in characteristics that occurred as primates became more highly evolved.

All living things are classified into groups that form a hierarchy. A hierarchy is a series of groups that move from broad general categories to narrow specific ones (Figure 17.2). Living things are grouped first into kingdoms. Two of the kingdoms are the plants and the animals. Primates are animals. Each kingdom is then divided into groups known as phyla (singular **phylum**). Each phylum is further divided into classes, and classes are divided into **orders**. All primates belong to the order Primates. As we go down the hierarchy, the organisms in each group have more and more characteristics in common. This is illustrated in Table 17.1 (on page 254) and Figure 17.2.

Therefore, to answer the question posed at the start of this section, primates are members of the order Primates. Examples of different types of living primates are given in Figure 17.1 and Figure 17.2. They are classified into that order because they all share certain important characteristics. There are also differences between the primates and some of these differences can be identified as evolutionary trends. In this chapter we will focus on some of the evolutionary trends shown by primates. In the following chapters we will concentrate on one particular primate – humans.

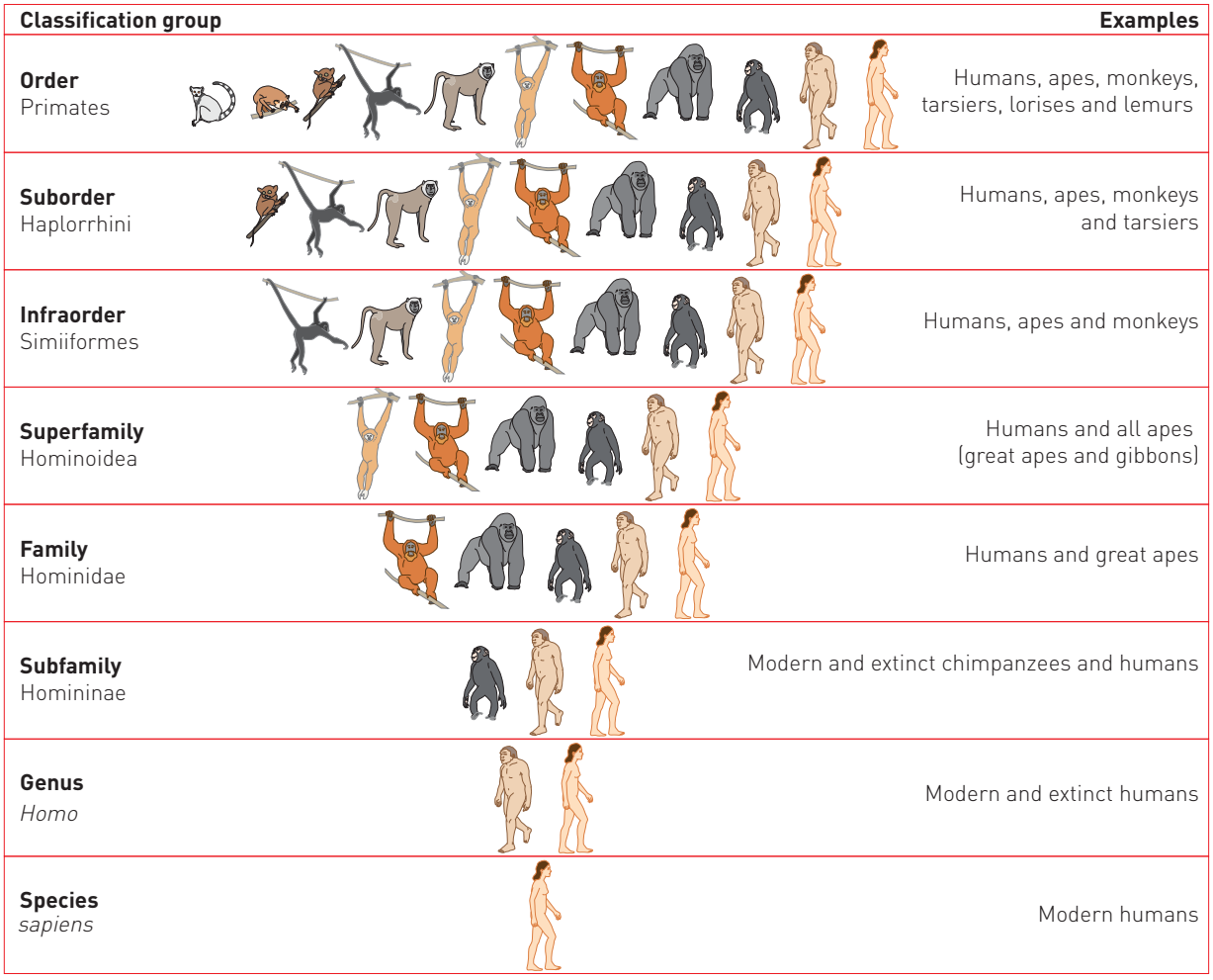


Figure 17.2 A diagrammatic representation of the hierarchy within the primate order

Table 17.1 The classification of humans within the primate order

Level of classification	Name	Examples
Order	Primates	Primates include tarsiers, lemurs, lorises, monkeys, apes and humans
Suborder	Haplorrhini	Haplorrhini include tarsiers, monkeys, apes and humans
Infraorder	Simiiformes	Simiiformes include monkeys, apes and humans
Parvorder	Catarrhini	Catarrhines include Old World monkeys, apes and humans
Superfamily	Hominoidea	Hominoids include apes and humans
Family	Hominidae	Hominids include all modern and extinct orang-utans, gorillas, chimpanzees and humans
Subfamily	Homininae	Hominines include all modern and extinct chimpanzees and humans
Tribe*	Hominini	Hominins include extinct ancestors of humans and modern humans
Genus	*Homo*	*Homo* includes some extinct ancestors of humans and modern humans
Species	*sapiens*	*Homo sapiens* are modern humans

**Note*: Tribe is a classification group within a subfamily. The meaning of tribe here is different from the use of tribe to describe an ethnic group of people.

Classifying primates

Like all aspects of science, classification is dynamic. It is constantly changing as new evidence about relationships between organisms is discovered. The classification of the primates is no different. It is almost in a constant state of change as new information becomes available. Evidence from the study of protein sequences and DNA (see Chapter 15) has changed the way scientists view the relationships between various groups of primates. For example, classification schemes that were based solely on morphology (body form and structure) have been changed as a result of these molecular studies. Earlier classifications divided the primates into two groups – the prosimians (primitive primates) and the anthropoids (monkeys, apes and humans). In those classifications, the tarsiers were included with the prosimians. Many scientists now consider the tarsiers to be more closely related to monkeys, apes and humans. They divide the order Primates into the suborders Strepsirrhini and Haplorrhini. Strepsirrhini contain the non-tarsier prosimians, while the Haplorrhini include the tarsiers, monkeys, apes and humans. A simplified classification of the primates is shown in Figure 17.3; keep in mind that this is only one interpretation of the evidence.

Primate images
This website has some excellent photos of primates.

EXTENSION

Using a variety of research techniques, discover what evidence led scientists to change the classification of primates at the suborder level. In doing so find out:

- if this evidence is widely accepted by the scientific community
- what evidence contradicts such a classification.

Humans are classified in the same family as the great apes: chimpanzees, bonobos, gorillas and orang-utans. The great apes are our closest living relatives and share many of our characteristics, including very similar DNA (see Table 15.1 on page 217).

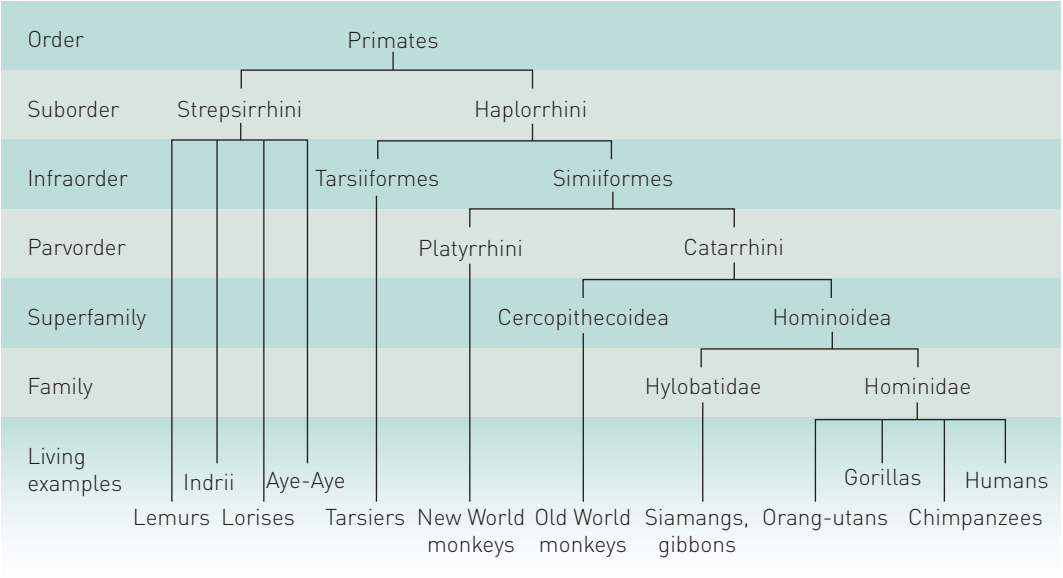


Figure 17.3 A simplified classification of the primates

Characteristics of primates

There is no one characteristic that can be used to separate the primates from all other mammals. However, some features shared by all primates can be used to identify them as a group. Most of these features are a result of primates having evolved in an **arboreal**, or tree-like, environment (Table 17.2). Two of these, grasping fingers and toes and overlapping vision, when taken together are distinctive to the primates.

Table 17.2 A summary of the characteristics of members of the order Primates

Feature	Primate characteristics
Body	Not specialised for a particular environment
Limbs	Generally unspecialised
Hands/feet	Pentadactyl – five fingers or toes Nails instead of claws Grasping fingers and toes with friction ridges for gripping First digit opposable
Eyes	Forward facing for three-dimensional (stereoscopic) vision Most are able to distinguish colour
Sense of smell	Very poor
Teeth	Four incisors in both the upper and lower jaw
Brain	Large and complex Cerebrum size increases as primates become more highly evolved
Reproduction	Not restricted to a breeding season Rhythmical sexual cycle Usually only one offspring at a time Long period of parental care for offspring

What is a primate?
This website provides a detailed account of the features we use to identify a primate.

Primate characteristics
This website provides information about what makes a primate a primate.

The distribution of primates
This website provides information about the distribution of primates and their characteristics.

Evolutionary trends within the primates

Primates – more than any other order of mammals – show a gradual change in characteristics from the lemurs and lorises to the monkeys, apes and humans. This series of characteristics suggests an evolutionary trend within the order that will be explored in more detail in the remainder of this chapter.

Digits

The limbs of primates tend to be unspecialised in structure, which allows for great diversity in their use. They are **pentadactyl**, which means they have five digits on each limb. The digits are highly mobile, a feature that can be related to the arboreal way of life of primate ancestors. Grasping, or **prehensile**, digits were essential for climbing by wrapping the digits around the branches of trees. The evolutionary trend is toward increasing ability to move the digits independently of one another. The most highly developed digits in this respect are the thumb and the big toe. Not only are they independent, but they are also opposable in most primates. **Opposability** means that the first digit can be moved in such a way that it can touch each of the other digits.

The degree of opposability varies from species to species and depends on the relative length of the first digit compared with the other four (Figure 17.4). Almost all species of primate show some opposability of the big toe, with humans being the one notable exception. Our big toe is not opposable at all. Opposability was lost when the human foot became a weight-bearing rather than a grasping appendage. However, humans do possess the longest thumb of all primates and this has contributed considerably to our ability to manipulate objects with our hands (Figure 17.5).

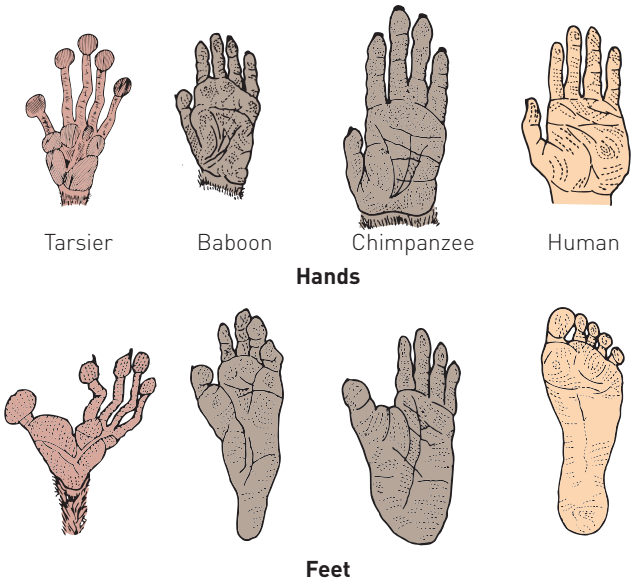


Figure 17.4 Hands and feet of four primates. Unlike other primates, humans do not have an opposable big toe.

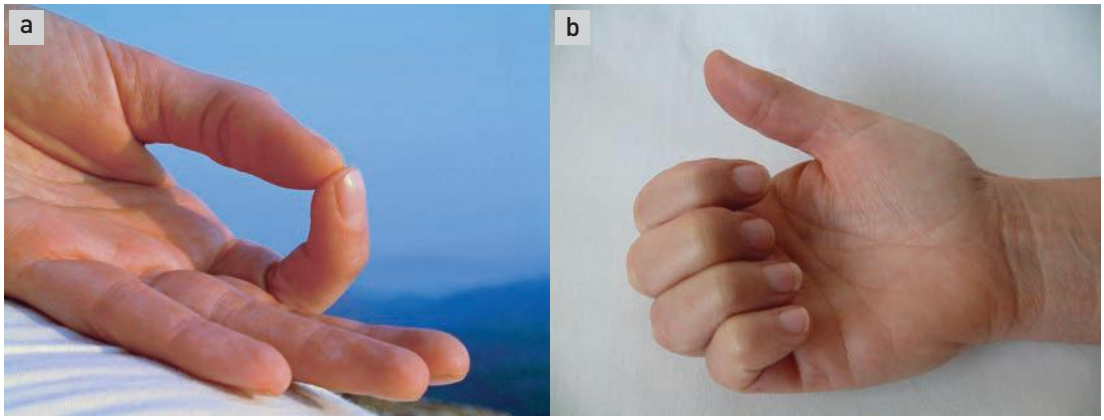


Figure 17.5 Manual dexterity of the human hand: **a** opposability of the thumb as it moves across the palm to touch the other digits; **b** prehensile digits are capable of being wrapped around an object – here the fingers are being curled towards the palm of the hand.

For primates to find and maintain a secure grip in trees, the tips of the digits have gradually become modified. Primates therefore have **nails** instead of claws on their fingers and toes. Claws limit grasping, as they prevent the opposable surfaces from coming together (Figure 17.6). Nails evolved from claws that became flattened. Some of the evolutionarily less advanced primates still possess claws. For example, aye-ayes have claws on all their digits except the big toe, and lemurs have a claw on their second toe. This is known as a 'toilet claw' and is used for scratching (Figure 17.7).

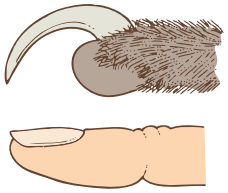


Figure 17.6 Differences between claws and nails

As a further development, the ends of the digits have sense receptors so that the digits can grip and manipulate objects. Nails on the backs of the digits and tactile pads on the under surface evolved together. These pads developed small ridges to increase the grip between the ends of the digits and an object. These are called **friction ridges**, or fingerprints, and the pattern varies between individuals and from species to species (Figure 17.8).

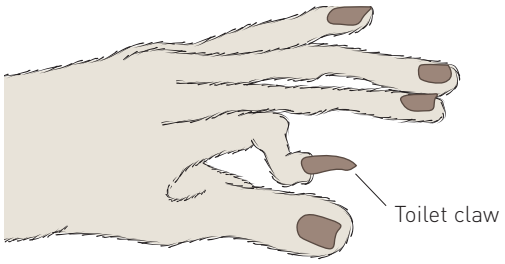


Figure 17.7 The toilet claw of a lemur

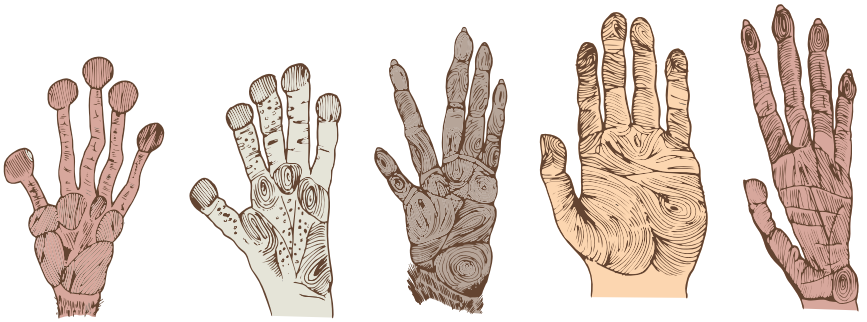


Figure 17.8 The fingerprint patterns of a variety of primates

Having highly mobile digits has enabled humans, more than any of the other primates, to manipulate objects with great skill. The human hand is short and broad, with short, straight fingers and a long, strong thumb, compared with that of the other primates. This arrangement gives the thumb a great degree of freedom, and it can readily oppose each of the other digits, thumb tip to fingertip, allowing humans to grasp objects with precision. The **precision grip**, such as that used for holding a pencil when writing (Figure 17.9), or a needle when sewing, is one of the hallmarks of being human, although it is not unique to humans. What is unique, however, is the amount of contact between the index finger and thumb. This enables humans to handle small or delicate objects effectively.

The precision grip requires the presence of a truly opposable thumb and is also seen in Old World monkeys, particularly the ground-living baboons, mandrills and macaques. These monkeys are second only to humans in their manipulative abilities.

Figure 17.9 The precision grip

Dentition

Evolutionary changes have taken place in the dentition of the primates, in both the number of teeth and their structure. As with most mammals, primates have two sets of teeth, deciduous and permanent, and teeth of different shapes that perform different functions.

The number of each type of tooth that a species has can be expressed as a **dental formula**. The formula gives the number of each type of tooth in one quarter of the jaw. Primitive mammals had a dental formula of 3:1:4:3 – that is, three incisors, one canine, four premolars and three molars on each side of each jaw, a total of 44 teeth (Figure 17.10).

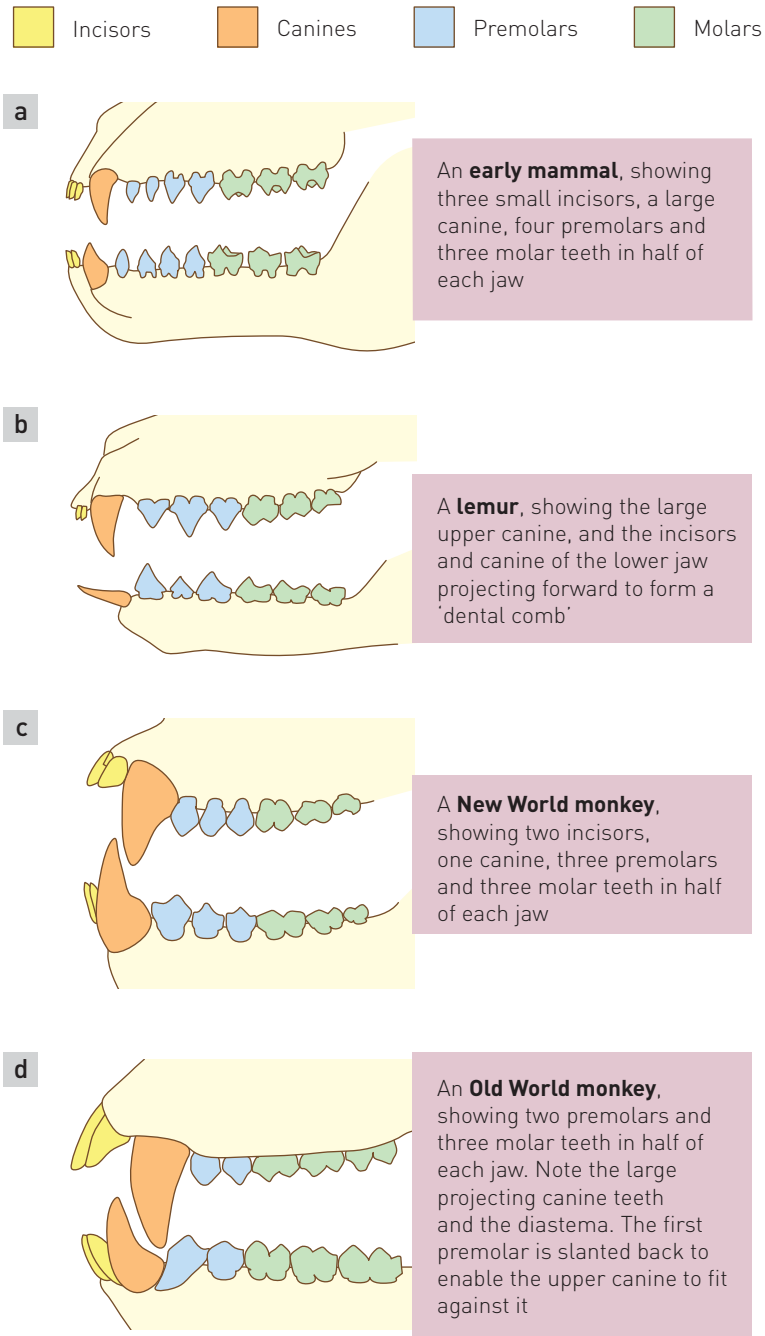


Figure 17.10 The dentition of **a** an early mammal, **b** a lemur, **c** a New World monkey and **d** an Old World monkey

Natural selection has resulted in a decrease in the number of teeth in primates compared with early mammals. This is probably related to the gradual reduction in the size of the face and jaw that has occurred in primates. Lemurs and lorises, for example, have 36 teeth and a dental formula of 2:1:3:3, while tarsiers have lost two incisors from their lower jaw to give a dental formula of 2:1:3:3 for the upper jaw and 1:1:3:3 for the lower jaw. New World monkeys have the same number of incisors, canines and premolar teeth as the lemurs and lorises, but they show an evolutionary trend for the third molar. This tooth is usually small and often absent in many of these monkeys, and it is not present at all in the marmosets. Old World monkeys, apes and humans all have 32 teeth and a dental formula of 2:1:2:3; however, there is considerable difference between them in the structure and arrangement of the teeth.

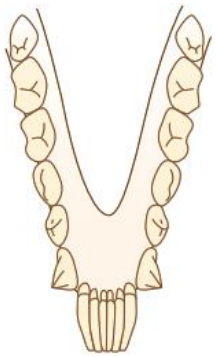


Figure 17.11 The 'dental comb' of the lemur lower jaw, used for grooming

Besides the trends observable in the number and arrangement of the teeth, there is also variability in tooth form. Both the lemurs and the lorises have an unusual specialisation of the incisor teeth. The lower front incisors, and sometimes the canines, are slanted forward with the crowns narrow and closely spaced to form a 'dental comb' (Figure 17.11). This 'comb' is used in the grooming of the fur, and only rarely for feeding or fighting.

The canines are usually large and sharply pointed in the Old World monkeys and apes, and they project beyond the level of the other teeth. Such large canines have required modifications to adjacent teeth so that the mouth can be closed. Most primates with large canines have a gap, or **diastema**, between the upper second incisor and the upper canine to accommodate the large lower canine (see Figure 17.10d). To allow for the large upper canine, the crown of the first lower premolar is slanted back and has a sharp edge. The upper canine fits tightly against this premolar and is sharpened by the grinding that occurs.

In general terms, the molar teeth of primates show little change from those of early mammals. This may be related to the somewhat generalised diets that most primates have. The three-cusped molars of early mammals have evolved into a highly distinctive four-cusp pattern in Old World monkeys. A further trend is seen with apes and humans where the lower molars have five cusps forming what is frequently called a Y-5 pattern (Figure 17.12). This pattern has been useful in identifying the teeth of fossil apes and humans, and is presumed to have evolved due to the predominantly fruit diet of the apes.

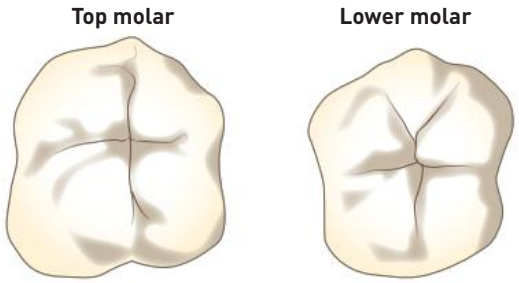


Figure 17.12 The difference in structure between a four-cusp and a five-cusp tooth. The 'valleys' between the four cusps of the top tooth form a '+' pattern, while the 'valleys' between the five cusps of the lower tooth form a 'Y'.

As mentioned in Chapter 16, when searching for remains of human and primate ancestors, anthropologists frequently find teeth (see Figure 20.15 on page 313). The hard enamel covering helps them to resist decomposition. Scientists often use fossil teeth as an indication of diet, but care needs to be taken in making any interpretation. As we have just seen, not all primate dentition is related to diet, the 'dental comb' of lemurs and lorises being a good example. In addition, the large canine teeth of Old World monkeys and apes are more important in predator defence and social displays than for a meat-eating diet.

Primate dentition
This website provides more information on primate dentition and other primate characteristics.
Click on 'technical characters (teeth)' for a comparison of teeth from different primate families.

EXTENSION

Anthropologists searching for fossils of early primates frequently find teeth.

Find out:

- why teeth are more frequently found than other parts of the body
- what information teeth can provide to the anthropologist.

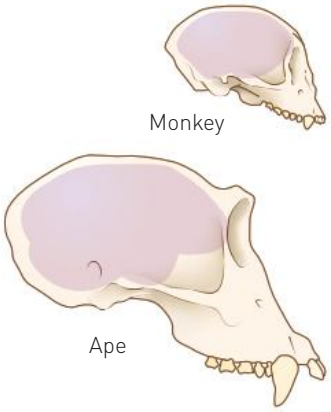


Figure 17.13 Comparison of the size of the brains and skulls of a monkey and an ape (both skulls are drawn to the same scale)

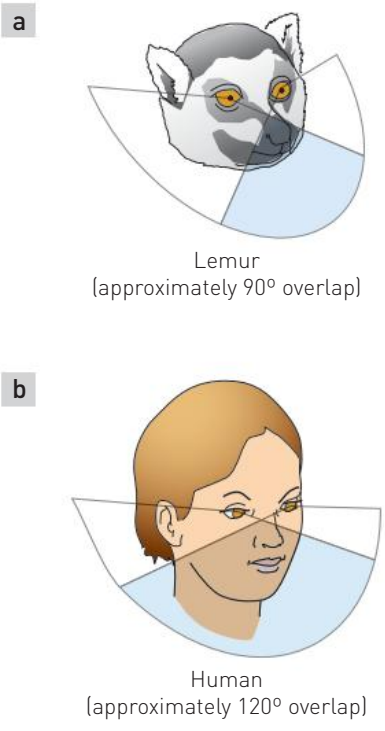


Figure 17.14 Fields of view of **a** a lemur and **b** a human. As the eyes become more forward facing, the total field of view decreases but the degree of overlap of the fields of the two eyes increases. The greater the degree of overlap, the better the stereoscopic vision.

Colour vision in primates
This website provides an interesting article on colour vision in primates.

Evolutionary trends in vision

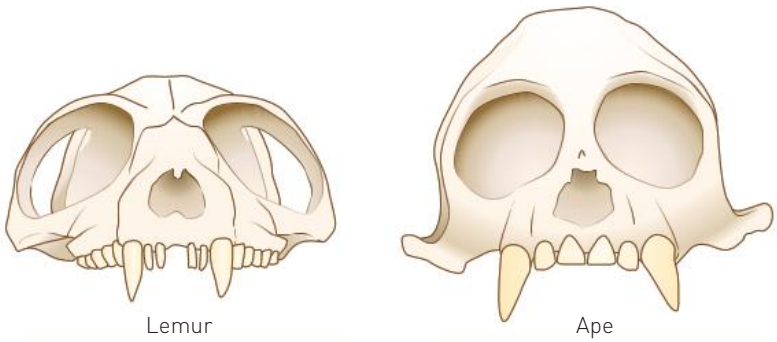
All animals rely on their senses to gain information about the environment around them. With an arboreal life, primates gradually evolved an increasing emphasis on vision accompanied by a decreasing reliance on the sense of smell, or **olfaction**. This shift in sensory orientation was accompanied by an overall change in the shape of the skull compared with other mammals. There has been a general tendency for the facial portions of the skull, particularly the region around the nose and snout, to become smaller and flatter (see Figure 17.16 on page 261), while the region that houses the brain has become larger (Figure 17.13). Observable behaviour in living primates supports this shift. Lemurs, for example, use their snout and teeth for what apes would use their eyes and hands for – investigating an object, grooming or communicating with other members of their group.

The flattening of the face of primates and the movement of the eyes to face fully forward has been an important evolutionary trend. **Forward-facing eyes** allow for **stereoscopic** (or three-dimensional) **vision**. Most other mammals have eye sockets that face sideways, but primates have developed eye sockets that face forward. This enables the fields of vision of each eye to overlap, so that distances can be judged accurately. This is an important adaptation for a tree-living animal. Figure 17.14 illustrates this trend by comparing the field of view of a lemur with that of a human. Look at the primates in Figure 17.1 and compare the positions of their eyes.

For primates, evolved for life in trees, the importance of depth perception cannot be overemphasised. A mistake in judging distances can be fatal. However, with both eyes facing forward, the field of view is much narrower than if the eyes face sideways. Primates have compensated for this by evolving a highly mobile head and neck. In addition, most primates have both rods and cones in the retina of their eyes. The **rods** are important for vision in dim light, while the **cones** are concerned with fine visual discrimination and with colour vision (nocturnal primates, such as the tarsier – see Figure 17.1 – have only rods). The nerves connecting the rods and cones to the brain have also improved in primates, and so vision is more acute in each eye and the coordination between the two eyes is far better than in other mammals. These modifications have also enhanced stereoscopic vision.

As the eyes have become more forward facing, a bony eye socket has developed to give protection. The gradual change in the eye sockets is clearly visible in the fossil primate skulls that have been found. As the position of the eye socket has changed for the eyes to face forward, bone has gradually closed in the side and rear of the socket (Figure 17.15).

Finally, with the increasing importance of vision to primates, the region of the brain concerned with the interpretation of visual information increased in size while that concerned with olfaction decreased. This is shown in Figure 17.16, where the region shaded blue indicates the area of the brain concerned with vision, and Figure 17.17, in which the relative sizes of the brains are compared.



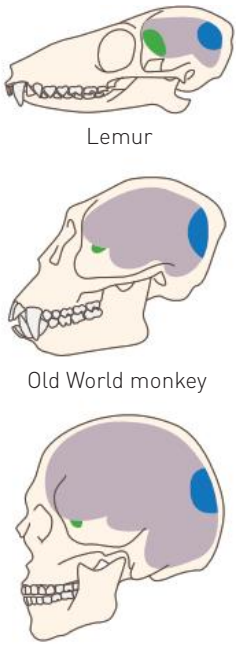
Lemur

Eyes face slightly sideways and eyeball is not completely enclosed in a socket. The sides and rear of the eyeball are exposed.

Ape

Eyes are facing forward and eyeball is completely enclosed in a bony socket. There is bone at the sides of the socket and a plate of bone at the rear.

Figure 17.15 The change in the shape of the eye sockets for a lemur and an ape



Lemur

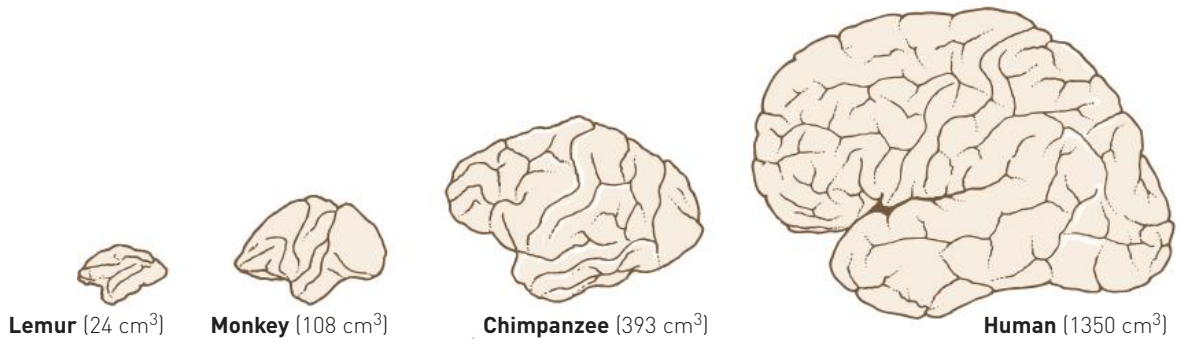
Old World monkey

Human

Figure 17.16 Relative sizes of the centres for olfaction (green) and vision (blue) in the brains of a lemur, an Old World monkey and a human

Relative size of cerebral cortex

In the primates the part of the **brain** responsible for complex functions, the cerebrum, has progressively increased in size. This is especially true of the outer region called the **cerebral cortex** (see Chapter 5). It is this region of the brain that is concerned with so-called higher functions – vision, memory, reasoning and manipulative ability – functions necessary to cope successfully with changes in the environment. Figure 17.17 illustrates the increase in size and complexity of the cerebrum from lemurs to humans. This is one of the most significant features of primate evolution. There is a noticeable trend from the lemurs through the monkeys to apes and humans of an expansion and reorganisation of the brain with resultant consequences for behaviour.



Lemur (24 cm^3) **Monkey** (108 cm^3) **Chimpanzee** (393 cm^3) **Human** (1350 cm^3)

Figure 17.17 The increase in size and complexity of the cerebrum in various primates (drawn to scale)

Primates have large brains for their body size. Again this seems to be a consequence of their tree-dwelling environment. The pressure of natural selection in an arboreal environment would have favoured more accurate visual and tactile perception along with better coordination between such sensory stimuli and any muscular response. Unlike smell or hearing, the reliance on vision to move about, and to locate and manipulate food, generates a large amount of complex sensory information that has to be processed and stored. In primate brains, such operations are carried out by the cerebral cortex. Progressive expansion of the cerebral cortex has resulted in it becoming so large that it covers the rest of the brain. This is most noticeable in humans.

The brains of apes and humans have a strong pattern of convolutions. These **convolutions**, or folds, enable the surface area of the brain, and hence the cerebral cortex, to be greatly increased. Notice how, in Figure 17.17, the cerebrum becomes larger and more convoluted as we progress from lemur to monkey, chimpanzee and human. These convolutions have resulted in a 50% increase in the surface area of the human brain compared with what it would be on a brain with no convolutions.

The increase in size of the cerebral cortex has had far-reaching effects on the way primates live. It has enabled them to move about and locate food, and to develop special skills. One of the most significant of these is tool making. This is most highly developed in humans, but is also seen in chimpanzees. Tool making, as opposed to tool use, involves a predetermined image of what the completed tool should look like – something only possible with a highly developed brain.

In addition, an increase in the size of the cerebral cortex would have allowed a greater variety of behavioural responses to meet a wide array of environmental problems. For most primate species, daily life involves numerous interactions with relatives, allies and adversaries. Mutual cleaning and grooming helps to reinforce relationships, while threats – sometimes followed by fighting – maintain the hierarchy of dominance that pervades many primate troops. Such behavioural flexibility has taken the place of further physical specialisation.

Primate brains
This website shows views of the brains of various primates and other mammals. Click on the particular species and then on the brain photographs to see an enlargement.

Even though the apes and humans show an increase in body size over the other primates, the increase in the size of the brain is proportionately greater. The greater size of the brain has resulted in a corresponding development in the cranial portion of the skull – the part that encases the brain. As a consequence, the head in apes and humans tends to be larger and more rounded than it is in monkeys. This can be seen by comparing the two skulls in Figure 17.13.

Gestation and parental care

Another evolutionary trend in primates is in reproductive physiology and behaviour. Most species are not restricted to a limited reproductive season and show a rhythmical sexual cycle. Again, most primates have only a single offspring at a time, probably an adaptation to arboreal life. Associated with this is a long period of growth and maturation, during which there is a marked degree of parental care.

Primates are placental mammals with the offspring developing inside the mother's body, taking nourishment from her bloodstream via a special structure called the **placenta**. The placenta is attached to the wall of the **uterus**, or womb, the structure in which an embryo develops until it is ready to be born. Compared with the other primates, the apes, along with humans, have a more efficient placenta that allows a closer contact between the blood supplies of the mother and the developing offspring.

The time between conception and birth is called **gestation** and is remarkably long in primates compared with other mammals of similar size. For example, a tarsier gives birth to a single offspring after a period of gestation of nearly six months. In contrast, a rodent of similar size will often give birth to six or more offspring after a gestation period of only three weeks. Among the primates, gestation is at its longest in apes and humans (Figure 17.18), and the offspring, when born, are more immature, requiring much care and protection. Most primates usually give birth to a single offspring, although some species, such as lemurs and marmosets, frequently have twins or triplets.

Once the offspring are born, the period of parental care can be even more protracted. The length of this period increases with the progression from lemurs and lorises through to the monkeys, apes and humans. For example, in lemurs the young are usually **weaned**, the time that breastfeeding is stopped, after about five months. Apes are often fed on their mother's milk for three or four years, and they may continue to rely on her protection for six or more years. While some of the lemurs, such as the lesser mouse lemur, have multiple nipples, most have only a single pair. This is the case for most primates, and as only one offspring is born at a time, it can be adequately nourished.

Along with this trend in the lengthening of the period of growth and development, there is an associated delay in maturation (Figure 17.18). As a result, sexual maturity is attained much later in apes and humans than in lemurs, lorises and monkeys. The fact that apes and humans have such a long period of maturation means that their period of learning is also greatly extended. This is an important facet of a primate's life as it enables ideas and techniques to be passed on from one generation to the next.

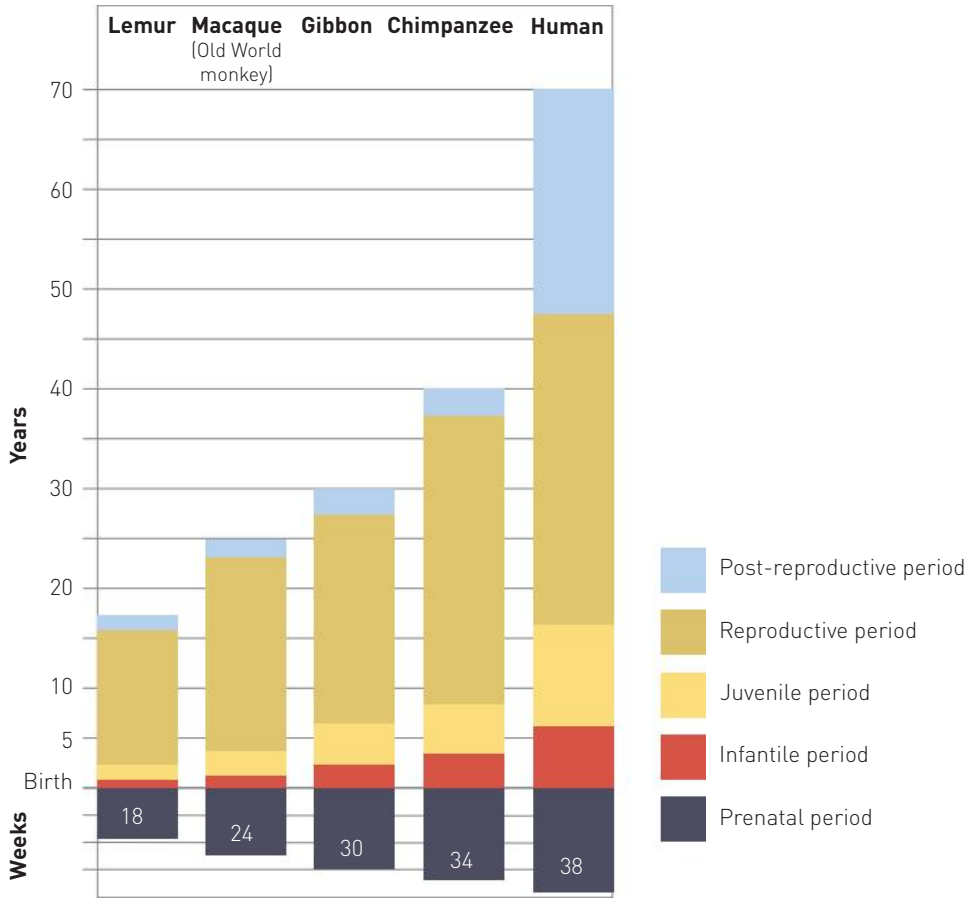


Figure 17.18 The increase in female developmental and reproductive periods with progression from the lemurs to humans

The delay in maturation and the late arrival of sexual maturity, especially in apes and humans, tends to reduce the number of offspring a female can have during her lifetime. This makes each offspring particularly important, and considerable time and effort is invested in their care and survival. The investment in prolonged parental care has evolved because it increases the survival chances of the offspring and provides a long period during which the young can learn from older members of the group.

Table 17.3 A summary of the evolutionary trends that occur in the order Primates

Characteristic		Trend
Digits	Mobility	Increasing mobility and ability to move digits independently of one another
	Opposability	First digit opposable and increasing length results in increased effectiveness of opposability
	Claws/nails	Primitive primates retain claws on some digits; higher primates have nails on all digits.
Dentition		36 teeth in lemurs, lorises and New World monkeys; 32 in Old World monkeys, apes and humans. Monkeys and apes – large projecting canines with diastema 4-cusped molars in monkeys; 5 cusps in apes and humans
Smell		Sense of smell reduced with gradual reduction in length of the snout
Vision	Eyes	Increasing efficiency in vision Eyes becoming gradually more forward facing, to give stereoscopic vision
	Eye socket	Eyes gradually becoming enclosed in a protective bony socket
	Visual area of brain	Increasing proportion of the cerebrum devoted to vision
Brain	Size	Increasing size of brain relative to size of body
	Convolutions	Gradual increase in the number of folds in the surface of the cerebrum
	Cerebral cortex	Cerebral cortex making up an increasingly large proportion of the brain
Gestation		Increasing length of time between fertilisation and birth
Development	Dependence	Increasing length of time that the offspring are dependent on the parent/s
	Sexual maturity	Increasingly later development of sexual maturity

Evolutionary trends

Science inquiry

ACTIVITY 17.1 Living primates and trends in evolution

Primate classification

Meet the primates

In this activity you will examine the primates' evolutionary trends discussed in this chapter. To do so, you will need to study some of the structural and behavioural characteristics of a selected number of primates. The best outcomes from this activity will be achieved if you are able to observe living primates in a zoo. However, if this is not possible, you could use reference books on primates or use the weblinks 'Primate classification' or 'Meet the primates'.

WHAT TO DO

Select a lemur or a loris, a New World monkey, an Old World monkey and two species of ape. For each of the selected species make as many of the following observations as you can. You will need to keep detailed records of your observations.

1. Record the common name and the scientific name of the species.
2. Observe the hands and feet of each selected primate carefully and make notes on the following.
   - Is there a claw present on any of the digits?
   - Is the first digit opposable to the others?
   - What is the relative length of the first digit to the others?
   - How mobile are the digits of the hands?
   - How mobile are the digits of the feet?
   - How does this species use its hands and feet for gripping objects?
   - Is this species able to use the precision grip?
3. Look at the mouth and teeth of each selected primate and answer the following.
   - Do the front teeth protrude to form a 'dental comb'?
   - How many incisors and canines can you see in each jaw?
   - Do the teeth appear to be of the same size? If not, which teeth appear to be larger?
   - Do any of the teeth overlap those in the jaw above or below? If they do, can you see a gap between the teeth that allows this to occur?
   - What type of food does the species eat? Are you able to relate this to the size and shape of the teeth?
4. Examine the shape of the face and the behaviour of each selected primate, and pay particular attention to the position of the eyes.
   - Is there a snout present, or is the face flat?
   - Does the species appear to use its sense of smell to explore its environment?
   - Are the eyes directed slightly sideways or are they fully forward facing?
   - How large are the eyes? Is the species nocturnal?
   - Are you able to estimate the degree of overlap of vision from the left and right eye?
   - Does the species appear to have to judge distances accurately, such as when leaping from one branch to another?
   - How mobile does the head appear to be on the neck? How far is each species able to turn its head?
5. Look at the size and shape of the cranial portion of the skull. This will give some indication of the size of the brain. Determine:
   - whether the skull appears rounded or flat
   - the proportion of the size of the head compared to the rest of the body
   - whether any tool making or other complex behaviours are taking place
   - whether there is social interaction with other members of the species.

6 If the species you have selected has young present, be patient and observe:
- the number of young and whether you can determine their parents
- the maturity of the young members of the species
- any interactions between adults and young
- the dependence of young animals on their parents.

STUDYING YOUR OBSERVATIONS

1 Collate your observations of the different species to describe the discernible trends from lemurs and lorises to monkeys and apes. Describe each of the following separately.
   - **a** mobility and flexibility of the digits
   - **b** size, arrangement and shape of the teeth and how this may relate to diet
   - **c** shape of the face and the presence of overlapping or stereoscopic vision
   - **d** proportional size of the head compared to the rest of the body and how this may relate to the complexity of behaviour that you observed
   - **e** comparative size of offspring and their dependence on their mother or other adults.

2 Describe any behaviour you observed in any of the species studied that was similar to human behaviour. Is it possible to see an evolutionary trend in any of the behaviour observed?

IN SUMMARY

Write a short summarising statement that accounts for all the observations you made during this activity and the evolutionary trends discussed in this chapter.

ACTIVITY 17.2 Mobility of the human thumb

Apes and humans have very mobile digits, but only humans can grip an object with true precision. The human hand differs structurally and functionally from that of the other primates. A longer, stronger thumb that can readily oppose each of the other digits enables humans to manipulate objects using a precision grip. Humans are also able to use a power grip, where an object is grasped between the undersides of the fingers and the palm of the hand, with pressure in the opposite direction being applied by the thumb. We use a power grip when holding a hammer.

In this activity you will compare the two main ways in which humans use the thumb and fingers to grip objects. Manipulation of objects with both power and precision enabled our ancestors to become efficient tool makers.

YOU WILL NEED

A short length of broom handle or a ruler; a pencil or pen

WHAT TO DO

1 Hold your hand out in front of you with the back of your hand towards your face. Observe how the position of the thumb is different from the fingers.
2 Move your thumb across the palm of your hand to touch each of your fingers in turn. Note the movement of the thumb.
3 Use your thumb and fingers to pick up a pen or a pencil from your table. Observe the way in which the thumb and fingers are employed in the grip you used. This is the precision grip.
4 Squeeze the pen tightly and note which muscles are in use.
5 Grasp a length of broom handle or a ruler as you would a hammer. Observe the differences in the position of the thumb and fingers when this method is used to hold an object.
6 Squeeze the broom handle tightly and note which muscles are used. This is the power grip.

STUDYING YOUR OBSERVATIONS

1 In relation to the palm of your hand, how is the position of the thumb different from the fingers? Give two reasons to explain the advantage of the thumb in this position.
2 What term is used to describe the movement of the thumb when it touches each fingertip in turn?

3 **a** Describe the position of your thumb and fingers when picking up a pen.
   b Which muscles were used to hold the pen in this precision grip?
4 **a** List the differences in the position of the thumb and fingers when using the precision grip and the power grip.
   b How did your thumb assist in holding an object in the power grip? Describe how it did this.
   c Which muscles were employed in the power grip? Were these different from the ones used in the precision grip?
5 Which of the two grips would be the most efficient at holding an object against force?
6 List the features of the thumb that make both the power and precision grips possible.

ACTIVITY 17.3 A comparison of primate skulls

In this activity you will use a website to compare a number of primate skulls, observing trends in the size and shape of the skull and teeth as one goes from the lemurs and monkeys to apes and humans.

eskeleton

WHAT TO DO

1 Go to the weblink 'eskeleton'.
2 Select 'Comparative Anatomy' from the menu at the top. This will enable you to compare two different species of primate.
3 In the comparative anatomy screen select 'baboon' and 'mouse lemur' from the taxon column; then from the 'bone' column select 'cranium' and select 'lateral' from the view column.
4 You should now have the lateral (side) view of a mouse lemur and a baboon skull next to each other to compare. Click on the + sign above the images to increase their size.
5 Look carefully at the two skulls, noting the scale listed for each, and take this into consideration when answering the following questions. For some questions it may help to go back and select other views of the skulls for comparison.
   a Using the scale provided, estimate the length of each skull.
   b Which skull has a more rounded profile?
   c Estimate the length of the cranium of each skull. Which species would have the larger and more complex brain? Give reasons for your answer.
   d Compare the superior view of each skull. (To do this, choose 'superior' as the two views to compare.) What differences would there be in the eyes of these two animals?
   e Identify and count the teeth that are visible. What is the dental formula for each species?
6 Repeat steps 3 to 5 so that you can compare:
   a a baboon with a squirrel monkey
   b a squirrel monkey with a chimpanzee
   c a chimpanzee with a human.

STUDYING YOUR OBSERVATIONS

Review your answers to the questions and use the information collected to describe evolutionary trends in the size and shape of the skull and teeth from lemurs to monkeys, apes and humans.

Review questions

1 Describe the contribution that Carolus Linnaeus made to science and how this helped in understanding the evolution of primates.
2 To which of the primate families do humans belong? Who shares this family with us?
3 Unlike most other mammals, primates are not distinguished by one or two conspicuous characteristics, but rather by a set of characteristics that serve to differentiate them from other mammals. List the characteristics that tend to be shared by all primates.
4 **a** Differentiate between the terms 'opposable' and 'prehensile'.
b Explain the advantage to primates of having friction ridges and nails, instead of claws, on the digits.
5 Describe the evolutionary trend evident in primates concerning the mobility of the thumb and the other digits.
6 **a** Explain how the number and composition of the teeth has changed as one progresses from lemurs to monkeys, apes and humans.
b What factors may have contributed to this change in the number of teeth?
7 **a** Describe the noticeable shift that has occurred in primates from strong reliance on the sense of smell to almost complete dependence on vision.
b What selection pressures in the habitat of primates may have contributed to this shift?
8 As the eyes become more forward facing, the field of view for each eye increases in its degree of overlap with the other.
a How has this been advantageous to primates?
b What has compensated for the resultant decrease in the total field of vision?
9 How has the increased importance of vision affected the region of the primate brain concerned with the interpretation of visual information?
10 **a** Explain why the skull of an ape has a proportionately larger cranium than that of lemurs and monkeys.
b List the advantages of having a large number of convolutions in the cerebrum of the brain.
c Describe the trend in the number and complexity of the convolutions in the cerebral cortex as one progresses from the lemurs to the monkeys, apes and humans.
11 Why would it be necessary for the placenta of apes and humans to be more efficient than that of other primates?
12 **a** What is the gestation period?
b How does the gestation period change as one progresses through the primate order from lemurs to humans?
c Describe the significance of this trend in terms of the development of the offspring.
13 Of what advantage has the increased length of parental care been to the survival of apes and humans? List any disadvantages an increased period of parental care may have for a species.

Apply your knowledge

1 Scientific classification is not perfect. This is especially true of primate classification. Not all species fit neatly into the 'boxes' developed by those attempting to classify the primate order. Using a variety of research techniques find out:
a the current problems that exist in the classification of the primates.
b how general the acceptance is among scientists of the classification presented in this chapter.
2 Animals that have an acute sense of smell tend to have larger snouts than those that do not rely as heavily on smell. Humans have a reduced snout and our sense of smell is not as good as that of many other primates. What other sense organ has compensated for this reduction? How do you think this may have evolved?

3 **a** Describe why primates would have found claws difficult for a tree-dwelling environment.
b How would friction ridges have improved the way primates could use their hands and feet?

4 It is thought that primates evolved from an arboreal ancestor. Explain how life in trees would contribute to the evolution of:
a vision
b prehensile digits
c intelligence.

5 Explain why tarsiers only possess rods, whereas most primates have both rods and cones in the retina of the eye.

6 Chimpanzees have been observed using a range of simple tools, mainly associated with feeding. Describe the structural characteristics of chimpanzees that enable them to make and use tools.

7 Primates tend to show an evolutionary pattern of a reduction in the number of young and a corresponding increase in the degree of parental care. Set out reasons to explain why primates have evolved in this way.

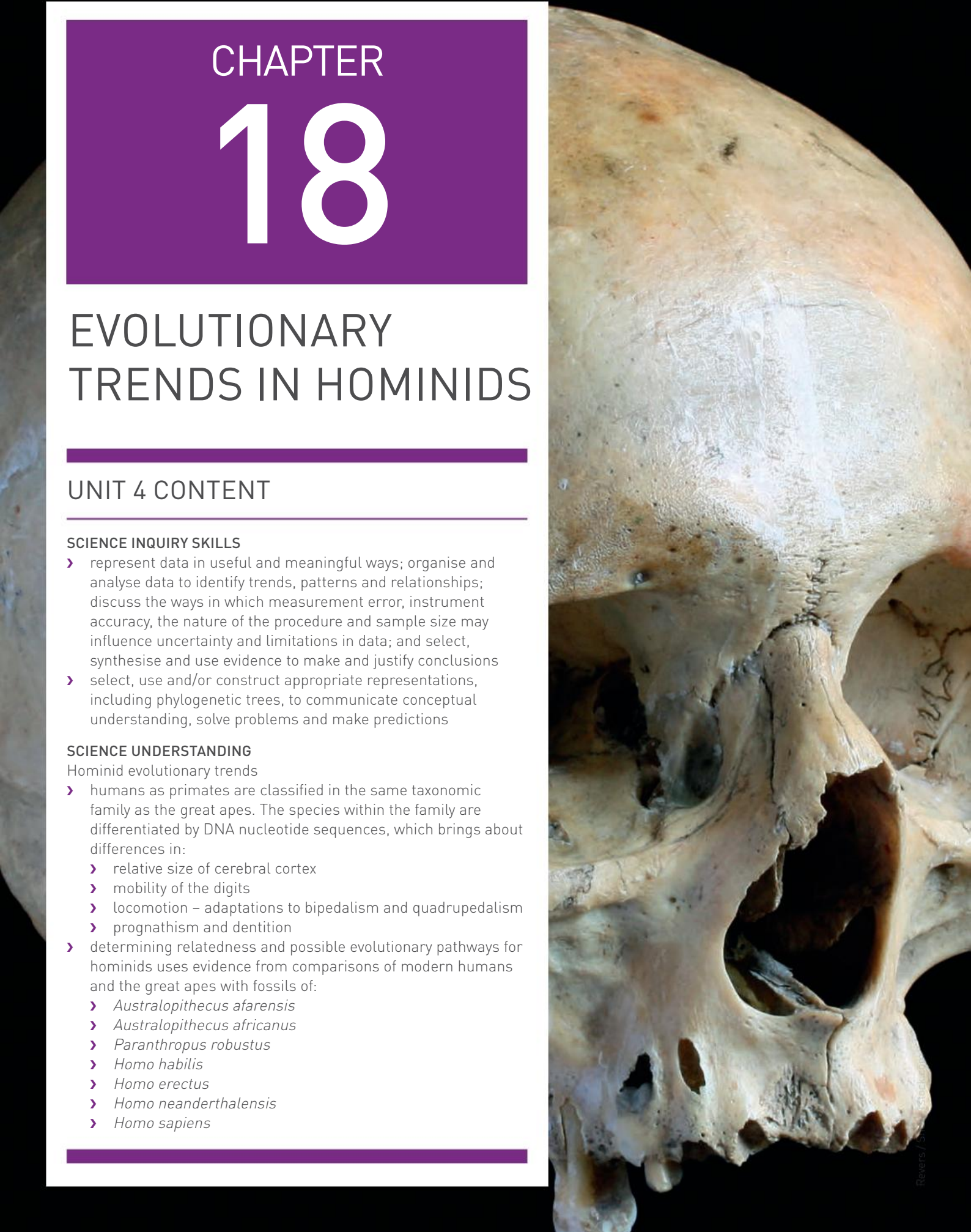
8 Describe the trends that can be observed in primates concerning the duration of gestation, length of infancy and adolescence, and life span. How would these trends contribute to species survival?

9 One of the evolutionary trends in primates is the gradual change from eyes that face partly sideways to eyes that are fully forward facing. Describe how natural selection would have brought about this change in eye position. You may need to refer to the summary of the principles of evolution through natural selection on page 205.

CHAPTER

18

EVOLUTIONARY TRENDS IN HOMINIDS



UNIT 4 CONTENT

SCIENCE INQUIRY SKILLS

- represent data in useful and meaningful ways; organise and analyse data to identify trends, patterns and relationships; discuss the ways in which measurement error, instrument accuracy, the nature of the procedure and sample size may influence uncertainty and limitations in data; and select, synthesise and use evidence to make and justify conclusions
- select, use and/or construct appropriate representations, including phylogenetic trees, to communicate conceptual understanding, solve problems and make predictions

SCIENCE UNDERSTANDING

Hominid evolutionary trends

- humans as primates are classified in the same taxonomic family as the great apes. The species within the family are differentiated by DNA nucleotide sequences, which brings about differences in:
  - relative size of cerebral cortex
  - mobility of the digits
  - locomotion – adaptations to bipedalism and quadrupedalism
  - prognathism and dentition
- determining relatedness and possible evolutionary pathways for hominids uses evidence from comparisons of modern humans and the great apes with fossils of:
  - *Australopithecus afarensis*
  - *Australopithecus africanus*
  - *Paranthropus robustus*
  - *Homo habilis*
  - *Homo erectus*
  - *Homo neanderthalensis*
  - *Homo sapiens*

More than three million years ago the ancestors of modern humans walked over wet volcanic ash in what is now Laetoli, in Tanzania, leaving behind their footprints. As the ash dried it hardened and the footprints became fossilised (Figure 18.1). Further layers of ash covered them until they were discovered, by chance, in 1978. The people who made the footprints, forerunners of modern humans, were walking upright in very much the same way that we do. This upright, bipedal form of locomotion clearly differentiated them from apes.

Getty Images/Science Photo Library

Figure 18.1 The Laetoli footprints – footprints made in volcanic ash 3.56 million years ago. More than 3 million years ago, the ancestors of modern humans were walking in very much the same way that we do today.

Humans have the same basic characteristics as the apes and together they are classified in the family Hominidae. However, humans differ from apes in their appearance and structure. Each animal species has developed adaptations that help it to survive and reproduce in its particular environment. Humans are no different, and have developed features that set us apart from the other primates. As such, humans are classified as hominins; they belong to the tribe Hominini.

A **tribe** is the name given to a relatively new level of classification between subfamily and genus. The tribe Hominini is used to distinguish humans and our extinct ancestors from gorillas, chimpanzees and their extinct ancestors.

The great apes (gorillas, chimpanzees and orang-utans), together with humans, are classified in the family Hominidae (the hominids). Chimpanzees, gorillas and humans are separated from the orang-utans and are placed together in the next level of classification, the subfamily Homininae (the hominines). Humans (along with some of our extinct ancestors) are then classified into the tribe Hominini (the hominins) (Figure 18.2).

Hominins differ from apes in their appearance, structure and behaviour. Most noticeably, hominins are relatively hairless compared with apes, and the structure of their upper and lower limbs allows for a fully bipedal way of walking. Walking with **bipedal locomotion** means walking on two legs with the body upright.

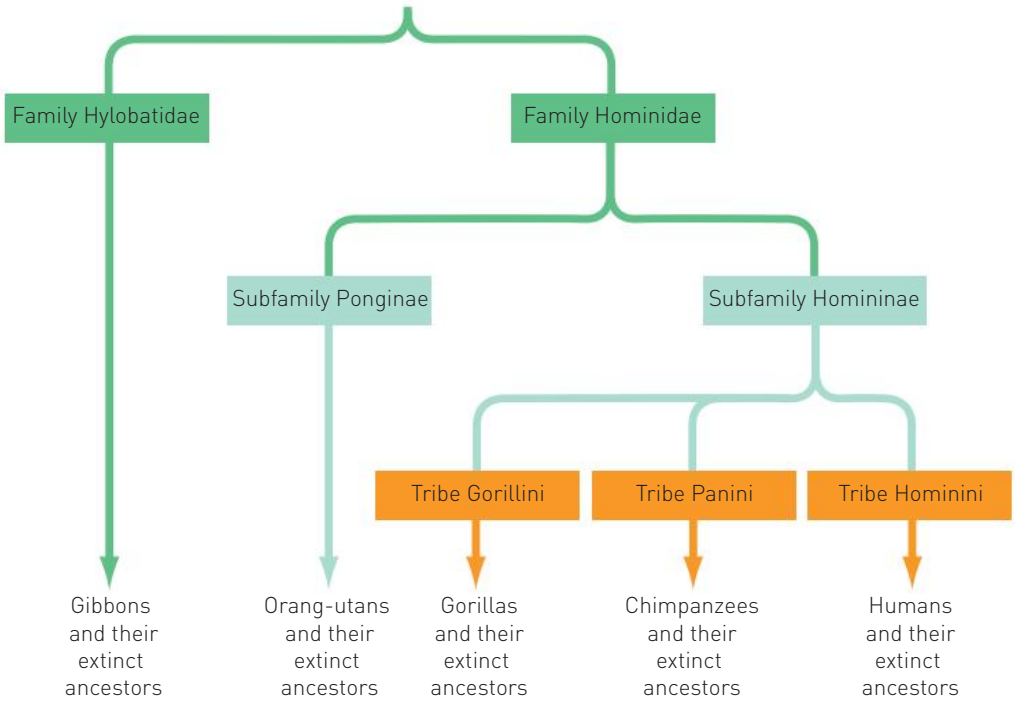


Figure 18.2 Classification of apes and humans

Humans stand and walk with an erect posture and a striding gait that is unique. It is not found anywhere else in the animal kingdom.

Hominins also have greater development of the brain, changes in the size and shape of the teeth, development of speech and sexual characteristics, all of which separate them from the other hominids.

Evolutionary trends

Hominid and hominin
This website discusses the use of the terms 'hominid' and 'hominin'.

Human ancestors

Throughout this chapter we will be referring to the extinct ancestors of present-day humans. Apes and humans share a common ancestor, an ape-like creature. From that ancestral ape the first hominins evolved. These were the **australopithecines** – hominins classified in the genus ***Australopithecus***. From one or more of the australopithecine species evolved early members of the genus ***Homo***. Species of early *Homo* gradually evolved into a number of different species, including ***Homo erectus*** and ***Homo neanderthalensis***, and eventually into modern humans, ***Homo sapiens***.

Scientific naming of hominins
This National Geographic website explores how new evidence raises questions about the way we name species.

The evolutionary trends described for primates in Chapter 17 continue in the hominins. However, hominins are set apart from the other hominids by some very special adaptations that give them a unique position in the animal kingdom.

Adaptations for an erect posture

For humans to be able to stand on two legs and walk bipedally with a striding gait, the skeleton and muscles had to evolve. Compare the skeletons of the gorilla and human in Figure 18.3. The differences that you can see have evolved over millions of years so that present-day humans can stand and walk erect on two legs.

An **adaptation** is any characteristic that helps an organism survive and reproduce in its natural environment. Erect posture helped our human ancestors to survive. Some of the adaptations that make erect posture possible are discussed below.

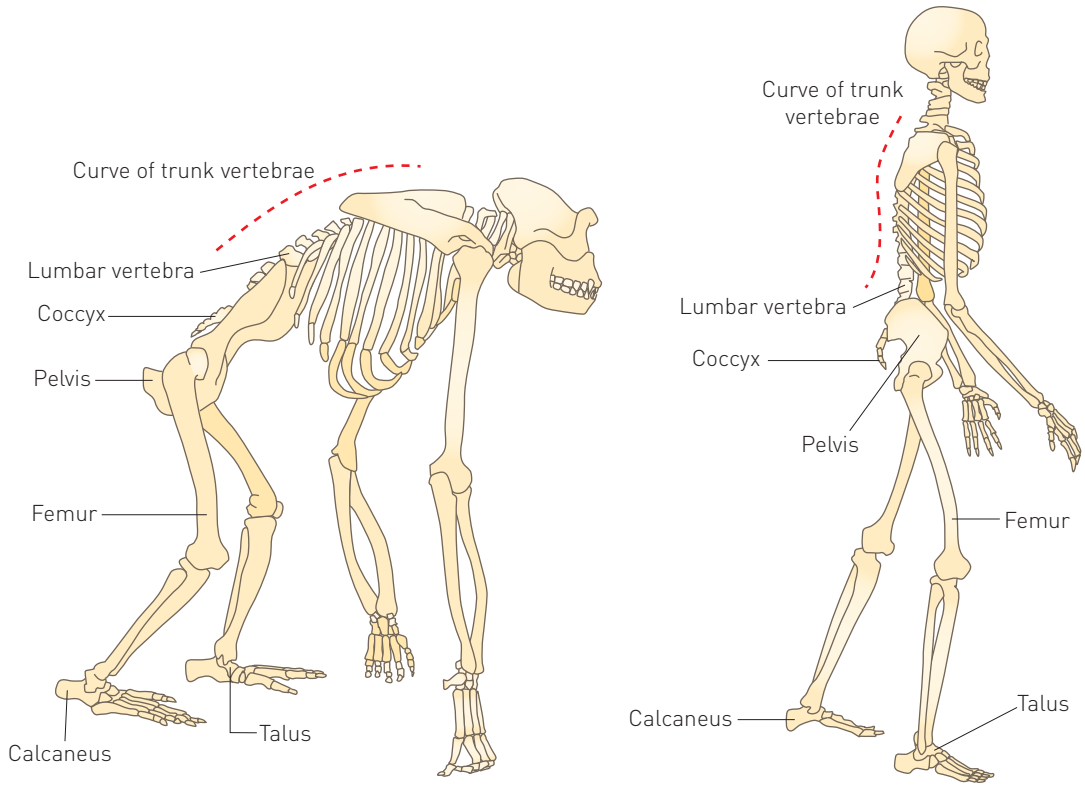


Figure 18.3 Posture of the skeletons of a gorilla and a human

Position of the foramen magnum

Where the brain joins the spinal cord there is a hole in the skull called the **foramen magnum**. In humans this hole is located centrally underneath the skull (Figure 18.4), but in quadrupeds the hole is towards the back of the skull. This difference can be seen clearly in Figure 18.3.

During the evolution of modern humans from an ape-like ancestor, the foramen magnum has gradually moved forward until the skull is able to balance on top of the vertebral column. An ape like a gorilla needs large neck muscles to hold the head in position (Figure 18.5). In humans, the weight of the skull is borne by the vertebral column and so large neck muscles are not required.

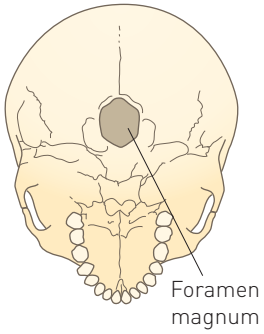


Figure 18.4 The base of a human skull, showing the position of the foramen magnum

Curvature of the spinal column

Figures 18.3 and 18.5 clearly demonstrate the difference in curvature of the spinal column between an ape and a human. Humans have a double curvature, giving the spine an S-shape that contributes to upright stance. The vertebrae in the lower, or **lumbar**, region (the small of the back) are wedge-shaped from front to back, thus forming a forward-jutting curve (Figure 18.5). This lumbar curve of the vertebral column improves body balance in the upright position. It enables the head to balance on top of the neck. In addition, the cervical curve in the neck (Figure 18.6) brings the vertebral column directly under the centre of gravity of the skull.

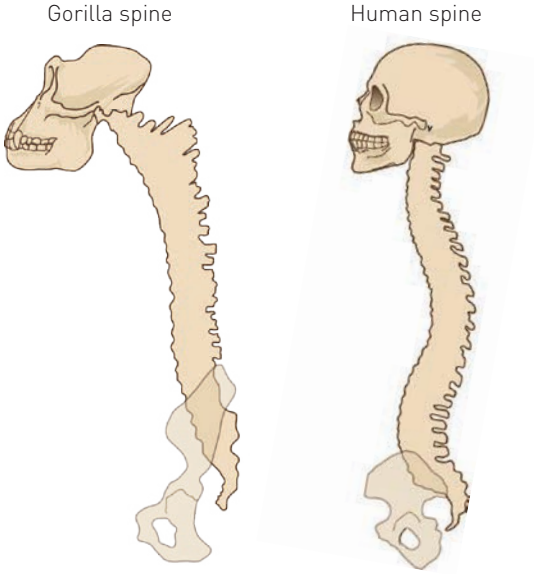


Figure 18.5 Differences in curvature of the vertebral columns of a gorilla and a human. Also shown is the position of the skull: in humans, the skull balances on the vertebral column; in gorillas, most of the weight of the skull is in front of the column, so strong neck muscles are required to hold the skull in place.

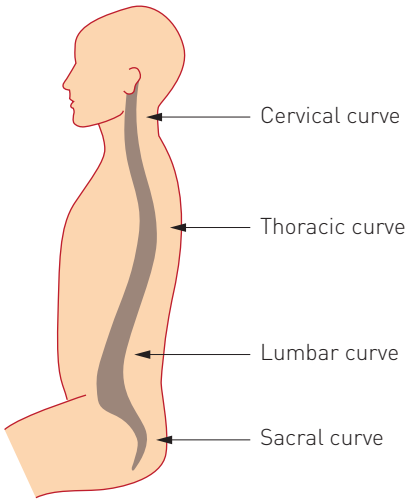


Figure 18.6 The curves of a human spine

The jaw

Apes have a protruding jaw, whereas in humans the facial profile is much flatter (Figure 18.5). During evolution from an ape-like ancestor, the size and protrusion of the human jaw has gradually been reduced. This change has been important in allowing the skull to balance on the top of the spine, because the weight in front of the foramen magnum is approximately equal to the weight behind. Balance is thus achieved with a minimum of muscular effort. Other significant implications of the reduction in jaw size will be discussed later.

The pelvis

At its lower end, the vertebral column articulates with the pelvis. The pelvis in humans is broader, and shorter from top to bottom, than in apes, and bowl-shaped (Figure 18.7). This bowl shape supports the abdominal organs when standing erect, and in the female it supports the developing foetus during pregnancy. The female pelvis tends to be slightly broader than that of the male to allow for the passage of the infant at birth.

The broad hip bones provide space for attachment of the large buttock muscles, which move the legs and keep the upper body erect.

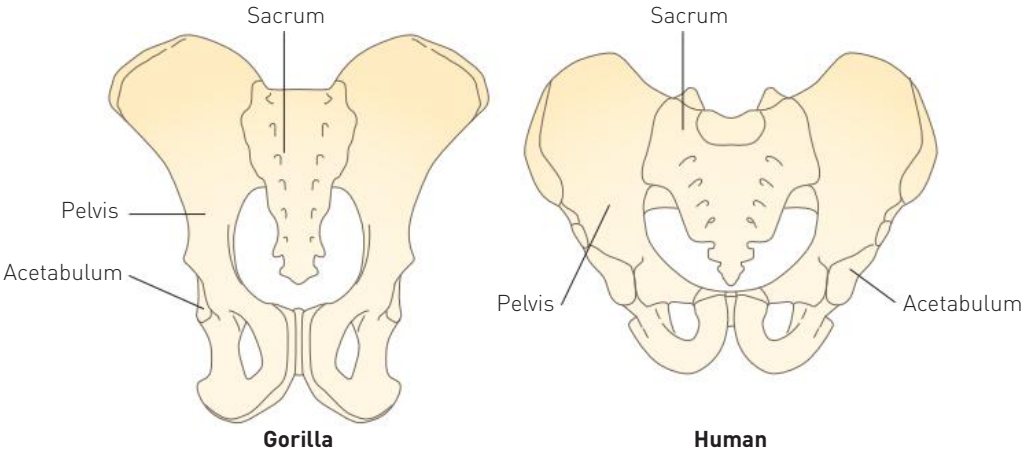


Figure 18.7 Pelves of a gorilla and a human

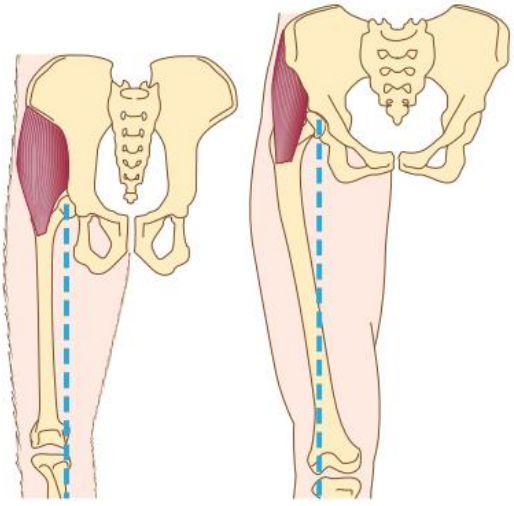


Figure 18.8 The pelves and femurs of chimpanzees and humans, showing how humans have a carrying angle, with the femur angled in towards the knee (the dotted line shows the direction of weight transmission)

The carrying angle

The shape and orientation of the pelvis result in the hip joint being directly under the trunk and head. This allows the weight of the body to be transferred from the pelvis to the legs. The head of the **femur**, or thigh bone, is large and fits into the **acetabulum** (hip socket) of the pelvis. Because the pelvis is broad, the hip sockets are wide apart, but the femurs tend to converge towards the knees. This arrangement of the femurs forms an angle to the vertical, termed the **carrying angle** (Figure 18.8), which ensures that weight distribution remains close to the central axis of the body when walking. This arrangement also allows for greater stability when walking as it enables the body to be rotated about the lower leg and foot, and each footstep to follow a more-or-less straight line. It enables humans to have a striding gait instead of swaying from side to side as do gorillas or chimpanzees when walking on two legs. As Figure 18.8 indicates, in humans the weight transmission tends to fall through the outside of the femur, whereas in the apes the reverse is true.

The knee

The weight of the body is transmitted down the outside of the femur to the knee. The knee joint is a two-part hinge joint, with one 'hinge' on either side of the ligaments in the middle of the joint. Because the weight is transmitted to the outer 'hinge', it is larger and stronger than the inner one. Although the weight of the body is transmitted down the outside of each leg, the centre of gravity of the body tends to fall through a line just in front of the knees. This results in a force that tries to bend the knee backward but is resisted by the ligaments making up the knee joint. This natural resistance produces a joint that requires no energy to support the body in a standing position.

The foot

From the knee joint, most of the weight of the body is transmitted through the tibia to the ankle. The tibia is the larger and stronger of the two lower leg bones. At the ankle, body weight is transmitted from the tibia through the talus (ankle bone) to the other tarsal bones, then to the metatarsals and phalanges via the arches of the foot (see Figure 18.9).

The human foot is one of the most distinctive adaptations for bipedal locomotion. In becoming a highly specialised locomotory organ it has lost its grasping ability, or **prehensility**. This is most noticeable with the big toe, which in humans is quite large and aligned alongside the other toes. The bones of the foot between the toes and the ankle, the **metatarsals**, are shaped in such a way that they form two arches: a **longitudinal arch** running from front to back, and a **transverse arch** running from side to side. The transverse arch is unique to humans (Figure 18.10). These two arches have enabled humans to perfect bipedal locomotion. Humans walk bipedally using the **striding gait** – walking in such a way that the hip and knee are fully extended (see Figure 18.14 on page 277).

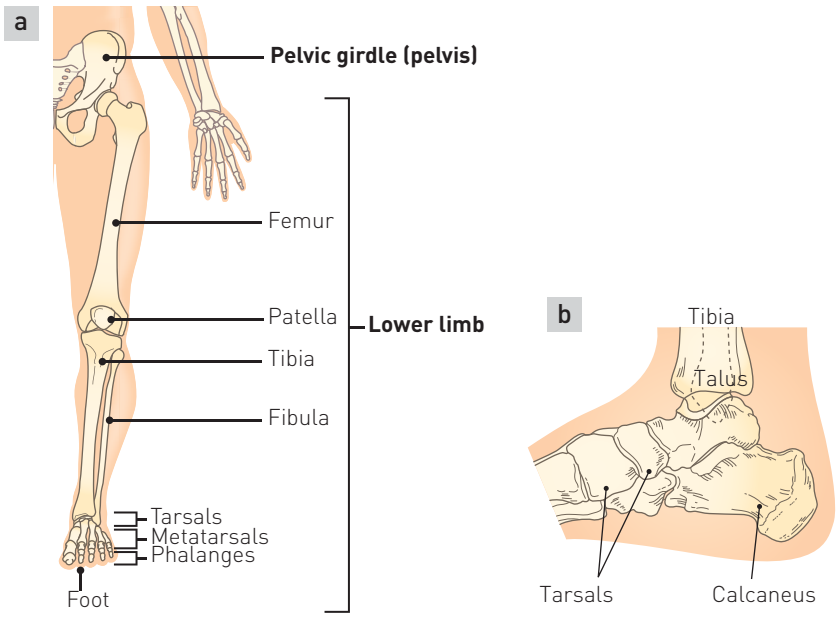


Figure 18.9 a The lower limb showing the weight-bearing bones; **b** the tarsal bones of the foot

Centre of gravity

Unlike apes, humans have legs that are longer than the arms. The relatively long legs increase the length of the stride when walking. Surprisingly, they also serve to lower the centre of gravity of the body, the point at which all the weight of the body appears to be concentrated. In contrast to humans, where almost half the total height is in leg length, in apes only about one-third of the total height is taken up in leg length. This results in their centre of gravity being further up the body, as Figure 18.11 on page 276 indicates. Whereas the centre of gravity for the ape is at chest level, for humans it is at the level of the pelvis. The lower centre of gravity in humans contributes to stability when moving bipedally or when standing erect.

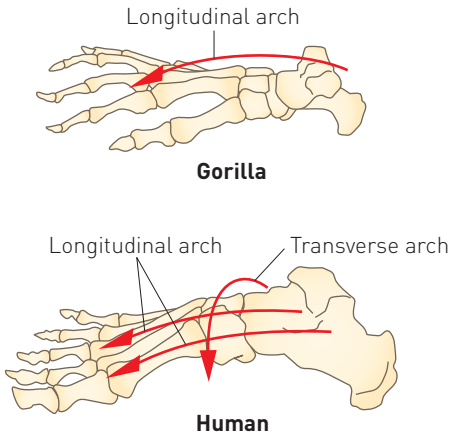


Figure 18.10 The arches of the foot of a gorilla and a human: humans have a longitudinal arch and a transverse arch; gorillas only the former.

Stance and locomotion

A major distinguishing feature of hominins is that they walk bipedally on two legs with the body upright. Humans are the only living hominins, but by examining fossilised bones of primates scientists are able to determine whether ancient primates would have been able to walk bipedally. Anatomical features such as the position of the foramen magnum, shape of the pelvis, structure of the knee joint and arches in the foot can be used to decide whether a human ancestor was bipedal (Table 18.1). *Homo neanderthalensis* (Neanderthal man), *Homo erectus* and *Australopithecus* are extinct hominins that we know from fossils. The fossil bones show us that these people could walk upright on two legs; therefore, they are classified as hominins.

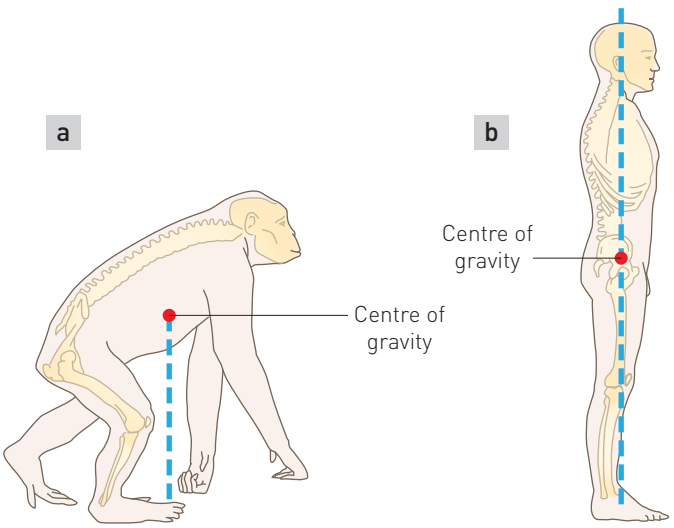


Figure 18.11 Centre of gravity of **a** an ape and **b** a human

Bipedal locomotion
This website provides additional information about adaptations for bipedal locomotion.

Table 18.1 A summary of the main hominin adaptations for erect posture

Structure	Adaptation
Foramen magnum	Located centrally in the base of the cranium
Jaw bone	Small and non-protruding, enabling the skull to balance on the vertebral column
Vertebral column	Lumbar vertebrae wedge-shaped, producing an S-shaped curve that brings the vertebral column directly under the centre of the skull
Pelvis	Broad; shallow from top to bottom. Provides support for the abdominal organs. Attachment of femurs is wide apart, contributing to the carrying angle
Femurs	Large head of the femur contributes to carrying angle
Knee joint	Outer 'hinge' larger and stronger, to take weight of body. Knee is able to be straightened
Legs	Longer than arms, contributing to a low centre of gravity. Carrying angle allows the weight of the body to be kept close to the central axis
Foot	Large heel bone and aligned big toe form a pedestal on which the body is supported. Foot has both longitudinal and transverse arches

One of the essential elements for maintaining an upright stance is muscle tone. **Muscle tone** is the partial contraction of skeletal muscles. To keep the head erect, for example, and stop it from slumping forward onto the chest, the muscles in the back of the neck are partially contracted; that is, they have tone. If someone falls asleep while sitting up, the decrease in tone is evident as the head nods until the chin is close to, or resting on, the chest.

Sustained muscle tone is most evident in those muscles that support the body in an upright position. In humans, the muscles that do this are those that bring about movement of the spine, hip, knee and ankle, and also the abdominal muscles. These are illustrated diagrammatically in Figure 18.12. The nervous system and a variety of sense organs work together to maintain the tone in these muscles and the equilibrium of the body.

Walking upright in such a way that the hip and knee are fully straightened is referred to as the striding gait. Hominins are the only animals that have perfected this form of locomotion. Even when walking on their hind legs, the apes have their knees bent and their bodies bent forward at the hips (see Figure 18.14).

In the striding gait, when the foot hits the ground, weight is transmitted from the heel along the outside of the foot as far as the ball, crosses the ball of the foot (via the transverse arch) and is finally borne by the big toe. At the final moment of striding, the whole weight of the body is propelled by the big toe, as Figure 18.13 illustrates. Try this for yourself. Walk slowly but normally in a straight line and observe which part of the foot is taking the weight of your body at each phase of the stride. It should now be evident just why the hominins lost the opposability of the big toe. The human foot has evolved into a weight-bearing appendage rather than a grasping one.

When walking, the trunk rotates about the pelvis. The forward swinging of the arms compensates for this natural rotation of the body: the right arm naturally swings forward as the left leg is extended, and vice versa. Swinging of the arms tends to keep the shoulders at right angles to the direction of travel, and reduces the amount of energy expended. If the arms did not move as they do, energy would be wasted in reversing the rotation of the body after each stride.

In the discussion of the carrying angle earlier in this chapter it was shown that, although the human pelvis is broad and the hip sockets are wide apart, the femurs converge towards the knees (Figure 18.8 on page 274). This arrangement of the femurs ensures that weight distribution remains close to the central axis of the body during walking. The arrangement also allows for stability during walking, as the body can be rotated about the lower leg and foot, thus allowing each footstep to follow a more-or-less straight line. (Look at the tracks left by the australopithecines in Figure 18.1.) Apes, like chimpanzees, lack a wide pelvis and carrying angle. When walking on two legs they must sway from side to side so that the body weight is over each leg in turn (Figure 18.14).

Figure 18.12 Muscles supporting the body against gravity

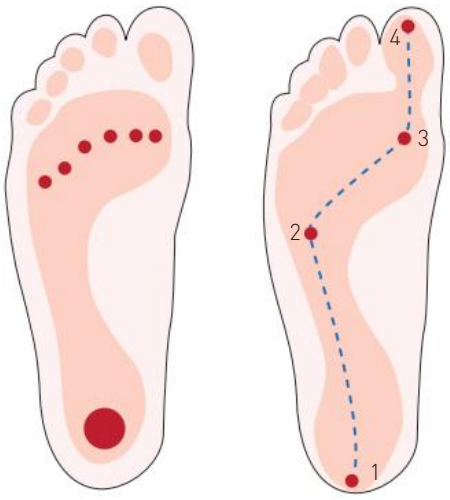


Figure 18.13 The diagram on the left shows how body weight is borne by the foot when standing still. The one on the right shows the distribution of body weight as a step is taken: the weight of the body is progressively borne on points 1 to 4 as the heel of the foot hits the ground and the big toe thrusts off.

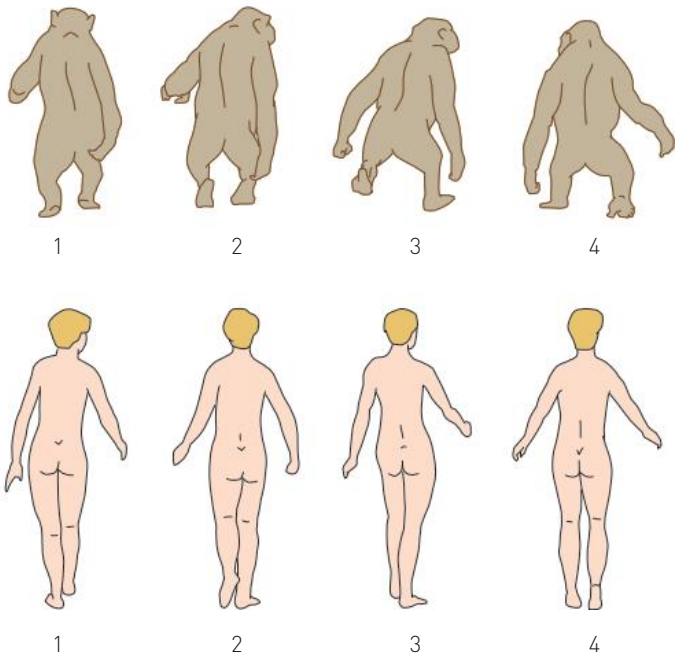


Figure 18.14 Comparison of the bipedal walking of a chimpanzee and a human

Relative size of the cerebral cortex

Humans have relatively large brains: they range in size from 900 cm^3 to 2200 cm^3 but average around 1350 cm^3. This contrasts markedly with those of the apes, which average between 400 cm^3 and 500 cm^3. Most of the difference in brain size is associated with the **cerebrum**. The outer portion of the cerebrum is the **cerebral cortex**, and it is this portion of the human brain that shows the greatest degree of development. As mentioned in Chapter 17, the surface area of the cerebral cortex is greatly increased by folds, called **convolutions**, which give a surface area 50% greater than a brain that has no convolutions.

Compared with apes, the front part of the cerebrum, known as the **frontal lobe**, has the greatest enlargement in surface area. In humans it makes up 47% of the total cortical surface, whereas in apes it comprises only 33%. It is in the frontal lobe that the higher functions of thinking, reasoning, planning and processing take place.

A large brain requires a large brain case, or **cranium**, and in humans more of the skull is used in housing the brain than in the apes. As a consequence, the brow tends to be vertical and lacks the prominent brow ridges possessed by the apes. These features, together with a shortening of the snout, have given humans a flat face, although the bones of the nose still protrude. For this reason humans have a far more prominent nose than any other primate.

Unlike bipedalism, which was well established in early hominins (see Figure 18.1), the gradual increase in the size of the cranium to house a larger and more complex brain is an evolutionary trend in hominins. Early hominins such as *Australopithecus afarensis* had a cranium that was much closer in size to that of modern apes. When fossil remains of *A. afarensis* were first discovered in the 1970s it became clear that bipedal locomotion evolved before any significant increase in brain size.

The brains of early hominins have not been fossilised, but because the brain fills the whole of the cranium, brain size can be determined by measuring the volume inside the cranium. This is known as **cranial capacity**.

Subsequent fossil evidence confirmed a gradual increase in cranial capacity as the hominin species evolved towards modern humans (Figure 18.15). The average brain size of the first australopithecine fossils found placed them within the range of modern gorillas. However, the body weight of these fossil australopithecines was probably only a third that of the gorilla, so their *relative* brain size lay somewhere between that of chimpanzees and modern humans.

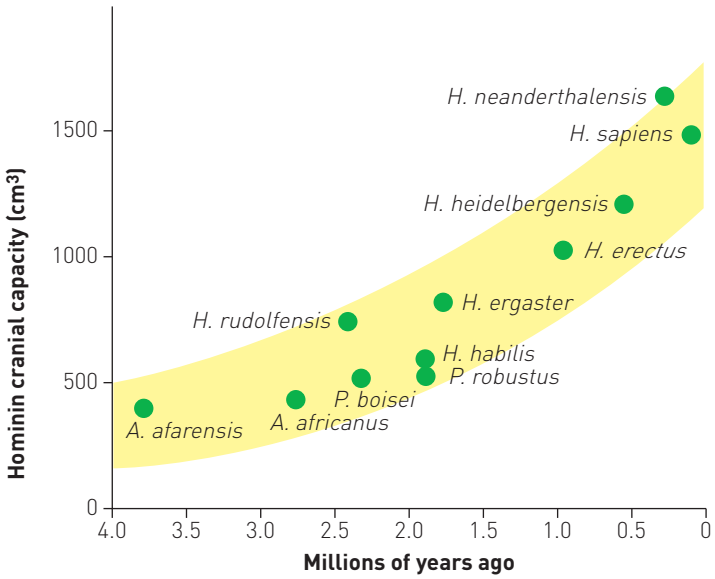


Figure 18.15 A graph demonstrating the gradual increase in cranial capacity of hominins over time. Average cranial capacity is shown for each species. See Table 18.2 for the full name of each of the species shown.

The shape of the brain surface has been determined from **endocasts**, impressions of the inside of the skull made from rock or some other solid material. Endocasts may occur naturally, or they can be made using the skulls found. The endocasts of australopithecines indicate that their brains were more human-like than ape-like. In addition, the foramen magnum was more forward than it is in the apes, and the skull more rounded at the back.

Sometimes only fragments of fossil skulls are found. Without an endocast, determining cranial capacity is very difficult, and even experts vary in their estimates. For example, when the first specimen of *Homo habilis* was discovered in Olduvai Gorge, Tanzania, in 1960, three different anthropologists gave three varying estimates for the cranial capacity: 590 cm^3, 647 cm^3 and 710 cm^3. Such a range of figures from an examination of the same material shows that estimates of cranial capacity must be treated with caution. The averages listed in Table 18.2 must be considered approximations at best.

Table 18.2 Hominin cranial capacities

Hominin	Cranial capacity (cm^3) (an estimate of brain size)
Australopithecus afarensis	430
Australopithecus africanus	457
Australopithecus garhi	450
*Paranthropus boisei**	491
*Paranthropus robustus**	542
Homo habilis	590
Homo rudolfensis	774
Homo ergaster	800
Homo erectus	1004
Homo heidelbergensis	1226
Homo neanderthalensis	1485
Homo sapiens	1350

**Note*: Many classification schemes include the genus *Paranthropus* in the genus *Australopithecus*.

Fossil endocasts reveal more than just an increase in cranial capacity. A gradual increase in the number of convolutions and the size of the frontal lobe is also evident. These trends can be seen in *Homo erectus* fossils. Over the period of time that this species lived on Earth, the cranial capacity of *H. erectus* increased from about 750 cm^3 to 1250 cm^3. As the brain case expanded, the face tended to become flatter and a noticeable forehead began to develop in the later members of the species. This was probably due to an expanding frontal lobe (Figure 18.16).

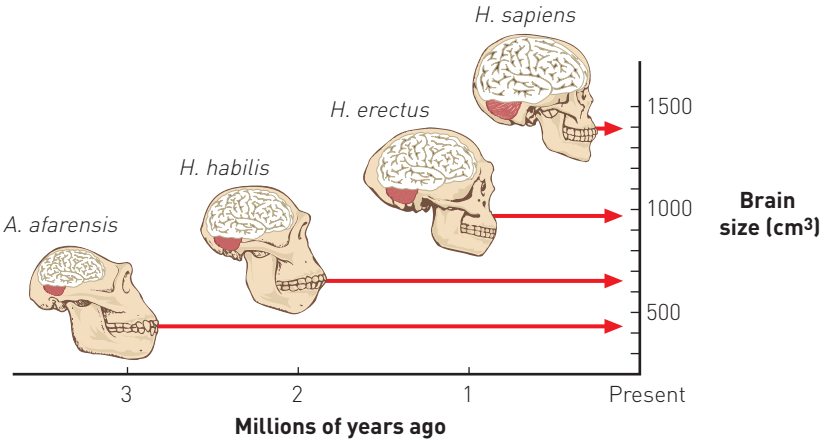


Figure 18.16 The increase in brain size in four hominin species over time. Note the marked expansion of the frontal region.

Increasing brain size
This website provides information on the increase in brain size in hominins

Hominin timeline
This website provides a timeline and more information about the various hominin species.

An interactive timeline
This website has an interactive timeline with detailed information about hominin evolution.

Prognathism and dentition

Compared with other primates, human dentition is very distinctive. In humans the canine teeth do not project beyond the level of the other teeth and interlock, as they do in the Old World monkeys and apes. Human canines look more like incisors. These small canine teeth and relatively small incisors take up less room in the jaw. As a consequence, the shape of the tooth row, or **dental arcade**, has evolved into a different shape. Instead of the U pattern of the apes, it has become parabolic in shape, as shown in Figure 18.17.

The change in the dental arcade of hominins is another discernible evolutionary trend. Early hominins, such as *Australopithecus afarensis*, had a lower jaw and face that was more like that of an ape. The teeth were large and, as in apes, there was a distinct gap between the canines and the incisors, with the rows of teeth parallel rather than curved. However, by the time of *Homo habilis*, the molar and premolar teeth had become smaller and narrower, but the canines were still prominent, as can be seen in Figure 18.18.

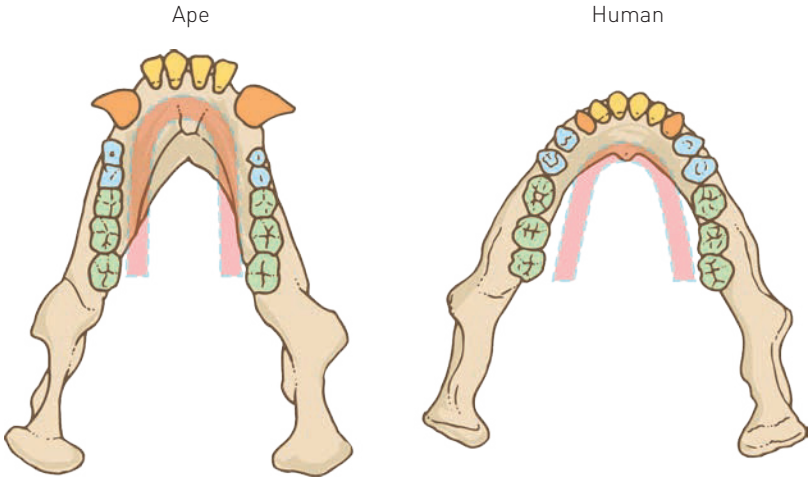


Figure 18.17 The dental arcade of an ape and a human

Figure 18.18 A fossil skull of *Homo habilis*

Hominin species
This website provides more information on each of the hominin species.

The trend towards smaller molars and a decrease in the robustness of the teeth continued in *Homo erectus* and is noticeable in modern humans. Humans that lived about 100 000 years ago had teeth that were about 10% larger than humans of today. Modern humans also appear to be gradually losing their wisdom teeth (the third molar), with an increasing number of people having no wisdom teeth at all.

EXTENSION

Anthropologists studying a cave in north-east Spain during 2008 discovered teeth and a lower jawbone that has pushed back the date of hominins in Europe. The site, called the Sima del Elefante, is a cave 15 m wide and 18 m deep. Use the Internet to find out:

- the age of the fossil material
- the shape of the jaw and the size of the teeth
- the significance of this fossil for hominin evolution.

Apes and the early hominins have a forward-jutting jaw, a characteristic known as **prognathism**, and a distinct **brow ridge**, the bony ridge located above the eye sockets, very evident in adult gorillas (see Figures 18.3 and 18.5). Accompanying the gradual reduction in tooth size was another evolutionary trend – the flattening of the face, development of a chin and a prominent nose (Figure 18.19).

Figures 18.19 and 18.20 show that the australopithecine skull has a projecting jaw that makes it appear almost ape-like, while the skull of *H. erectus* is less prognathic and that of a modern human is the least prognathic of the three. Gradual enlargement of the cranial portion of the skull

to accommodate the increasing size of the frontal region of the brain also led to a more distinct forehead and a reduction in the size of the brow ridge.

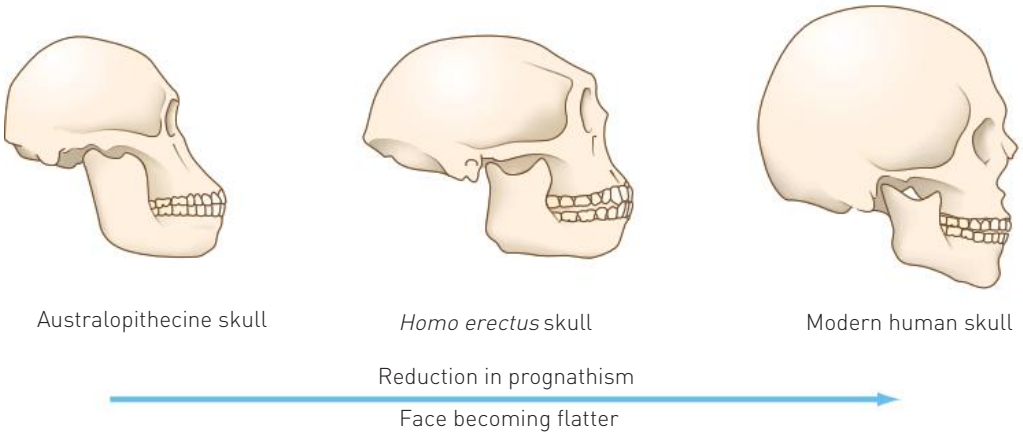


Figure 18.19 The evolutionary trend towards a flatter face

Reduction of prognathism
This website provides an excellent series of images illustrating the reduction in prognathism in hominins over time.

Adaptations for erect posture

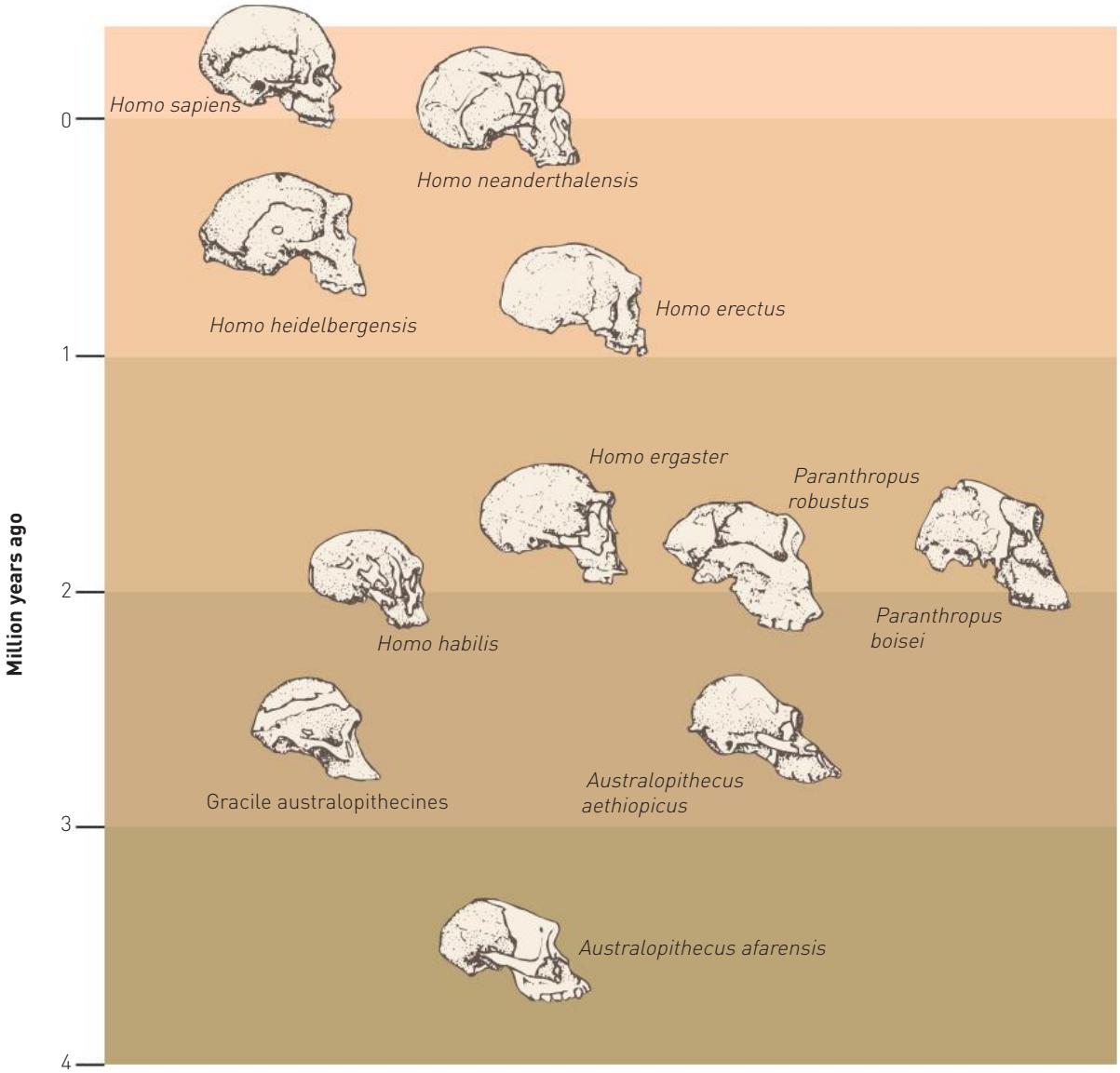


Figure 18.20 Fossil hominin skulls located in a time frame to indicate the period during which they lived. Note the reduction in prognathism from the early australopithecines to modern humans.

Science inquiry

ACTIVITY 18.1 Hominin skulls

In this activity you will research aspects of hominin evolution that show a distinct trend over the past 4 million years or so. Anthropologists have found hominin skulls that represent a number of different species over a significant time frame. They show two main features: an increase in brain size and a trend towards a flat face.

A: INCREASE IN BRAIN SIZE

Human evolution timeline

WHAT TO DO

1. Go the weblink or a similar website that lists all of the species included in Table 18.2 on page 279. Use the information there to determine how long ago each of the species became extinct (except for *Homo sapiens*, which of course still exists).
2. Construct a table similar to Table 18.2 showing the average cranial capacity of the species, but add an extra column to show how long ago each species ceased to exist.
3. Draw a graph of average cranial capacity versus the time when extinction of the species occurred.

STUDYING YOUR DATA

1. Describe the evolutionary trend that the graph illustrates.
2. Are there any anomalies in the trend? If there are anomalies, suggest explanations for them.

B: DECREASE IN PROGNATHISM

WHAT TO DO

1. For the species listed in your table, use the extinction times from Part A.
2. Construct a graph of the facial angle (from Table 18.3) plotted against the extinction time. The closer the facial angle is to 90°, the flatter the face.

Table 18.3 The facial angle of various hominin crania

Hominin	Facial angle (degrees)
Australopithecus afarensis	65
Australopithecus africanus	67
Paranthropus robustus	63
Homo rudolfensis	69
Homo erectus	70
Homo sapiens	78

STUDYING YOUR DATA

1. Describe the evolutionary trend that the graph illustrates. Are there any anomalies in the general trend?
2. Does this graph follow the same trend as that drawn in part A? Comment on any similarities or differences.

IN SUMMARY

Write a summarising paragraph to describe the relationship between an increase in cranial capacity and the trend towards a flatter face. What is the evolutionary significance of these trends?

ACTIVITY 18.2 Cranial capacity and phylogenetic trees

The subfamily Homininae includes humans, chimpanzees and gorillas, and their extinct ancestors (Figure 18.2 on page 271). One of those extinct ancestors was *Ardipithecus ramidus*, who lived around 4.4 to 4.2 million years ago and who many scientists believe gave rise to the australopithecines and therefore could be a direct ancestor of modern humans. Even if *A. ramidus* is not on our direct evolutionary line, it must have been closely related to the direct ancestor, and was probably similar in appearance and adaptation.

Estimates of the cranial capacity of *A. ramidus* are between 300 and 350 cm^3, similar in size to modern female chimpanzees.

In this activity, you will use the information on cranial capacity from Activity 18.1 to construct a phylogenetic tree of the hominines.

WHAT TO DO

1. Assume that *A. ramidus* is the common ancestor of all the other species.
2. Consider which species may have become extinct and which species may have evolved into one or more other species. Draw up a phylogenetic tree to show the possible evolutionary relationships between the species in the table. Remember, there is no such thing as a correct tree. Scientists themselves cannot agree on all the relationships.
3. Once you have constructed your tree, go to the 'Human evolution' weblink to see how your tree compares with the information provided on that page.

Human evolution

STUDYING YOUR DATA

Compare your phylogenetic tree with the summary you wrote for the previous activity. Does the phylogenetic tree represent the same evolutionary relationships that you described in Activity 18.1?

ACTIVITY 18.3 Upright stance and the striding gait

A striding gait is a form of locomotion that distinguishes humans from the other living primates. Its evolution depended on changes to the skeleton and associated muscles and joints. In this activity you will examine some of these features to gain a greater understanding of the way we move.

YOU WILL NEED

A model of a human skeleton, charts or diagrams of the skeleton, the skull of an ape, reference to some of the diagrams in this book. If you wish, you could do the whole activity by comparing the human skeleton with that of the chimpanzee or gorilla, at the weblink.

Skeletons

WHAT TO DO

Answer the questions below. As you answer the questions, refer to the model of the human skeleton, ape skull and figures in the text as directed, or to images on a website.

STUDYING YOUR OBSERVATIONS

1. Compare the skull of an ape with that of a human. List the differences in the size and shape of the crania (brain cases).
2. Locate the position of the foramen magnum. The foramen magnum is the opening in the base of the skull where the spinal cord enters the brain (refer to Figure 18.4 on page 273). Look at the base of each skull and compare the position of the foramen magnum in the ape and in the human. Where is the foramen magnum in the human skull? Where is the foramen magnum in the ape skull?
3. Which skull is most easily balanced on the vertebral column: ape or human?
4. Look carefully at the model of the skeleton, and then refer to Figure 18.3 on page 272. Describe the curves of the vertebral column of the ape and the human. What extra curve exists in the vertebral columns of humans? (You may wish to refer to Figure 18.6 on page 273 to answer this question.)

5 Look at Figure 18.7 on page 274 and compare the shape of the human pelvis with that of the gorilla. Which pelvis is wider? Which is longer? Suggest reasons for the relatively wide pelvis in humans.
6 The human pelvis is tilted forward and curves inward, creating a basin shape. List the advantages this arrangement has for upright stance.
7 Look carefully at the model of the skeleton again, and then refer to Figure 18.8 on page 274. The narrow pelvis of the ape (Figure 18.7) makes the legs hang vertically. This means the ape must keep its feet apart when standing and, when walking, sway from side to side to maintain balance (Figure 18.14, page 277). Describe how the breadth of the pelvis contributes to the carrying angle of the femurs.
8 Explain the effect of the carrying angle on the arrangement of the knees, lower limb bones and the position of the feet in humans. What advantage does this arrangement have for human walking?
9 The vertebral column of humans acts as a weight-supporting column. How does the shape of the lumbar vertebrae contribute to the lumbar curve? Look closely at the angle between the lumbar curve and the pelvis. (You may wish to refer to Figure 18.5 on page 273.) What effect does the lumbar curve have on the position of the trunk and legs in humans?
10 Refer to Figure 18.11 on page 276 and compare the position of the centre of gravity in humans and apes. Which animal has the lower centre of gravity relative to body size? What features of the skeleton contribute to this difference?
11 Describe the pathway the body weight in humans follows from the pelvis down to the feet.
12 Remove your shoe and run your fingers over the top of your foot from little toe side to big toe side. Can you feel the transverse arch? Referring to Figure 18.10 on page 275 may help. How is this arch different from the longitudinal arch? What is the main function of the two arches?
13 Look at the model of the skeleton again, and then refer to Figure 18.10. Compare the toes of a gorilla and a human. What differences can you see?
14 When humans stride, the big toe provides the thrust. What features of the big toe assist this? Would an ape be able to use the big toe in a similar way? Explain your answer.
15 Refer to Figure 18.13 on page 277 and describe how the arches of the foot enable weight to be distributed from the heel to the big toe. Remove your shoes and try this for yourself.
16 Take a number of steps in your bare feet. Describe what occurs from the time your left heel hits the ground until your right heel hits the ground. Referring to Figure 18.13 on page 277 may help you with your description.
17 Summarise the main features in the human skeleton that are adaptations for an upright stance and for walking bipedally with a striding gait.

Review questions

1 **a** In the hierarchy of biological classification, what does the term 'tribe' mean?
b List the three tribes in the subfamily Homininae, and give an example of a member of each.
2 **a** List the components of the skeleton that allow humans to adopt an erect posture.
b How do these components differ from the corresponding ones in a quadrupedal animal?
c What are **i** the advantages and **ii** the disadvantages of an erect stance and bipedal locomotion?
3 **a** What is muscle tone?
b How does muscle tone help to support the body against the force of gravity?
4 **a** What is the carrying angle?
b Compare the carrying angle of an ape with that of a human.
5 **a** How does the wide pelvis and carrying angle of the femur enable humans to walk without the body swaying from side to side?
b What contribution do the arms make to stabilising the body during walking?
6 What is an endocast? What can it tell us about the size and shape of the brain?
7 Describe the major anatomical and functional developments that have occurred in hominin brains over the past four million years.
8 Human dentition is said to be unique.
a List the differences between the teeth of a human and those of an ape, such as a gorilla.
b How has the dental arcade changed in hominins compared with that of an ape?
9 Describe the change in the shape of the face of hominins over the past four million years or so.

Apply your knowledge

1 For humans to be able to stand upright, a number of adaptations have taken place. Changes have occurred to the skull, vertebral column, pelvis, legs and feet. Describe how each of these has contributed – and how they have interacted – to enable humans to adopt an erect stance.
2 As a result of various conditions, the normal curves of the vertebral column may become exaggerated. Use references to describe the conditions known as scoliosis, kyphosis and lordosis.
3 If you have seen chimpanzees or gorillas walking bipedally, you will have noticed that they sway from side to side as they walk. Explain why they cannot stride as humans do.
4 What assumptions are made when scientists infer the degree of intelligence from the cranial capacity of a skull?
5 The human canine tooth is much smaller than that of the other hominids, especially in the males of the species. Describe the evolutionary processes that would have taken place in hominins to produce the current size of that tooth in humans today.
6 The primitive ancestor of the hominins is thought to have moved through trees by brachiation. Outline the characteristics that a brachiator, such as the gibbon, would possess that are likely to be of advantage for bipedal locomotion.
7 The term 'hominid' used to have the same meaning that 'hominin' now has. 'Hominid' was used to refer to the various members of the human family tree. Scientists who study human origins have changed the classification scheme by introducing a new level, the tribe (see Figure 18.2 on page 271). 'Hominid' is now defined in a much broader way so that it refers to all great apes and their ancestors. 'Hominin' refers only to present-day humans and our extinct ancestors. Why would scientists make changes to the classification scheme for apes and humans? Suggest as many reasons as you can.
8 This chapter has discussed the evolution of erect stance and bipedal locomotion, and a large brain, under separate headings. In the previous chapter, the development of the human hand and the precision grip were discussed. However, it is unlikely that these features would have evolved independently of each other. Discuss a possible evolutionary sequence that would account for the development of each of these characteristics.

CHAPTER

19

HUMAN ANCESTORS

UNIT 4 CONTENT

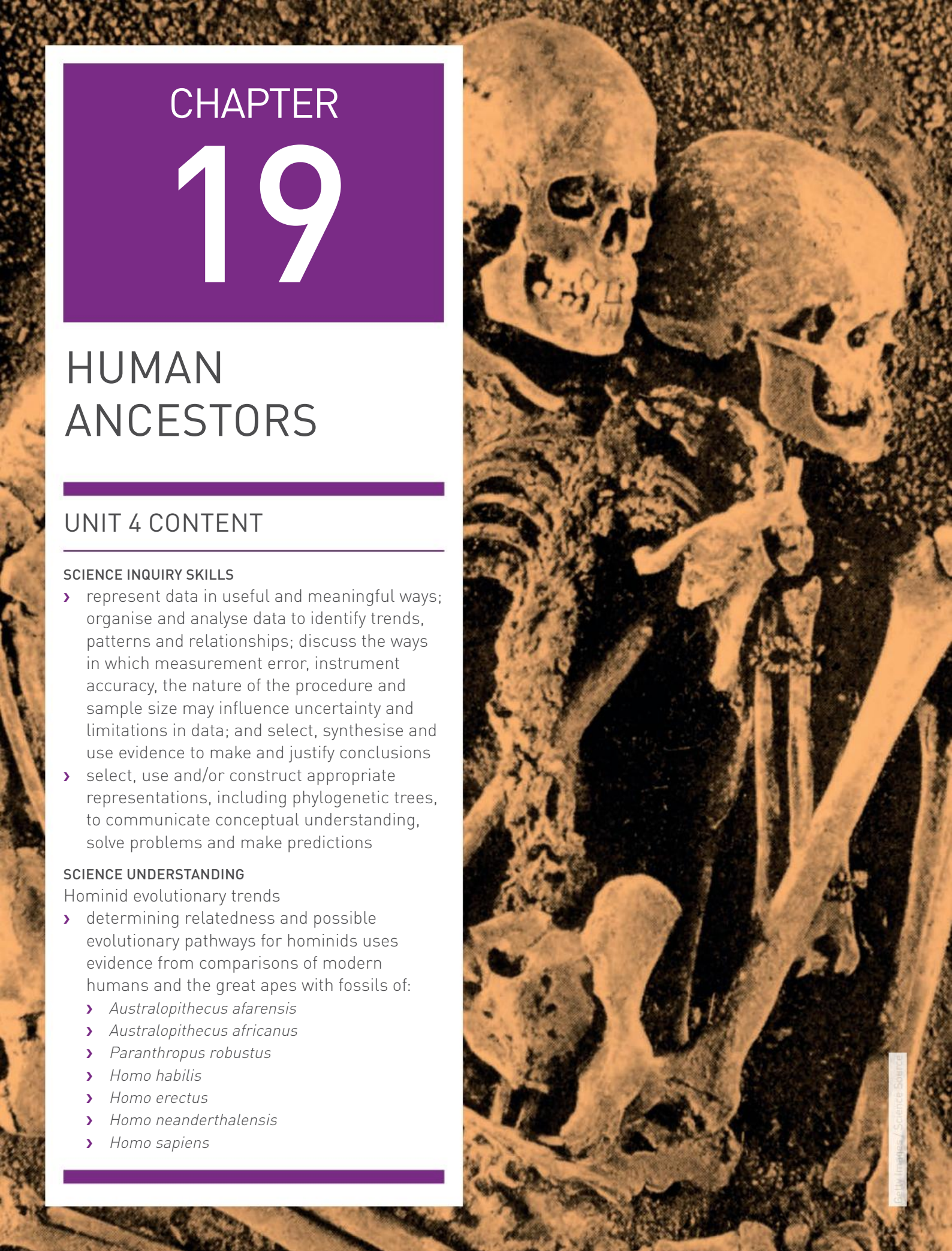
SCIENCE INQUIRY SKILLS

- represent data in useful and meaningful ways; organise and analyse data to identify trends, patterns and relationships; discuss the ways in which measurement error, instrument accuracy, the nature of the procedure and sample size may influence uncertainty and limitations in data; and select, synthesise and use evidence to make and justify conclusions
- select, use and/or construct appropriate representations, including phylogenetic trees, to communicate conceptual understanding, solve problems and make predictions

SCIENCE UNDERSTANDING

Hominid evolutionary trends

- determining relatedness and possible evolutionary pathways for hominids uses evidence from comparisons of modern humans and the great apes with fossils of:
  - *Australopithecus afarensis*
  - *Australopithecus africanus*
  - *Paranthropus robustus*
  - *Homo habilis*
  - *Homo erectus*
  - *Homo neanderthalensis*
  - *Homo sapiens*



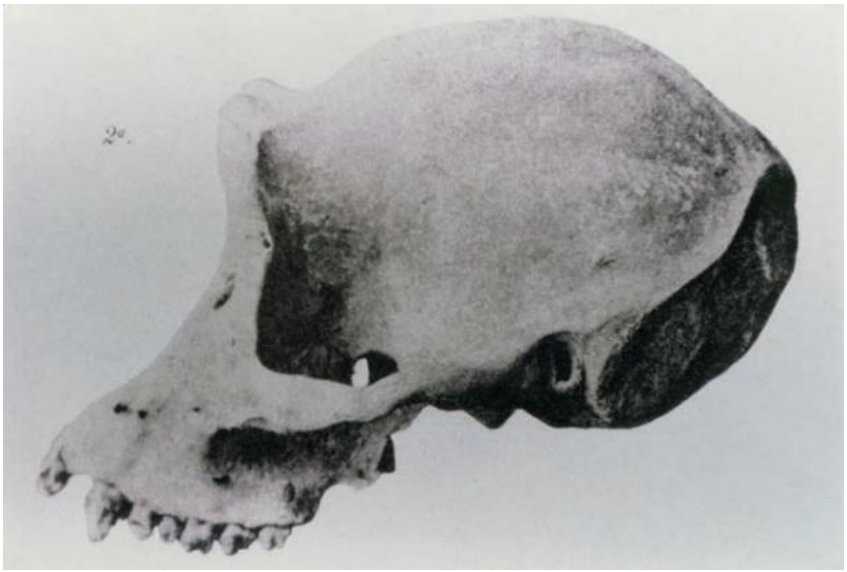
The publication of Charles Darwin's book *The Descent of Man* in 1871 sparked much public and scientific debate about human origins. Darwin suggested that, because the great apes and humans have many structural similarities, they may share a common ancestor. However, the significance of the few fossil remains of human ancestors was not realised at that time, and so there was no evidence to support such a hypothesis. Many scientists speculated about what such an ancestor would be like and one, Ernst Haeckel, even drew up a family tree that included a human ancestor something like an ape. Haeckel and his colleagues named this hypothetical human ancestor 'Pithecanthropus allus', or 'speechless man-ape'. It was supposed to have given rise to modern humans via an intermediate species, 'Homo stupidus'.

Haeckel's speculations, together with the writings of the biologist Alfred Russel Wallace, persuaded a young Dutch anatomist, Eugène Dubois, to go to Sumatra to search for fossil evidence of human ancestors. Before leaving for Sumatra, Dubois studied all the evidence then available. This included the Neanderthal fossils – human fossils unearthed in a limestone cave in the Neander Valley near Düsseldorf in Germany. He considered that these fossils were definitely human and, therefore, not the missing link between apes and humans. He reasoned that the fossils he was going to search for must have lived a long time before Neanderthal, and that Europe would have been far too cold at that time for a human-like animal to have survived. So he turned his attention to the tropics, and to the islands of Sumatra and Borneo.

To enable him to search for fossils, Dubois enlisted as a doctor in the Dutch East Indian Army and went to Sumatra in 1887. He began looking for fossils of human ancestors in caves, but without success. He was transferred to Java, where he continued his research with the help of a local crew of convict labourers. In September 1891, his workers came across a single ape-like molar tooth at a site along the Solo River. About a month later, approximately a metre from the spot where the tooth was found, part of a skull was uncovered.

Considering both fossils together, and recognising ape-like and human-like features in each, Dubois concluded that he had found evidence of the past existence of a human-ape. The following August, he found a thigh bone that was distinctly human in all respects, except that it was heavier than that of modern humans. Another tooth was also found and the four fossils together suggested an erect creature with a skull intermediate between apes and humans. Dubois named the creature after Haeckel's hypothetical ancestor of humans, *Pithecanthropus*, but added the species name *erectus* to indicate its upright stance. Thus, in 1893, Dubois was confident that he had found the missing link between apes and humans: *Pithecanthropus erectus* (Figure 19.1).

Dubois' discoveries sparked a scientific controversy. Some scientists thought *Pithecanthropus* was an ape with human-like characteristics; others thought it was a human with ape-like attributes. Those in the middle suggested it was transitional between ape and human. Subsequent evidence



Science Photo Library

Figure 19.1 A drawing made by Eugène Dubois of the skull he found in 1891 and named *Pithecanthropus erectus*

suggests that Dubois' discovery is an example of a species now known as *Homo erectus*. However, in searching for the 'missing link', Dubois generated great interest in human origins. Many others were stimulated to join the search, and so today there is a vast range of fossils available for study. However, many questions remain unanswered and the search begun by Dubois in 1887 continues today in many parts of the world.

In this chapter the physical appearance and possible evolutionary pathways for hominins will be examined using evidence from fossil discoveries. The next chapter discusses the cultural changes that have occurred during this time.

Effect of the environment on hominin evolution

To understand how natural selection caused the evolutionary trends in hominins that were described in the previous chapter, scientists have to determine what the environment was like millions of years ago.

Using geological and chemical information, and information about the types of fossilised plants and animals found, a picture can be built up of the environment at the time when ancestral hominins were alive.

Early hominins and early chimpanzees evolved from a common ancestor. Just after their split from the chimpanzee lineage, hominins are thought to have lived in a woodland or forest environment. These early hominins were ape-like, with arms and hands that retained features suited to living in trees, much like modern orang-utans. Orang-utans frequently move over small springy branches in a bipedal manner using their arms for balance (Figure 19.2). This kind of upright locomotion may have been used where there were gaps in the forest canopy and early hominins needed to travel across open ground. Therefore, many believe bipedalism originated in an arboreal ape-like hominin that lived in a forest environment.

Stephane Bidouze / Shutterstock.com

Figure 19.2 A female orang-utan with baby moving bipedally at the edge of a forest

Somewhere between 5 and 6 million years ago, the environment was changing. Temperatures began to fall and forest areas diminished in size, leaving patches of forest separated by increasingly open grassland. In such conditions many arboreal animals would not be able to survive. However, some of the features that help apes live in trees also allow for limited bipedalism on the ground. As the forests thinned and trees got farther apart, there were more open spaces. In this situation, natural selection may have favoured apes that were better at bipedal walking.

Those apes evolved into the early hominins. Natural selection favoured individuals with a more erect stance who were able to move bipedally across the expanding grasslands. The advantages of an erect stance, and the bipedal locomotion that evolved later, are:

- an increased range of vision for detecting prey and predators at a greater distance
- increased size, deterring predators
- hands free for carrying food and, perhaps, for tool use
- higher reach when picking fruit from trees
- improved cooling of the body.

When the body is vertical (instead of horizontal, as in quadrupedalism), the sun strikes a smaller fraction of it, helping to avoid overheating. In addition, the upper body is above the ground where there is more wind to help cool the body and where air temperatures may be marginally lower than at ground level.

As African forests were replaced by grasslands, food supplies became more limited. At this time, about 2.5 million years ago, the australopithecines were evolving from the earliest of the hominins.

EXTENSION

Groups of apes lived during the Miocene epoch (5.3 to 23 million years ago – see the geological time scale on page 243) and are collectively referred to as the dryopithecines.

Find out:

- how long ago these apes lived
- their appearance
- their significance for hominin evolution.

Australopithecines

The first australopithecine fossil was found in southern Africa in the early 1920s. Like many early fossil discoveries it was a chance event. Raymond Dart, a young Australian anatomist, had his attention drawn to fossil baboon skulls being found in limeworks at Taung, north-west of Kimberley. Dart asked the manager of the limeworks to send him any interesting fossils, which he did, sending a box full of limestone pieces containing bones. On clearing away the limestone, Dart was surprised to find the whole face, jaws and teeth of what appeared to be an ape. However, it was like no other ape: although it was a juvenile, Dart realised that the face was not as protruding as that of an ape, and the teeth, especially the first molars, were more like those of humans. The skull was more rounded and there was not even the beginnings of a brow ridge (Figure 19.3).

Natural History Museum, London/Science Photo Library

Figure 19.3 The Taung skull: a side view of a cast of the original fossil material

There was, however, a need for caution. Juvenile skulls are particularly difficult to assess because they tend to show features different from those of adults. As Figure 19.4 indicates, the skull of the young gorilla is more rounded than that of the adult gorilla, and the cranium is larger in proportion to its still

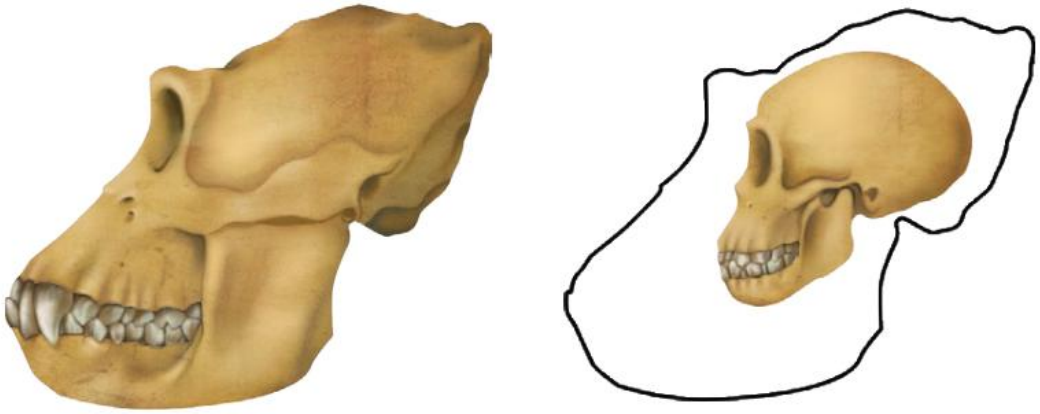
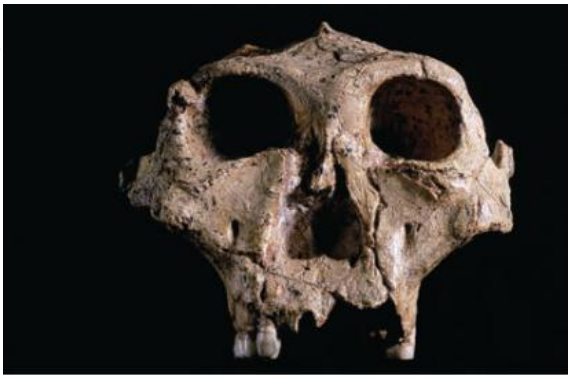


Figure 19.4 The skull of an adult male gorilla (left) and that of a juvenile gorilla superimposed on the outline of an adult skull (right). The juvenile skull is far more rounded than that of the adult.



Javier Trueba/Msf/Science Photo Library

Figure 19.5 A *Paranthropus robustus* skull found in a cave in South Africa. Note the large jaw and teeth. It is thought that they possessed powerful jaw muscles and had a vegetarian diet.

Figure 19.6 African sites where fossil Australopithecines have been found

undeveloped jaws. Even so, Dart recognised that the jaws and teeth, plus the more forward position of the foramen magnum, indicated that the skull belonged to a hitherto unknown group of human-like apes.

Dart's account of his discovery was published in *Nature* early in 1925. In his article, Dart suggested that the skull should be named *Australopithecus africanus*, 'the southern ape of Africa', and that it be put in a new family midway between apes and humans. This article was greeted with much scepticism, and the following edition of *Nature* published letters critical of Dart's interpretations. Perhaps the disbelief of many scientists was due to the evidence of Piltdown man (see page 242). This fossil, later shown to be an elaborate forgery, suggested that early humans had a modern skull with an ape-like jaw. One of Dart's few supporters was a Scottish doctor working in South Africa, Robert Broom, who was later to find more australopithecine remains.

Since Dart's Taung child of 1924, many other australopithecines have been discovered. The second fossil australopithecine was found by Broom at Sterkfontein in the Transvaal about 10 years later. He was enthusiastic in his search for australopithecine remains and, after his finds at Sterkfontein, found further fossils at nearby Kromdraai. The Kromdraai fossils appeared to be different from those from Sterkfontein, and this led Broom to name the Kromdraai skull *Paranthropus robustus*, which meant 'beside human' (Figure 19.5).

Two of the most exciting finds of australopithecines in more recent times are from two separate East African sites. One of these sites, in the Hadar region of Ethiopia, has yielded several hundred fossil fragments, including 'Lucy', a female skeleton that was 40 per cent complete. These fragments are thought to be of individuals who lived and died near a now vanished lake between 3 and 3.6 million years ago. At the second site, called Laetoli, three hominids left a 23-metre trail of footprints in volcanic ash. Using potassium-argon dating and stratigraphy the footprints were found to be 3.6 million years old.

The Laetoli footprints (see Figure 18.1 on page 271) are evidence that early hominins existed over 3 million years ago. Although there have been a number of interpretations of these footprints, with different numbers and sexes for the individuals who made them, most scientists agree that they were made by *Australopithecus afarensis* 3.56 million years ago. Features of the footprints that indicate a bipedal form of locomotion include a deep impression showing the heel hitting the ground first, the lateral transmission of weight from the heel to the ball of the foot, a well-developed longitudinal arch, a big toe that was parallel to the other digits, and a deep impression where the toe pushed the foot forward for the next stride.

The fossil remains known as 'Lucy' (shown in Figure 16.1 on page 235) have also been classified as *Australopithecus afarensis*. This classification was based partly on evidence gained from a comparison of the dental arcades of apes, early hominins and their Hadar specimens (Figure 19.7). The size of the canines and

the prominence of the cusps on the cheek teeth were somewhat intermediate between apes and early hominins, but the first premolar was more typically ape-like than hominin-like in that some specimens had one cusp rather than two. On the other hand, the large, flat cheek teeth were very similar to those of later hominins.

Raymond Dart
This website provides a biography of Raymond Dart.

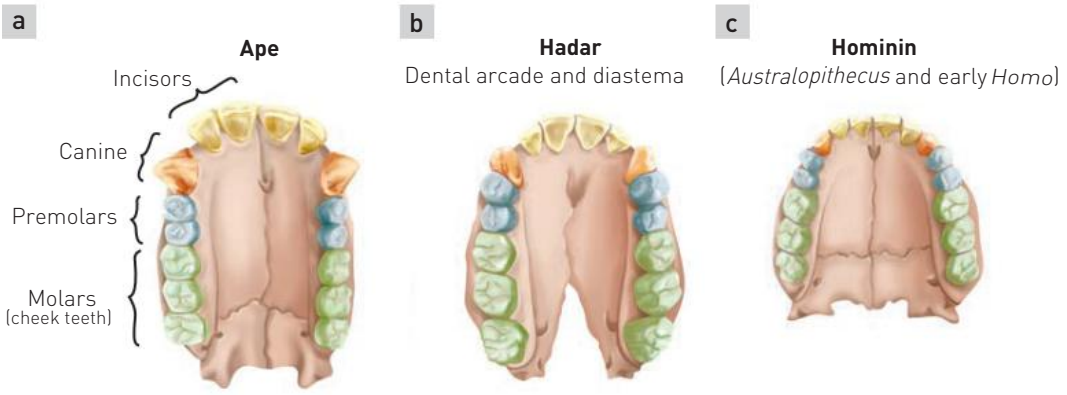


Figure 19.7 The dental arcades of **a** an ape, **b** a Hadar specimen and **c** an early hominin

The femur and pelvis in australopithecines are much more like those of a human than an ape, as Figure 19.8 indicates. Considering the evidence from fossil bones, and the evidence from the fossil footprints, it is safe to assume that these early hominins were truly bipedal, even though their gait would not have been quite the same as that of modern humans.

Finding 'Lucy'
This website provides an interesting video on the discovery of this fossil.

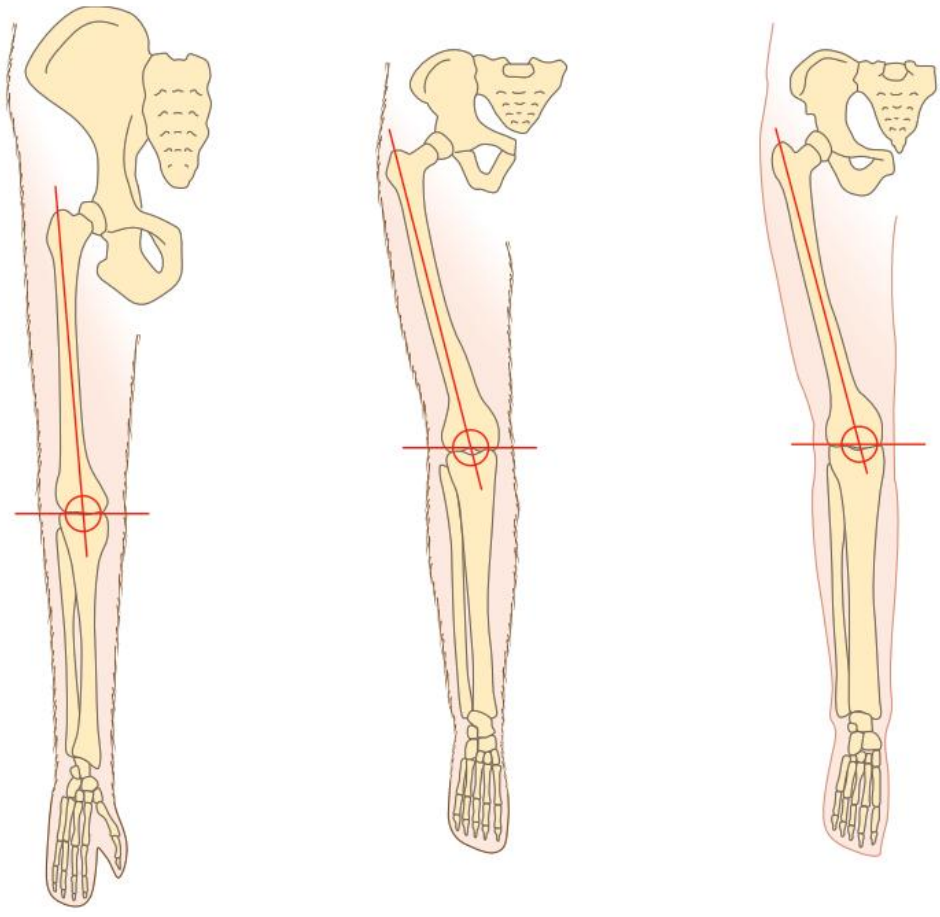


Figure 19.8 Australopithecines, like humans, had the femur angled so that the foot was under the centre of gravity, allowing bipedal locomotion with the striding gait. The femur of an ape is not angled in this way, so apes sway from side to side when they are walking erect.

Anatomical features of the genus *Australopithecus*

From the fossil evidence so far accumulated, it has been possible to construct a clear picture of the physical features of *Australopithecus*. Many of these resemble the features of later hominins. The teeth are typically those of a hominin: the canines are short and non-projecting, resembling the incisors, in sharp contrast to those of apes. Together the incisors and canines make a row of cutting teeth, and there is no gap between them and the following premolars. The teeth are in the parabolic shape distinctive of the hominids. (See Table 19.1 for a summary of primitive and modern features of hominins.)

Table 19.1 Anatomical trends in hominin evolution

Anatomical feature	Considered to be more primitive	Considered to be more modern
	Characteristics more ape-like →	Characteristics more human-like
Skull	Thicker bones forming cranium	Thinner bones forming cranium
	Smaller cranial capacity	Larger cranial capacity
	Heavier brow ridges	Brow ridges reduced or absent
	No forehead or sloping forehead	Increasingly larger and more vertical forehead
	Lower cranium	More dome-shaped cranium
	Less prominent cheek bones	More prominent cheek bones
	Possible crest on top of skull	No crest on top of skull
	Foramen magnum towards back of skull	Foramen magnum under centre of skull
Mandible and teeth	More prognathic jaw	Flatter face
	Heavier, thicker mandible	More slender, thinner mandible
	No chin	Increasingly definite chin
	Larger teeth, especially molars	Smaller teeth
	Diastema present	No diastema
	Canine teeth more prominent	Canine teeth less prominent
Torso	Narrower hips (pelvis)	Broader hips
	Back (lumbar) vertebrae less wedge-shaped	Lumbar vertebrae more wedge-shaped
Upper limbs	Shorter thumb	Longer thumb
	Fingers more curved	Fingers straighter
Lower limbs	Femurs more parallel	Femurs sloping inwards towards the knee
	Arms longer than legs	Arms shorter than legs

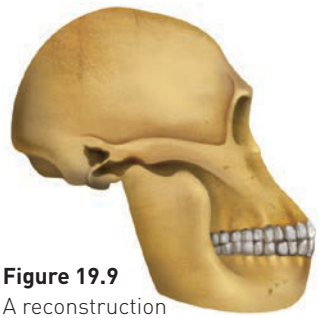


Figure 19.9
A reconstruction of an australopithecine skull

The facial profile of the australopithecines has a low forehead, and a more projecting upper and lower jaw than more modern hominin profiles (Figure 19.9). The average brain size is around 480 cubic centimetres, which is within the range of that of modern gorillas. However, the australopithecine's body weight was probably only a third that of the gorilla, and so their relative brain size lies somewhere between that of chimpanzees and modern humans. The shape of the brain surface has been determined from **endocasts**, impressions of the inside of the skull made of rock or some other solid material. The endocasts indicate that the brains of australopithecines were more human-like than ape-like. In addition, the foramen magnum was more forward than it is in the apes, and the skull more rounded at the back.

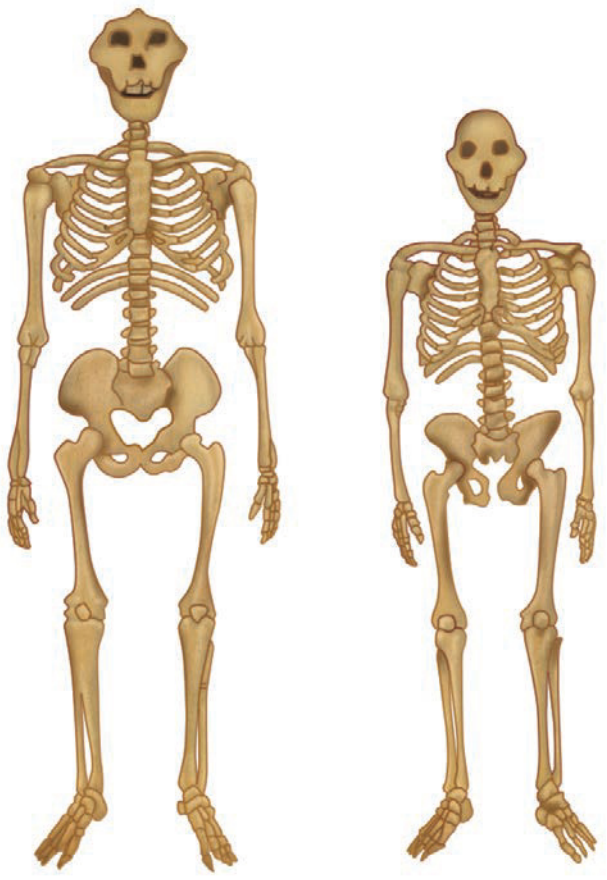
Limb bones found suggest that the australopithecines were bipedal. The pelvic and foot bones are typically hominin, with the foot possessing a non-opposable, strongly built big toe. Bones of the hand suggest that the thumb was shorter and less mobile than that of modern humans, and the fingers more heavily built, features indicating that the hand was better adapted for the power than the precision grip. Finally, the vertebral column displays the typical hominin curvature, and this, together with the position of the foramen magnum, indicates an erect stance.

Variation within the australopithecines

Two main variants of australopithecine have been discovered so far – those species that are slender, or **gracile**, and those that are heavier, or **robust**.

There are a number of differences between the gracile and robust forms, as Figure 19.10 illustrates. The most obvious is the difference in size: the robust form was about 30 centimetres taller than the gracile australopithecine, and weighed about 40 kilograms more. Gracile individuals generally stood between 120 and 140 centimetres in height and weighed between 25 and 35 kilograms. There are also differences in the features of the skull and jaws. The robust types had large, broad molar teeth that contrasted sharply with their small incisors and canines. The teeth were set in large jaws attached to the skull by powerful chewing muscles. The skull had massive bony crests and buttresses for the attachment of these muscles. On the other hand, the gracile forms had teeth more in proportion to each other, and the jaw muscles were smaller than those of the robust types. The differences between these two forms of skull are reminiscent of the differences between the skulls of the chimpanzees and gorillas of today.

Australopithecus africanus and *A. afarensis* are examples of gracile australopithecines. Today most scientists classify the robust australopithecines in a separate genus called *Paranthropus*. *Paranthropus robustus* (see Figure 19.5) is an example of a robust australopithecine.



Robust form **Gracile form**

Figure 19.10 Robust and gracile forms of australopithecines

Homo habilis

In 1964 Dr Louis Leakey published an account of a new species of *Homo* found at Olduvai Gorge in East Africa. Together with two colleagues, Professor Phillip Tobias and Dr John Napier, he had found a jaw, two cranial fragments, and several post-cranial remains dating back to 1.75 million years BP. They gave the new species the name ***Homo habilis***, or 'handy human', to indicate that it was adept at tool making. Usually the announcement of something 'new' in science causes other authorities in the field to question the interpretations of the discoveries. The case of *H. habilis* was no different. Many authorities considered it to be nothing more than an advanced australopithecine, or an East African variant of *Australopithecus africanus*. However, *H. habilis* had a larger brain and smaller teeth than the australopithecines, was taller than the gracile forms and stood more erect. At the time of its discovery it was thought to be the earliest tool user.

Later evidence tended to confirm the existence of *H. habilis*. In 1972, at the Koobi Fora site, a fossil skull with features midway between australopithecines and modern humans was found. Called 'Skull 1470' from the field number allocated to it (Figure 19.11), it was originally dated around 2.5 to 3 million years old but more recent techniques have given it an age of 1.9 million years. Skull 1470 has an estimated brain volume of 775 cubic centimetres. This was a problem because the younger specimen of *H. habilis*, found by Louis Leakey, had a smaller brain (about 600 cubic centimetres). However, Skull 1470 was not just an exceptional find. Other fossils found later in the same area show features similar to those of 1470. Pelvic bones found in 1974 reinforced the evidence suggesting that these hominids were fully bipedal, probably belonged to the genus *Homo* and lived alongside robust australopithecines. At one time there was considerable support for the view that these hominins were all members of the one species, *Homo habilis*. Evidence from numerous more recent finds indicate that there is more than one species and some experts no longer classify Skull 1470 as *Homo habilis*.

Figure 19.11 The cranium of 'Skull 1470'

Natural History Museum, London/Science Photo Library

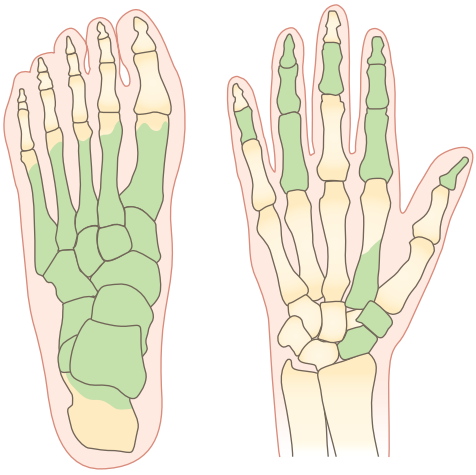


Figure 19.12 Hand and foot fossil bones (shown shaded) of *Homo habilis*; they resemble modern hominins. There is evidence of heavy musculature, indicating a powerful grip.

The discussion that follows will simply refer to early *Homo* because, with the evidence that has accumulated, labelling of individual hominins becomes problematic. This does not mean there is little evidence to go on – quite the contrary. As research has continued, and more and more fossils have been found, scientists have developed a greater understanding of hominin evolution between 3 and 2 million years ago. However, the problem of sorting out individual variations between fossils has been a major issue. There are clear indications that during this critical period a number of early *Homo* forms arose and different groups emerged, perhaps as they adapted to slightly different environments.

Detailed analysis of fossil evidence suggests that early *Homo* walked upright and had hands that were more robust than those of modern humans (see Figure 19.12). They would have had a more powerful grasp than ours, similar to the grip of chimpanzees. Like these modern apes, early *Homo* had a hand that would have been well suited to climbing trees. These two features suggest that early *Homo* may have spent the daylight hours walking bipedally on the ground, with food-gathering expeditions into the trees. At nightfall, it seems likely that early *Homo* would have retired to the safety of the trees to sleep, much like some of the non-human primates today.

The brain of early *Homo* was significantly larger than that of either the gracile or the robust form of australopithecines. The brain uses a lot of energy and can only grow larger in species that are routinely consuming high-energy food. Its growth also needs complex fats, which are hard to obtain or synthesise on a vegetarian diet. For the brain to increase in size, a shift to meat eating would be necessary. If meat did become a more significant part of the diet for early *Homo*, then

changes in behaviour would have occurred. Animals would have to be caught and killed, or stolen from predators, not simply gathered like plant food. As a result, early *Homo* would have had to become more aware of their surroundings and develop powers of reasoning and cunning. This, in turn, may have contributed to further development of their larger brains.

The larger brain, and the larger head that comes with it, may have resulted in infants being born earlier, before their heads became too big to pass through the birth canal. This would have required an extension in the period of parental care and perhaps greater cooperation and division of labour between males and females.

Until recently, most theories of human evolution have depended on the idea that one form progressively led to the next, slightly improved form, and so on. Scientists now believe that human evolution has followed pathways similar to those exhibited by other animal groups, where the ancestral stock usually contained more species than exist now, not fewer. We therefore should forget the old notion of a single pathway of human evolution and think more of a broad network of pathways with all but one, the path to *Homo sapiens*, gradually becoming extinct (Figure 19.13).

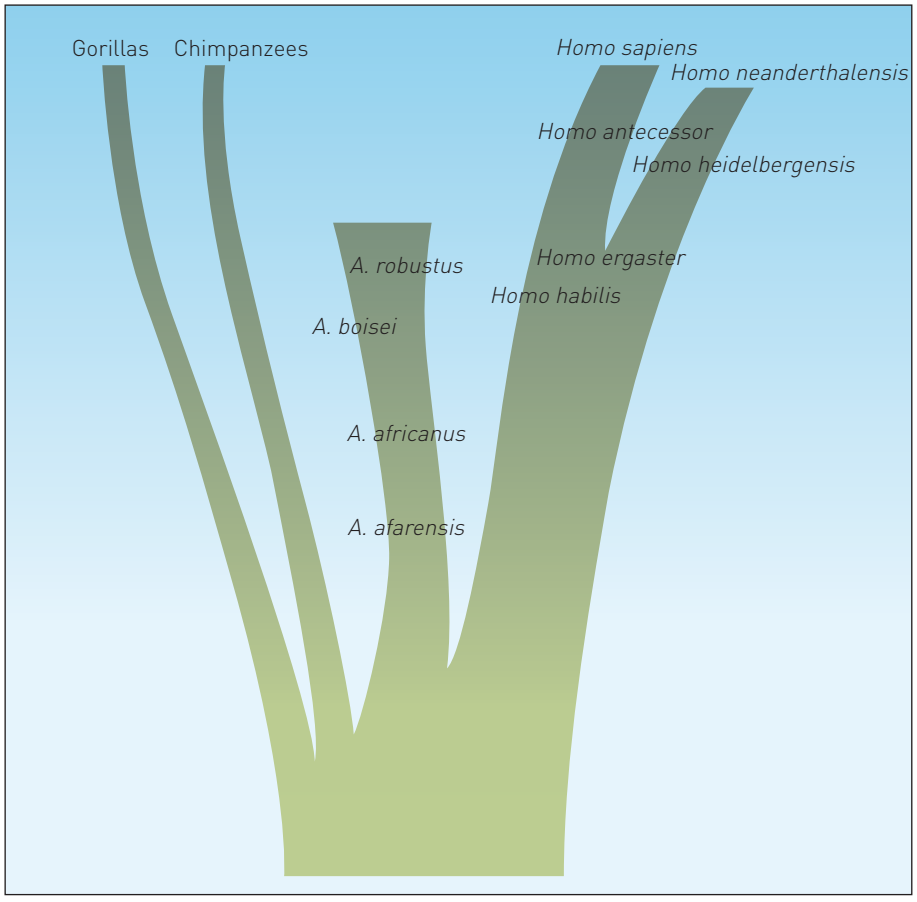


Figure 19.13 A phylogenetic tree representing a possible pathway to *Homo sapiens*

Homo habilis
This website provides more information and images on *Homo habilis*.

Homo erectus

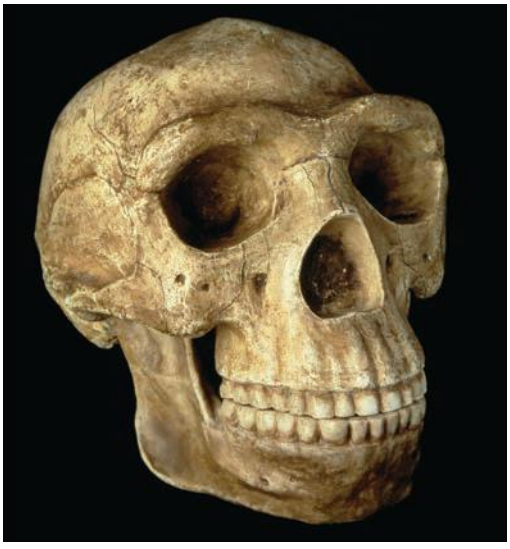
Dubois' so-called missing link, now called *Homo erectus*, stood virtually alone for 36 years, until in 1927 Dr Davidson Black announced that he had found a new species, which he called *Sinanthropus pekinensis*, or Chinese human of Peking (now known as Beijing). Black's announcement came after the study of teeth found in a limestone cave near Zhoukoudian, south of Beijing. Two years later the first skull was found and, in the years to follow, four more, plus skull fragments, lower jaws and teeth, were discovered. These fossils are now included in the species *Homo erectus*, and they are still some of the best examples ever found (Figure 19.14). Unfortunately, during World War II

the original fossils were lost, but good plaster casts had been made of them and each had been extensively described in the scientific literature, so the material is still able to be studied today.

'Peking man', as Black's find came to be known, was very similar to the Java fossils found by Dubois. However, there were some differences. The brain of the Beijing specimens was considerably larger, with an average size of 1075 cubic centimetres, and some aspects of the skull showed more modern features. The curve of the dental arcade was shorter and more rounded in front. The jaw was shorter and more compact, and suggested that a chin was beginning to form. Finally, the teeth were very modern and indicated a diet much like that of humans today (Figure 19.14). Evidence of the use of fire was also found in the cave, together with the remains of small, quartz, flake-like tools and animal bones. The significance of these finds will be discussed in the next chapter. The animal bones found in the cave suggested an age of around 500 000 years, younger than that of the Java fossils.

Peking man
This website suggests that 'Peking Man' may have been more sophisticated than once thought.

Since those early discoveries in China and Java, evidence about *Homo erectus* has accumulated from Africa, Asia and Europe. Some of those discoveries are listed in Table 19.2. Of particular interest were footprints found at Ileret in Kenya and described in 2009. The footprints, discovered in two 1.5 million-year-old sedimentary layers, provide the oldest evidence to date of an essentially modern human-like foot anatomy. Look carefully at Figure 19.15 and notice that the big toe is parallel to the other toes, and that the toes are short, like those of modern humans.



Natural History Museum, London/Science Photo Library

Figure 19.14 The reconstruction of a *Homo erectus* skull based on fossil remains found at Zhoukoudian Cave in China

Prof. Matthew Bennett, Bournemouth University

Figure 19.15 A footprint made by *Homo ergaster*, an African variant of *Homo erectus*, 1.5 million years ago

These footprints are believed to have been made by ***Homo ergaster***. However, not all scientists accept this species name and prefer to use the term 'African *Homo erectus*'. Using laser technology, scientists have established that the footprints show a pronounced human-like arch, a feature associated with an upright bipedal stance. These footprints are strong evidence that hominins have been walking upright, very much the way we do, for over 1.5 million years.

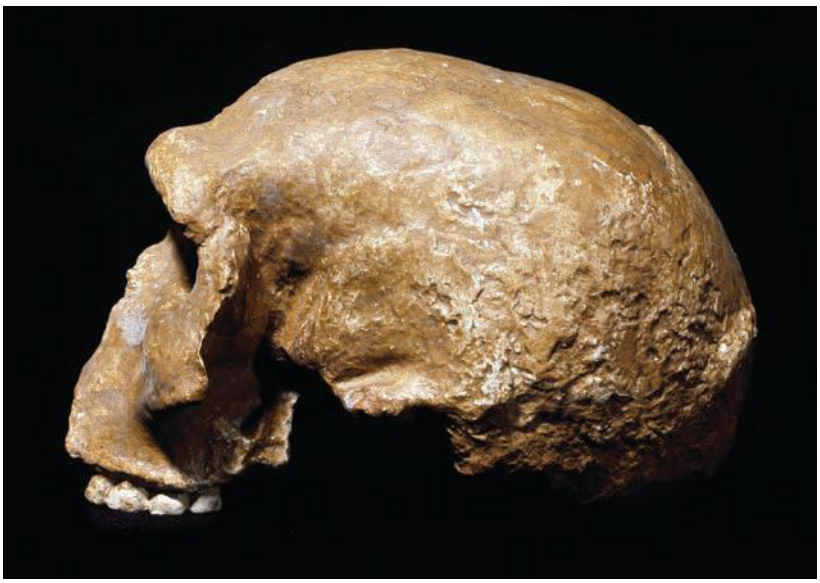
The teeth of fossils of *H. erectus* that are dated to later times are generally smaller than those of earlier members of the species. The molars particularly show a decrease in size over time, and this evolutionary trend is thought to reflect a progressive change in diet to softer foods, including a greater amount of meat in the diet, and eventually to cooked food.

Table 19.2 Some of the discoveries of early *Homo*

Common name	Scientific name	Age (years BP)	Year of discovery	Site
1470	*Homo rudolfensis*	1.9 million	1972	Koobi Fora (Africa)
	Homo erectus	1.8 million	1936	Java (Indonesia)
1813	*Homo habilis*	1.8 million	1973	Koobi Fora (Africa)
Handy man	*Homo habilis*	1.75 million	1960	Olduvai (Africa)
Turkana boy	*Homo ergaster*	1.6 million	1984	Nariokotome (Africa)
	Homo ergaster	1.6 million	2000	Ileret (Africa)
	Homo habilis	1.44 million	2000	Ileret (Africa)
	Homo erectus	1.4 million	1993	Dmanisi (Georgia)
	Homo erectus	1.0 to 1.4 million	1993	Java (Indonesia)
	Homo antecessor	780 000	1994	Gran Dolina (Spain)
Java man	*Homo erectus*	500 000 to 700 000	1891	Java (Indonesia)
Arago 21	*Homo heidelbergensis*	450 000	1971	Tautavel (France)
	Homo erectus	400 000 to 500 000	1966	Terra Amata (France)
	Homo erectus	300 000 to 500 000	1965	Vertésszöllös (Hungary)
Peking man	*Homo erectus*	250 000 to 350 000	1927	Zhoukoudian (China)

Transition to modern humans

In 1933, a skull was found at **Steinheim**, in Germany, with no lower jaw and severe damage behind the left eye. It also had a sizeable hole in the base but, even with this damage, it was an important discovery. Estimates of brain size averaged 1150 cubic centimetres, and the brain case had contours similar to those of modern human brain cases, as can be seen in Figure 19.16. Notice that the forehead is more prominent than in *Homo erectus*, but the brow is large and heavy, and the back of the skull has a more rounded profile. A number of the back teeth were preserved in



Leemage / Universal Images Group / Getty Images

Figure 19.16 The Steinheim skull

the upper jaw, and these appeared to be fairly modern. Clearly, there were advances over the *H. erectus* fossils, and an estimated age of perhaps 250 000 to 350 000 years suggested that this fossil was transitional between *H. erectus* and *H. sapiens.*

Two years later, in a gravel pit at **Swanscombe** on the River Thames in London, the first of three pieces of the back of the skull of a young woman were found. Nine months later the second piece was found and, *20 years* later, the third. The Swanscombe site has been dated around 400 000 years old, a little older than the Steinheim one, but the two skulls are very much alike and are obviously contemporaries. Together, these two skulls suggest that the brain had almost reached modern size 350 000 years ago, and that most of the modern contours of the skull had become evident.

A one million-year-old cranium from Eritrea, in East Africa, excavated between 1995 and 1997, has characteristics of both *H. erectus* and *H. sapiens*. Traditionally, fossils with these characteristics were considered to be an early (or archaic) *Homo sapiens* that was transitional between *Homo erectus* and modern humans. More recently it has been suggested that European hominids of this form should be classified as a distinct species, *Homo heidelbergensis*. This name comes from a mandible found near Heidelberg in 1907, and the species now includes many transitional forms.

Many scientists see *Homo heidelbergensis* as the common ancestor of both modern humans, in Africa, and Neanderthals, in Europe. However, another hypothesis about the evolution of modern humans was put forward after the discovery at Gran Dolina, in northern Spain, of the remains of at least six individuals dated from before 780 000 years ago. These fossils exhibit both modern features and more primitive ones, and the discoverers believe that they represent a new species, *Homo antecessor*. In their view, *Homo antecessor* evolved into *Homo heidelbergensis* and then to Neanderthals in Europe, while in Africa *Homo antecessor* evolved into *Homo sapiens*. Like many of the other hypotheses that currently exist about hominin evolution, more evidence is required before clear pathways become evident. However, it does appear that the family tree for *Homo* has far more branches than was once believed.

Neanderthals

As mentioned earlier in this chapter, the first recognised fossils of Neanderthal people were found in 1856 in a cave in the Neander Valley, near Düsseldorf, Germany. Since then a great many more fossils of this type have been found throughout Europe, Asia and northern Africa. Interpretations of data from the fossils have varied in the past, but fossils found in the 1990s suggest that the Neanderthals were only a side-branch along the pathway to modern humans. This was confirmed when, in 1997, molecular biologists extracted some DNA from a Neanderthal fossil and compared it with that of modern humans. They concluded that the Neanderthals were a distinct biological species, ***Homo neanderthalensis***. They existed in Europe during the last of the ice ages and were adapted to that particularly harsh type of environment. At some time in the past, the lineage diverged, with one branch leading to Neanderthals and another to modern humans. Exactly when, and how, this split took place we do not know, but there is considerable evidence that for a time Neanderthals and *Homo sapiens* lived together in Europe.

Javier Trueba/Msf/Science Photo Library

Figure 19.17 A Neanderthal skull showing the 'bun' shape at the back

Neanderthals had big faces, low but large skulls, and heavy brow ridges (see Figure 19.17). The brain was slightly larger than the average for humans today, and its shape was different. The back of the skull was drawn out in a 'bun' shape, the lower jaw lacked a definite chin, and the cheeks were swept back to give a streamlined appearance. These features can be readily seen in Figure 19.18, where the skull of *Homo neanderthalensis* is compared with those of *H. erectus* and *H. sapiens*. Note how it appears to have some features of both. The robust nature of the Neanderthal skull echoes the physical appearance of *H. erectus*, while the much larger brain of the Neanderthals is considered a modern feature.

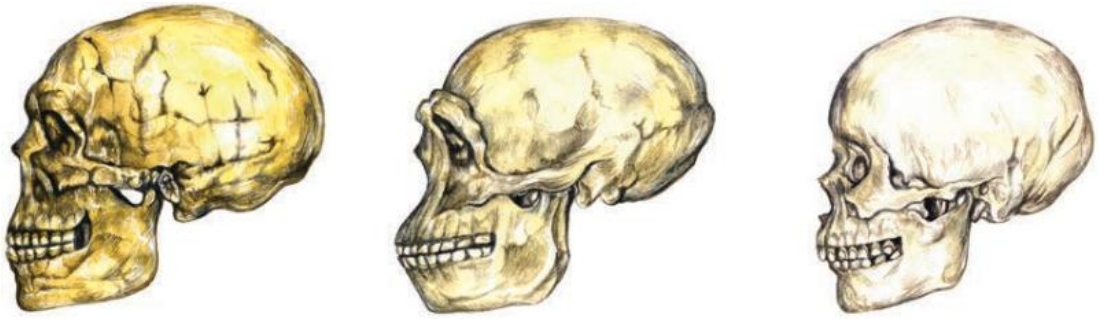


Figure 19.18 Skulls of *Homo erectus* (left), *Homo neanderthalensis* (centre) and a modern human (right)

Peculiar to the Neanderthals is the extreme forward thrust to the face, or prognathism, accentuated by the way the nasal bone projects forward. It is believed that the Neanderthal nose projected more than the modern human nose and was much wider. This larger, wider nose is thought to have been an adaptation for life in seasonally cold and dry environments.

The Neanderthals were short in stature, males being probably a little more than 1.5 metres in height, and females a little shorter. The limbs were short and heavily jointed with powerful muscles, so they would have appeared much more heavily built than modern humans. A barrel-shaped chest and thick neck muscles would have added to the rugged appearance. On top of this solid frame was a large skull containing a brain that was, on average, slightly larger than normal for modern humans, averaging 1485 as against 1350 cubic centimetres. It has been suggested that the additional brain capacity was probably required for control of the extra muscles. Apart from these differences in physical characteristics, Neanderthals would have walked, run and used their hands in much the same way as modern humans.

Modern humans

When the first fossils of modern humans were found in Europe, no one realised their significance or importance. It was not until 1868 that fossils of this type attracted the attention of scientists. In that year a number of skeletons were found at Cro-Magnon, under an overhanging cliff near the village of Les Eyzies in France. These fossils, of what are now called the **Cro-Magnon people**, were discovered by workmen constructing a railway. The site revealed the remains of more than five people, together with animal bones, sea shells in the form of necklaces, and stone tools. The stone tools were similar to those that had been found at Aurignac, tools that had become known as **Aurignacian**. Later discoveries suggested that these fossils were part of a once widespread population distributed throughout Europe from 40 000 to about 12 000 years ago. The best records of this habitation date from 25 000 years ago and occur in Spain, the French Pyrenees and the Dordogne Valley in France.

Human lineage
This website provides an interactive timeline showing our hominin ancestors.

Cro-Magnon people were members of our own species, *Homo sapiens,* and they possessed features far more modern than those of Neanderthals. In particular, their skulls tended to be shorter from front to back, higher in the region of the top of the skull and rounder at the back. Besides these, other features included less prominent brow ridges, a reduction in the projection of the face, and a smaller jaw, as can be seen in Figure 19.19. They had large brains, around 1350 cubic centimetres on average, housed in skulls that were long from front to back. The face was relatively broad and short, with the **orbits**, or eye sockets, well separated. The teeth also tended to be smaller and a chin had developed.

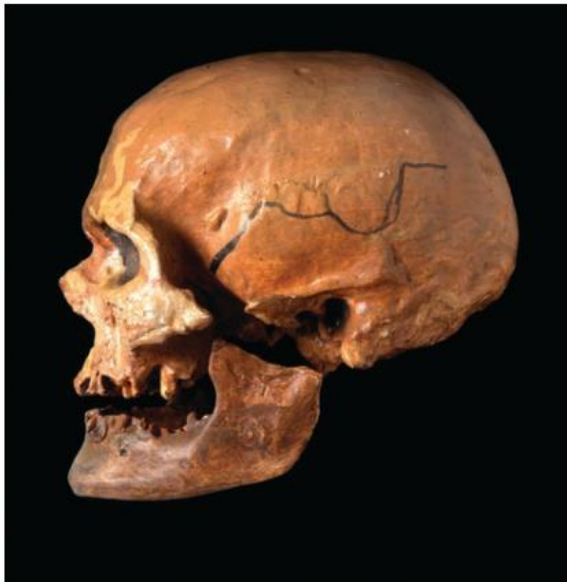


Figure 19.19 A Cro-Magnon skull

Science inquiry

ACTIVITY 19.1 Evidence for human evolution

Eugène Dubois was an anatomist who enlisted in the Dutch army so that he could go to Sumatra (in Indonesia) to look for fossils of human ancestors (see page 287). Remarkably, Dubois found what he was looking for: a tooth, part of a skull and a thigh bone that were clearly not from modern humans.

Dubois' discoveries generated great interest in human origins and raised the awareness of the importance of fossil material. One fossil that proved to be significant was taken to the Australian anatomist, Raymond Dart, who was working at the University of Witwatersrand in Johannesburg in the 1920s.

WHAT TO DO

Use a variety of research techniques to investigate the evidence for human evolution that Dubois and Dart discovered. Use your research to find out:

1. the fossils that were discovered
2. where and when the fossils were found
3. the scientific name that was given to the fossil finds at the time of their discovery
4. the significance of the finds at the time, and any controversy that they raised in the scientific community
5. the significance of the fossils today, given that much more fossil evidence is available for study.

Other scientists who made significant contributions in the early days of the search for human origins were Robert Broom and Louis and Mary Leakey. Find out about the work of each of these people. You may prefer to work in a group for this research.

ACTIVITY 19.2 A comparison of hominin skulls

In Activity 18.1 you examined the increase in brain size and the trend towards a flat face in a number of hominin species. In this activity, you will consider other aspects of the crania of five different species of hominins to observe the evolutionary trends that have occurred.

WHAT TO DO

Hominid species

1. Go to the 'Hominid species' weblink and select the following species from the list.
   Australopithecus afarensis
   Australopithecus africanus
   Homo habilis
   Homo erectus
   Homo sapiens sapiens
   Access all weblinks directly via **http://hp3and4.nelsonnet.com.au.**
2. For each species selected, click on 'Fossils' and then on the image that you wish to see enlarged. Select side and frontal views for a clear comparison.
3. Examine each of the fossils in turn. Using the numbers 1 for least to 5 for most, rank them according to the features listed below. Copy Table 19.3 and place your numbers in it.
   - **a** the least to the most vertical forehead
   - **b** the least prominent (or absent) brow ridge to the most prominent
   - **c** the least to the most projecting nasal bones
   - **d** the least prognathism to the most
   - **e** the smallest to largest cranial capacity
   - **f** the least to the most prominent cheek bones

Table 19.3 Anatomical trends in hominin evolution

Anatomical feature	*A. afarensis*	*A. africanus*	*H. habilis*	*H. erectus*	*H. sapiens*
Forehead					
Brow ridge					
Nasal bones					
Prognathism					
Cranial capacity					
Cheek bones					

STUDYING YOUR DATA

1 With the aid of Table 19.1, describe the evolutionary trends for each feature that you examined.
2 Are there any anomalies in any of the trends? If there are anomalies, suggest explanations for them.

Review questions

1. Briefly describe how the environment could have contributed to the first hominins evolving the free striding gait. How would this gait have increased the chance of survival in that environment?
2. The australopithecines are an important group of fossils, even though some scientists question their significance in the light of new evidence. Describe the main physical features of this genus and distinguish between the gracile and robust forms.
3. Who was Lucy, and why is she such an important 'person' in present theories of hominin evolution?
4. Describe the significance of the Laetoli footprints (Figure 18.1 on page 271). Why were they such an important discovery?
5. Who was *Homo habilis*? What does the available evidence suggest about this fossil hominin?
6. What assumptions are made when scientists infer the degree of intelligence from the cranial capacity of a skull?
7. Describe the features of *Homo erectus* that are evident from a study of the skull.
8. Outline the importance of the Steinheim and Swanscombe fossils. In your answer mention their age and their significance in the overall scheme of human evolution.
9. **a** List the differences between Neanderthals and modern humans.
   b Neanderthals were once thought to be ancestors of modern humans. What evidence is there that Neanderthals were a separate species that became extinct?
10. Describe the physical appearance of Cro-Magnon people.

Apply your knowledge

1. This chapter includes some good examples of science as a process of enquiry, and illustrates the way scientific knowledge accumulates as new discoveries are made. Refer to Figure 1.2 on page 6. How does the work of Dubois, Dart and Broom relate to the model for scientific method presented in Figure 1.2?
2. Dubois' discovery sparked a controversy among the leading scientists of the day. Because they were all examining the same material, why do you think there was so much disagreement?
3. There are two main physical forms for the australopithecines. Propose a hypothesis to account for the evolution of these two types from a common ancestor.
4. In the past, anthropologists have put a great deal of emphasis on the importance of the cranial capacity when defining the tribe Hominini. Does this seem reasonable, considering the hominins discussed in this and the previous chapter? What other physical features are important in a discussion of human evolution?
5. There is growing evidence that, like many of the other mammals, the pathway to modern humans may have many more species existing at a particular time than was once thought. If this is the case, how would it have been possible for closely related species to have lived on earth at the same time? Describe a possible situation where three species of early *Homo* lived in the same region of Africa.
6. Refer to Figures 19.1 (page 287) and 19.14 (page 296), both illustrations of a *Homo erectus* skull, and to Table 19.1 (page 292).
   a What features of the skulls enable you to say that it is not an ape skull?
   b What features of the skulls enable you to say that it could not have belonged to a modern human?
7. Describe the conditions that may have led to Neanderthals developing their characteristic anatomical features.

8 Imagine what would happen if a world-wide disaster that wipes out every living human on this earth were to occur tomorrow. If visitors from outer space arrived a thousand years from now and excavated fossils of present-day humans, what interpretations do you think they would make? Into how many species do you think they would classify present-day people?

9 Most of the major changes in human evolution from *Homo erectus* to modern *Homo sapiens*, identifiable from fossil evidence, are confined to the head. Identify five of these changes and explain their significance.

10 Compile a phylogenetic tree for the evolution of hominins from the early australopithecines to modern humans. List evidence in support of your evolutionary pathway and discuss any points of disagreement that others may have with it.

CHAPTER

20

CULTURAL EVOLUTION

UNIT 4 CONTENT

SCIENCE INQUIRY SKILLS

- represent data in useful and meaningful ways; organise and analyse data to identify trends, patterns and relationships; discuss the ways in which measurement error, instrument accuracy, the nature of the procedure and sample size may influence uncertainty and limitations in data; and select, synthesise and use evidence to make and justify conclusions
- select, use and/or construct appropriate representations, including phylogenetic trees, to communicate conceptual understanding, solve problems and make predictions
- communicate to specific audiences, and for specific purposes, using appropriate language, nomenclatures, genres and modes, including scientific reports

SCIENCE UNDERSTANDING

Hominid evolutionary trends

- tool use is seen in a number of hominid species and the study of these tools provides important insight into the evolution of the human cognitive abilities and lifestyle: trends are seen in the changes in manufacturing techniques and the materials used in the tool cultures of:
  - *Homo habilis*
  - *Homo erectus*
  - *Homo neanderthalensis*
  - *Homo sapiens*

In a group of organisms, those individuals with characteristics best suited to the environment are more likely to survive, reproduce and pass on their favourable characteristics to their offspring. Individuals with less favourable characteristics are more likely to die before they reproduce, so their unfavourable genes are less likely to be passed on to the next generation. This is **natural selection** and it leads to a species becoming better adapted to its environment.

As the environment gradually changes over thousands and millions of years, natural selection means that the characteristics of organisms gradually change to suit the environment. Hominins are no different in this regard than any other groups of plants or animals. Hominins have gradually evolved, through natural selection, to become more and more suited to the changing environment.

However, hominins *are* different from other organisms in that they have developed a complex culture. Anthropologists, people who study human societies and their development, may define **culture** as anything that is learned. Thus activities such as making stone tools, hunting techniques, food preparation, using language and art are all part of culture.

Just as the physical characteristics of hominins evolved over time, hominin culture has also evolved. Cultural development was an important means of overcoming some of the environmental challenges faced by early humans. This **cultural evolution** can be seen in the gradual improvement in tools, better methods of obtaining food, increased sophistication of language and a host of other changes culminating in the highly complex culture that we have today.

In this chapter we look at some of the environmental changes that have influenced hominin evolution and the cultural changes that accompanied changes in physical characteristics.

Australopithecine culture

The areas once occupied by australopithecines reveal the existence of home bases. From **home bases**, hunters and foragers went out to search for food. No evidence of the use of fire by australopithecines has been found to date, but tool use does appear to have been common. A range of **pebble tools** (Figure 20.1) have been found, including choppers, scrapers, flakes and chisels. These vary from about the size of a tennis ball (choppers) to that of a marble (scrapers and flakes), and are frequently referred to as **Oldowan tools**, after the site where they were first discovered. To use the scrapers effectively, the precision grip must have been employed. Tools of this type have been found at sites dating back 2.5 million years.

Getty Images/Javier Trueba/MSF/SPL

Figure 20.1 Pebble tools made by chipping flakes off a rounded pebble

This early tool making marked the start of a change in the way hominins interacted with their environment. These simple pebble tools enabled the australopithecines to exploit the resources in their environment more effectively and were the first stage in a succession of cultural changes still going on today.

Tool use by australopithecines enabled them to exploit a broader range of habitats, so they were eventually able to leave Africa and colonise other continents. Evidence suggests that the australopithecines began to disperse from Africa around 2 million years ago. They probably migrated north along the rift valley system, and then followed the River Nile into what is now Egypt, eventually going on to the Middle East and perhaps into Asia. What caused these migrations is unknown, but one possibility is that they were searching for more productive environments during the drier interglacial periods. Over this period the australopithecines gradually evolved, becoming taller and larger brained, and more able hunters.

The australopithecines were the first of the hominins but, at some point in the past, one of their many forms must have given rise to the first of the genus *Homo*.

Early *Homo*

Species within the genus *Homo* have larger brains than australopithecines. As mentioned in Chapter 19, complex fats are required to supply energy to the brain and to maintain its growth. Early *Homo*, such as *Homo habilis*, must have begun to consume meat. Observation of modern hunter-gatherers indicates that hunting parties more often than not return empty-handed. It is for this reason that many anthropologists believe that for a regular supply of meat to have been available, food sharing would have been essential. Adult male hominins were probably the early hunters, leaving the adult females to gather plant material while the young were left in safety at the home base. Both sexes would have brought the food they had acquired back to camp where it would have been shared, either among the immediate family or, more likely, among the group as a whole. This behaviour is typical of hunter-gatherers in recent times, but many argue that it could have had its origin up to 2 million years ago. Like recent hunter-gatherers, these early groups would have relied mainly on plant food, supplemented occasionally with meat. Sharing of food would have markedly changed the social structure of early hominins. The exchange of food within a group would have increased the sense of interdependence between the individuals, whether part of the family or not. This would have made the group more close-knit and enabled it to function as a social and economic unit. Communication within the group would have been important and thus pressure for development of a spoken language would have increased. There is some evidence that early *Homo* had a bulge in the speech-producing area of the brain, but the larynx may not have been capable of making complex sounds.

Evidence that early *Homo* was both a hunter and a scavenger of meat comes from animal bones found at fossil sites. A number of the bones show cut marks made by stone tools. With the naked eye it is difficult to distinguish between cut marks made by stone tools and those made by the teeth of a carnivore. However, examination under high magnification shows a clear distinction between the two. In Figure 20.2, notice how the tooth has left a broad, smooth groove on the bone, whereas the stone tool has made smaller, parallel grooves in the main cut. When interpreting the meat-eating behaviour of these early hominins it is important to determine which cut marks were made first. Were they scavenging the remains of prey killed by carnivores or were they consuming meat from animals they had killed and butchered? The bones recovered suggest that they were engaged in both activities. However, the evidence indicates that, as *Homo* evolved, the main source of meat was from hunting.

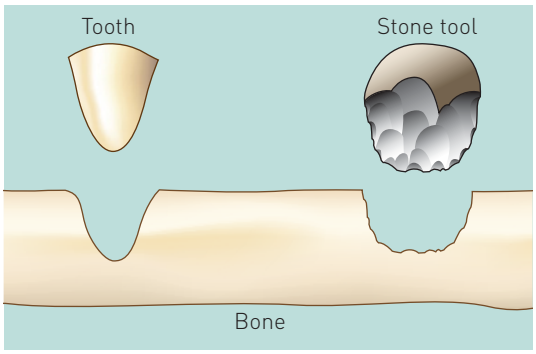


Figure 20.2 Difference in the marking patterns on bone produced by a tooth and by a stone tool

Culture of *Homo erectus*

By the time of *Homo erectus*, the effect of the environment as a selective agent was diminishing. These hominins were now modifying the environment to suit their own purposes. The use of fire, the building of shelters and a range of sophisticated tools had enabled *H. erectus* to become more independent of the environment.

Tools manufactured by *H. erectus* were flaked all round the edges, first in one direction and then in the other, until they formed roughly two-faced lumps, approximately teardrop in shape

(Figure 20.3). These tools were used as hand axes and are usually referred to as **Acheulian tools**, after the site at St Acheul in France where the axes were first discovered.

The discovery of a site on the Riviera in France in 1966 revealed much about the life of *H. erectus* in Europe 400 000 years ago. The site, called Terra Amata, contained 21 levels of habitation. Among important discoveries were the imprint of an adult foot, evidence of fire use and signs that *H. erectus* had constructed huts for shelter (Figure 20.4). Tool-manufacturing sites were also found and they included tools made from both stone and bone. However, no fossil hominins were found. The remains of animals indicated that hunting was important and the predominance of deer bones suggested that the inhabitants preferred this type of meat. The presence of some fish bones indicated that these hominins also fished from time to time.

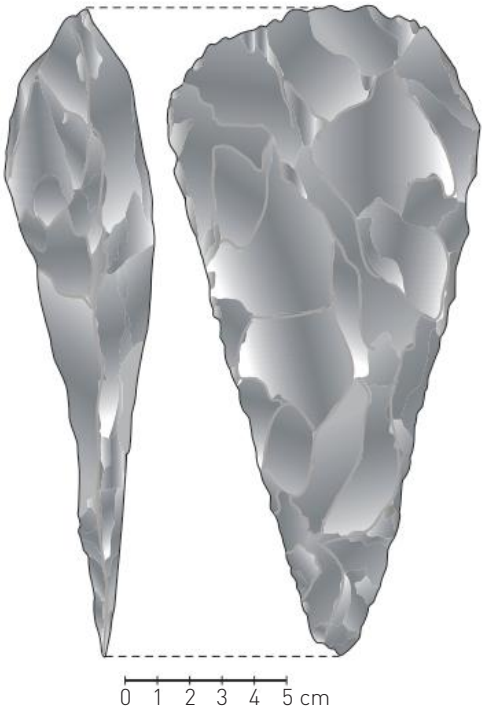


Figure 20.3 An Acheulian hand axe

Terra Amata
This website gives more information about Terra Amata.

Evidence from sites in other parts of the world reinforces the idea that *H. erectus* was a skilful hunter, employing a variety of techniques to capture game. At Olorgesailie, in south-western Kenya, the site of a massive slaughter of baboons has been located. This hunt must have been organised well in advance, as stones and tools had been carried to the site from up to 33 km away. Organisation like this also indicates that, half a million years ago, *H. erectus* was capable of logical thought and had the ability to communicate and work with others in an organised and efficient manner.

In Spain, at Torralba and Ambrona, evidence indicates that hominins lit fires to drive elephants into swamps where they were trapped and butchered. It appears that this driving technique was also employed at Olduvai Gorge, in Africa, to trap antelopes and pigs. Once captured, the animals were butchered using tools made from bone and stone. The butchery marks on the surface of fossil bones indicate that, as time passed, *H. erectus* became more systematic in the use of tools. This suggests an increasing commitment to routine meat eating.

Discarded bones and stone tools found at different sites suggest that although hunting was a major source of food it was probably not the most important source. Observations of modern hunter-gathering societies indicate that up to 70% of the total food intake for a group comes from gathering. In these societies, women tend to be the gatherers because of the demands of their child-caring role. It is therefore likely that gathering was very important for *H. erectus* and that, while the men were out hunting, the women of the group were involved in gathering vegetables, fruit and nuts from around the home base.

Figure 20.4 How a hut found at Terra Amata, in France, may have looked

The life of *H. erectus* was significantly influenced by the use of fire. Fire helped keep away predators, gave warmth and light at night, and may have been used to stampede animals. The warmth from a fire would have been important for migrating groups moving into Europe and Asia during the bitter cold of the ice ages. The illumination provided by a fire at night would have enabled groups to extend 'home-base' activities, such as the manufacture of tools and the butchering of carcasses (Figure 20.5, page 308). Fire also enabled cooking, which increased the

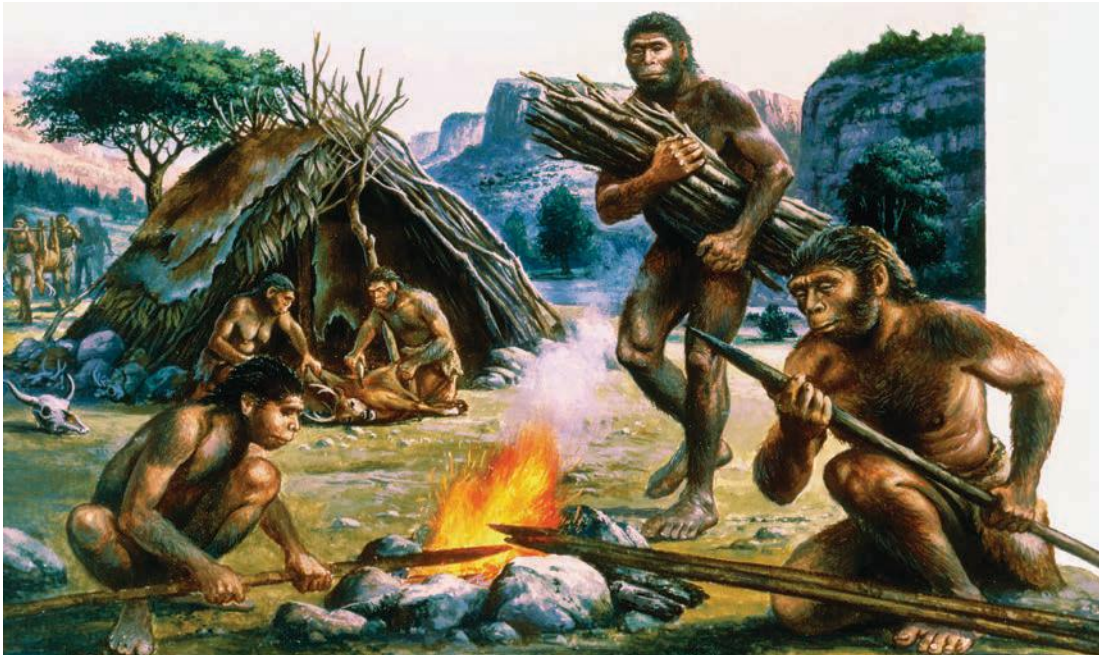


Figure 20.5 An illustration of what a *Homo erectus* camp may have looked like. A group of males is using fire to make spears while, in the background, a male and female are skinning a deer-like animal.

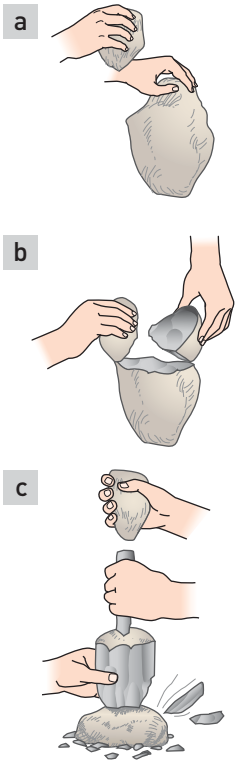


Figure 20.6 The production of flake tools: **a** and **b** show preparation of the core, and **c** shows how a large number of flakes can be produced.

range of foods that could be eaten by improving flavour and digestibility. It would also have made some foods safer to eat, either by destroying the early stages of parasites such as tapeworms, which may be present in meat, or by detoxifying some plant foods. The use of fire was the first step towards the manipulation of the environment to suit human needs.

Cultural changes such as the use of fire and the manufacture of tools would have influenced the social organisation of *H. erectus*. Greater emphasis must have been placed on mutual cooperation, and a complex society began to be established in which the care of the young would have gradually become increasingly important. A relatively complex spoken language could also have arisen by this time, but this is, of course, impossible to establish from the fossil record.

EXTENSION

Evidence suggests that *H. erectus* used fire to illuminate caves and other forms of shelter. To use fire effectively they must have developed ways of lighting a fire and maintaining it for long periods.

Use references to find out how early hominins may have lit fires and kept them burning.

Neanderthal culture

By the time of later hominins, such as *Homo neanderthalensis*, further cultural advances had greatly diminished the importance of the environment on how and where they lived. Tool making now involved the production of stone flakes that could then be trimmed to form various cutting, scraping, piercing and gouging tools. Commonly referred to as the '**Mousterian** industry', after Le Moustier in France where the first flake tools were found, these tools showed a cultural advance over the Acheulian hand axe. A piece of stone was first trimmed into a disc-shaped core, and then struck by another piece of stone to produce the flakes (Figure 20.6). Flake tools enabled people living in colder climates to become good clothes makers. Numerous scraping tools for preparing animal hides have been found at Neanderthal sites (see Figure 20.7).

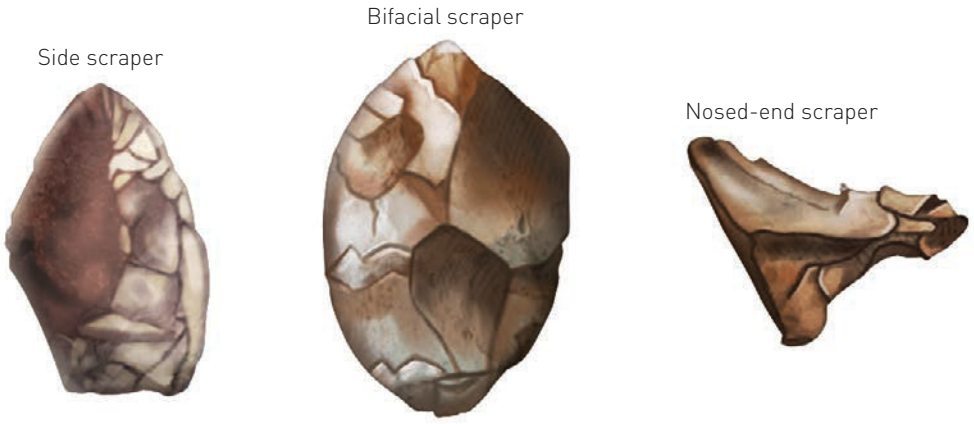


Figure 20.7 Neanderthal tools

Neanderthals
This website has a video on Neanderthals. Click on 'collections', then 'primate movies' and then select '*Homo sapiens* versus Neanderthals'.

The cultural advances of Neanderthals were not limited to tool making. There is strong evidence that Neanderthals buried their dead, leading to the suggestion that they believed in life after death. Ceremonial burial also seems to have been practised. At one site, the grave of a youth was surrounded by wild goat horns that had been thrust into the ground with the pointed ends downwards. At another site, a man had been buried on a bed of flowers. The shoulder blade, collar bone and upper right arm bone were all underdeveloped and there were no lower arm bones. Perhaps the man had been born with a withered right arm that had been successfully amputated above the elbow. It is likely that Neanderthals cared for disabled members of their group and had developed a social system for sharing food and other resources.

Transition to modern humans

Around 50 000 years ago new technologies associated with modern humans – finer blades and projectile weapons – began to appear. Scientists can only speculate on what triggered this technological spurt. Some have suggested that there was a mutation that affected the brains of a group of anatomically modern humans living either in Africa or in the Middle East. This may have resulted in new neurological connections that gave them new abilities. Perhaps it permitted fully articulate speech, so these people could pass on information more efficiently.

Whatever the cause, around 40 000 years ago modern humans moved into Europe. They brought with them innovations such as clothing, which had been sewn, and better shelters. This allowed them to survive the cold of glacial Europe, previously the exclusive domain of Neanderthals. The populations of both peoples were small and scattered. But while modern humans began to thrive, Neanderthal populations gradually decreased.

These modern humans became well established in Europe and were the makers of blade tools – flakes of stone with roughly parallel sides (Figure 20.8). Known as the **Cro-Magnon people** (named after the over-hanging cliff at Cro-Magnon in France where the first fossils were discovered), they had large brains housed in skulls that were long from front to back, similar to the present people of western and northern Europe. Cro-Magnon people were essentially hunters and gatherers, relying mainly on the hunting of herd animals that occupied the open plains. They mastered the art of hunting animals such as bison, mammoth and reindeer, often by stampeding them over cliffs or into

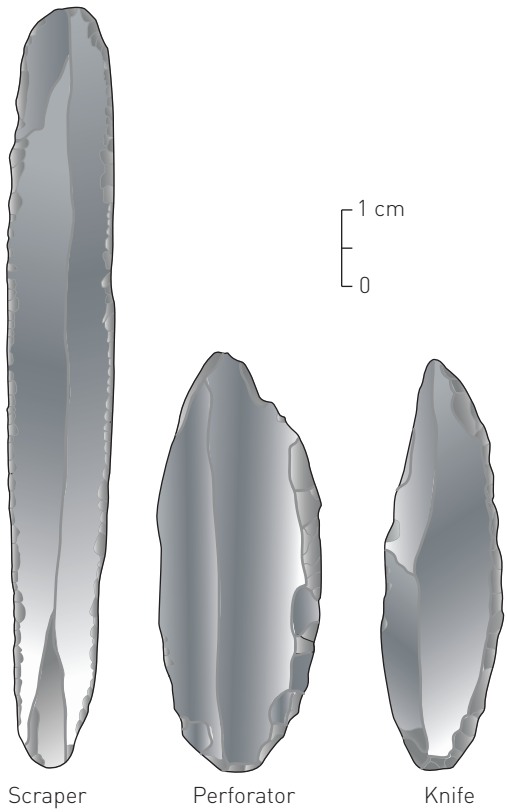


Figure 20.8 Blade tools

Figure 20.9 A Solutrean 'laurel-leaf' blade

narrow ravines. Besides being a source of meat, these animals also provided skins, which served as clothing or shelter. There is evidence to suggest that the fat from these animals was used for oil lamps, and that their bones and ivory were used to make tools.

When the first fossil remains were found at Cro-Magnon in 1868, the tools found with them were similar to those found eight years earlier at Aurignac, which had become known as **Aurignacian tools**. Besides this tool culture, two other cultures are associated with later Cro-Magnon people: the Solutrean and the Magdalenian. The **Solutrean culture** was characterised by beautifully made willow-leaf and laurel-leaf points (Figure 20.8). These were made by carefully retouching blades produced from the original stone core by pressure flaking. The laurel-leaf point illustrated in Figure 20.9 must have taken many hours of intricate skill to produce and is thought to have been an ornament, or perhaps a symbol of the tool maker's craft, as it would have served little practical purpose.

The **Magdalenian** cultural period, which followed the Solutrean, was named after the rock shelter of La Madeleine in France. This culture is known for the dominance of bone and antler tools over those of flint and stone, and for the works of art that were produced during this period (see Figure 20.10 for tools and Figure 20.13 for artwork). The bone and antler tools of this period were made using a burin, or chisel-like cutter, a tool used for the manufacture of other tools (Figure 20.11). This was a significant advance in tool making: humans had devised a tool for making other tools. To make the burin, a blade was shaped so that it had a sharp cutting point. With this, bone, antler and ivory could be cut to make a range of tools, from fine needles to barbed spear points and spear throwers.

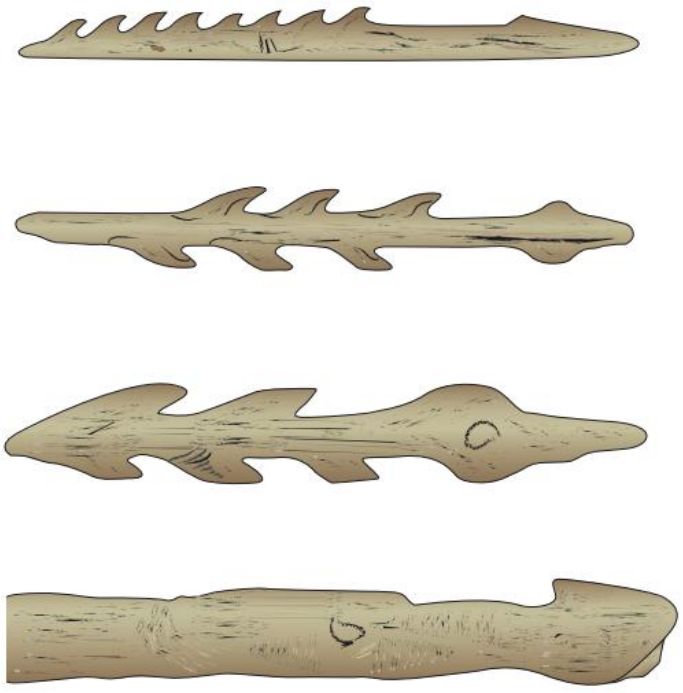


Figure 20.10 Magdalenian barbed points and spear thrower (bottom) made of bone or antler

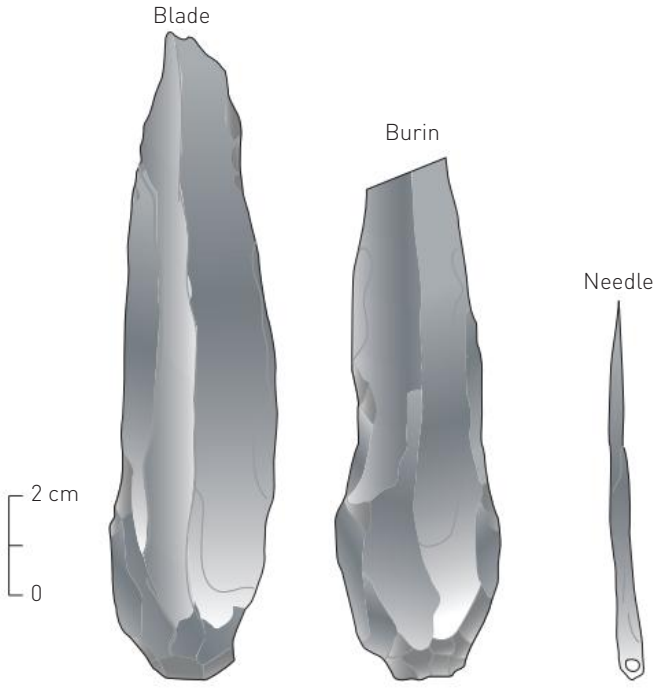


Figure 20.11 A burin was made from a basic blade. It was used to cut into antler and bone to make other tools, such as the needle.

Cro-Magnon people were responsible for some of the earliest known art. This was of two types: **portable art**, which could be carried (for example, carved figures); and **mural art**, which was attached to a permanent surface (for example, the wall or roof of a cave). A whole range of art objects have been found, including statuettes, figurines and decorated tools. These were made from stone, bone, ivory, horn and, in some cases, modelled clay (Figure 20.12).

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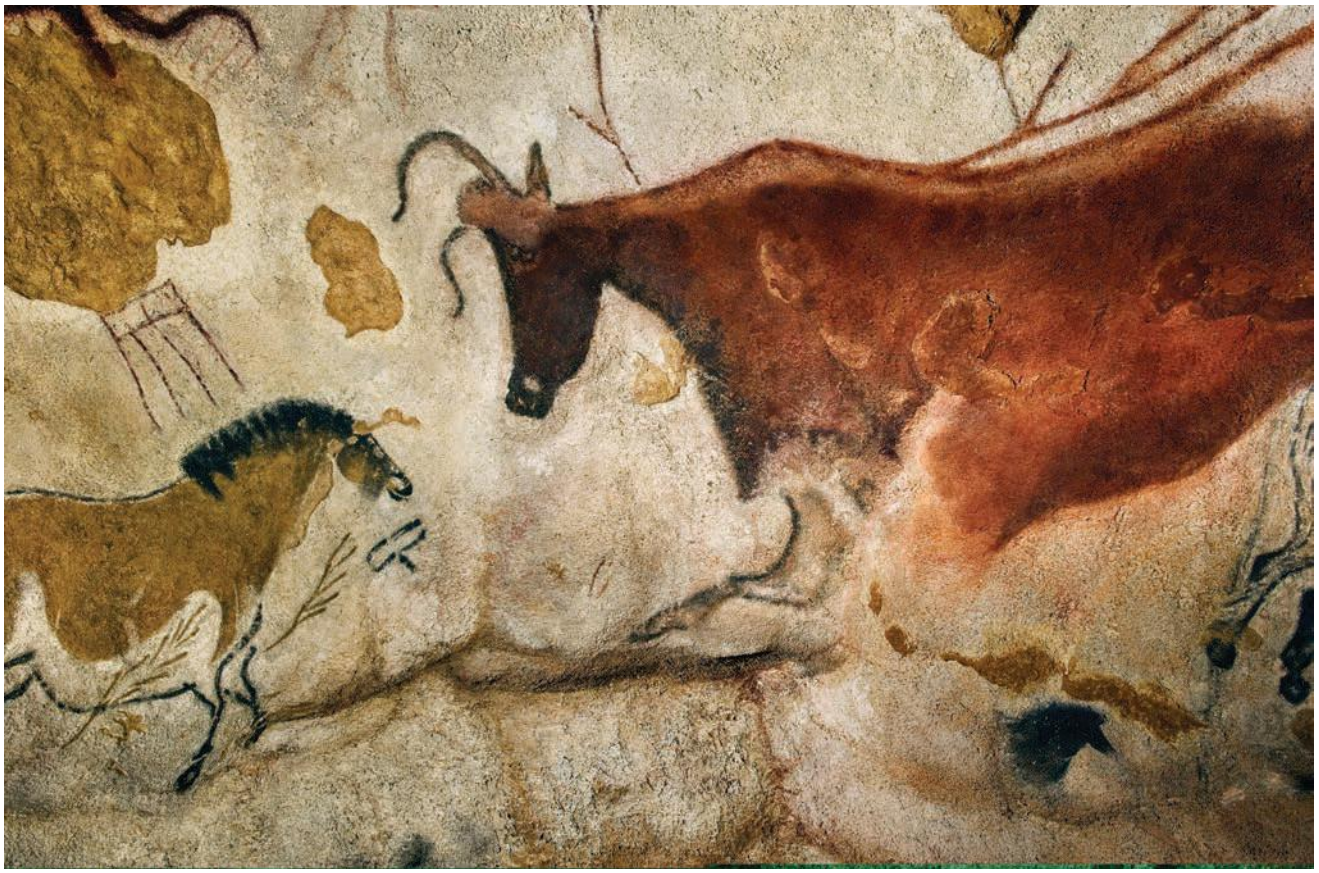
Corbis/Walter Geiersperger

Figure 20.12 Cro-Magnon carving: **a** a Venus statuette carved from sandstone and **b** a horse carved from ivory

Mural art appears to have begun in Aurignacian times, around 40 000 years ago, and it seems very crude compared with that of later Cro-Magnon cultures. These first artworks were simple outline drawings, usually small in size and with very simple contours. Today such art would be referred to as line drawings. Later, artists began to produce drawings of animals with the bodies filled in with colour, usually red or black. Later still, in the Magdalenian period, artwork became more colourful, with shading techniques used to highlight certain features of the animal (see Figure 20.13).

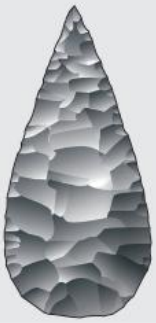


Philippe Psaila/Science Photo Library

Figure 20.13 Drawings representative of Cro-Magnon artwork

Table 20.1 summarises the cultural periods of the hominins, up to and including Cro-Magnon.

Table 20.1 Simplified table showing approximate age ranges and cultural periods of hominins

Common name	Scientific name	Approximate age range (years BP)	Type, location	Cultural period	Example
Australopithecines	*Australopithecus* sp.	2.6–1.7 million	Olduvai, Africa	Oldowan	
Homo erectus	*Homo erectus*	1.7 million–200 000	St Acheul, France	Acheulian	
Neanderthal	*Homo neanderthalensis*	200 000–40 000	Le Moustier, France	Mousterian – manufacture of flake tools	
Cro-Magnon	*Homo sapiens*	43 000–26 000	Aurignac, France	Aurignacian – manufacture of blade tools	
Cro-Magnon	*Homo sapiens*	22 000–19 000	Solutré, France	Solutrean – pressure flaking to retouch blades	
Cro-Magnon	*Homo sapiens*	18 000–12 000	La Madeleine, France	Magdalenian – predominance of bone and antler tools, and artwork	

Note: Tool cultures frequently persisted longer than shown; for example, a simple pebble tool would have been used by modern humans if this was all that was needed for a task. Age ranges are approximations, as different ages are associated with different sites.

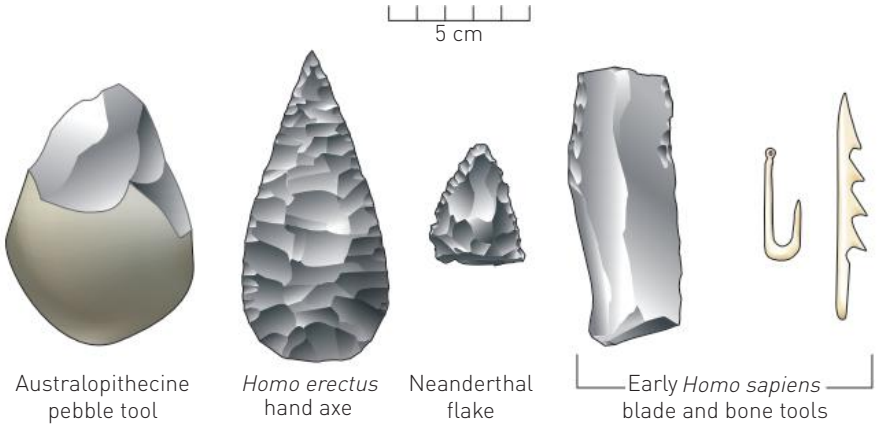


Figure 20.14 An example of cultural evolution – increasing sophistication of simple tools from australopithecines to early *Homo sapiens*

Cro-Magnon culture
This website provides more information on Cro-Magnon tool making and art.

Cro-Magnon art
This website provides photos and information about the painting, drawing and other art of Cro-Magnon people.

The Denisovans

In 2008, Russian scientists excavating in Denisova Cave in Siberia found part of a bone from the little finger of a hominin. Artifacts found at the same level in the excavation were carbon dated to about 40 000 years ago, so it is believed that the bone fragment is about the same age. This does not sound like a very exciting discovery, but when it was announced in March 2010 that mitochondrial DNA recovered from the finger bone was neither Neanderthal nor modern human, it became a very significant find indeed. Members of what is now considered a distinct group of hominins have become known as **Denisovans**, after the cave in which the first fossil was found.

The mtDNA of Neanderthals differs from modern humans by an average of 202 bases. The Denisovan fossil differed from modern humans by about 385 bases, which enabled scientists to calculate that the most recent common ancestor of Neanderthals, Denisovans and modern humans lived about 1 million years ago. This is a good example of how mitochondrial DNA can be used to determine relationships between hominins (see pages 219–20).

In December 2010 a report was published with details of the nuclear DNA of Denisovans. The genes recovered from cell nuclei showed that the Denisova hominin was more closely related to Neanderthals than to modern humans. However, the Denisovan genes do not fall within the range of variation for Neanderthals, confirming that Denisovans are a distinct group. Equally interesting was the report that Denisovan genes make up nearly 5% of the genome of living Melanesians. Denisovans must have bred with the ancestors of modern Melanesians. This is unlikely to have occurred at Denisova, so the Denisovans may have lived over a considerable area of eastern Asia. Australian Aboriginal people have also been shown to have some Denisovan ancestry.

A second bone and a molar tooth (Figure 20.15) have been recovered from Denisova Cave. The tooth gives us our only clue to the anatomy of the Denisovan people. It is larger than similar teeth from Neanderthals and early modern humans, suggesting that the Denisovans were an anatomically distinct group as well as being genetically distinct.

More fossils of Denisovans are needed to determine exactly how, genetically and anatomically, this group relates to other early humans. It is possible that fossils of Denisovans have already been found

with permission of the MPI for Evolutionary Anthropology

with permission of the MPI for Evolutionary Anthropology

Figure 20.15 The Denisovan molar tooth

but not recognised as such. Some fossil skulls found in China have characteristics that are neither Neanderthal nor modern human and could therefore be Denisovan. Only DNA analysis will provide the answer; however, DNA degrades with age, particularly in hot and humid conditions. It was only possible to obtain DNA from the fossil found in Denisova Cave because of the very cold conditions in Siberia.

The Denisovan story so far is an interesting reversal of the usual order of discoveries. Usually fossils and artifacts are found and a picture of a group's anatomy and behaviour can be built up before genetic relationships are explored. In this case, we have genetic information but anatomical evidence is very scarce and there is no evidence relating to behaviour. Although we have no evidence of their culture, the Denisovans are an important group and should be included in any discussion of human ancestors. As investigations continue it is very likely that evidence of their lifestyle will emerge.

Denisovans
This website allows you to meet the Denisovans.

The Red Deer Cave people

In 1979, scientists working in China unearthed a very distinctive skull in a cave in Guangxi Province, but it has only recently been fully analysed. It had thick bones, prominent brow ridges and a short flat face, but lacked a human-like chin. The scientists who discovered the skull described it as anatomically unique among all members of the human evolutionary tree. It had an unusual combination of features, some of which resembled those seen in hominin ancestors hundreds of thousands of years ago, with others that appeared modern, similar to living people.

More evidence of this new hominin has been found at another cave in a neighbouring Chinese province. At that site, scientists uncovered evidence that these people cooked large deer, which led to the name Red Deer Cave people. However, exactly where these people fit in hominin evolution is unclear. Australian scientist Darren Curnoe and his colleagues, who discovered the fossils, believe they could be related to some of the earliest members of our species, *Homo sapiens*. They suggest that, as they look so very different to African members of

The Red Deer people
This website provides more information on the discovery of these people.

Photo courtesy of Darren Curnoe

Figure 20.16 The reconstructed skull of one of the Red Deer Cave people

our species, they represent a new evolutionary line that evolved in East Asia in parallel with *Homo sapiens*, just as the Neanderthals did.

Other scientists have suggested different interpretations. One such suggestion is that the primitive features of these people might indicate that they are related to the Denisovans. The Denisovans were also living in East Asia and DNA analysis suggests that they did mate with our direct ancestors. One hypothesis is that the Red Deer Cave people could be the product of that mating.

It appears that the Red Deer Cave people survived until relatively recently. Some of the fossils found are 11 500 years old, but so far it has not been possible to extract material suitable for DNA testing. If this does occur, and a DNA analysis is accomplished, it may help to determine whether they mated with any other hominins, are truly a new species, or are off-shoots of the Denisovan people.

The beginnings of agriculture

One of the most crucial steps in human history was the change from a nomadic to a village way of life. This change is often called the **Neolithic Revolution**, and is characterised by the domestication of plants and animals and the construction of villages. Present evidence suggests that this first took place in South-West Asia, the earliest known settled communities being those of the **Natufians** of Palestine. Around 12 500 years ago, these people gathered wild grasses, including wild forms of wheat (Figure 20.17), either by hand or using a sickle made from flint blades set into a horn handle (see Figure 20.18).

During this period, wild grasses probably hybridised a number of times. Two of the hybrids were very important for agriculture. The first was the crossing of wild goat grass with wild wheat to produce the fertile hybrid, **emmer**. This strain of wheat was larger than the wild types, but it was still able to spread naturally by scattering in the wind. The second hybrid was the result of a cross between emmer and another wild goat grass. It was larger still and did not break up in the wind. The large grains could be ground into flour and used with water to make a kind of damper. Much later, with the discovery of yeasts, this wheat was found to be ideal for making bread.

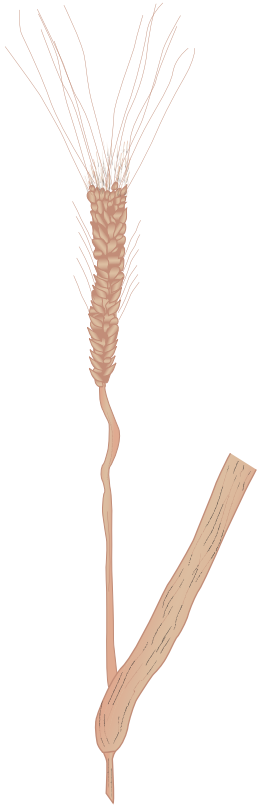


Figure 20.17 Wild wheat

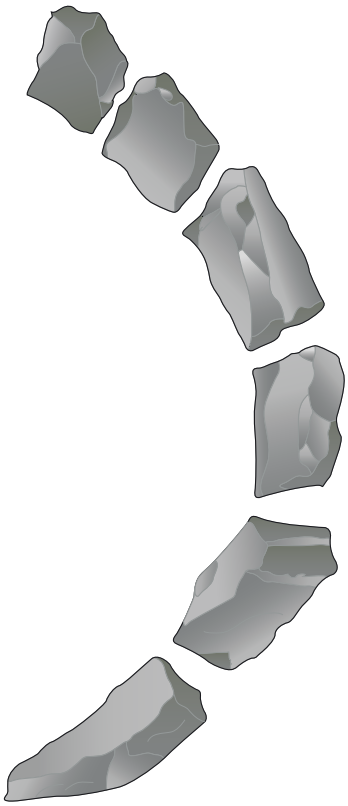


Figure 20.18 Pieces of flint used as blades for a sickle to harvest wheat

The domestication of crops occurred more than once and at different sites around the world. A second centre was in China, where rice, millet, soybeans and yams were domesticated. In Central America, where no natural forms of wheat grew, maize (corn) became the cultivated crop. A variety of corn occurred there naturally and, around 7000 years ago, was gradually domesticated. In addition, both the white and the sweet potato were cultivated, as were a number of varieties of bean, peanut, pumpkin, tomato and many other plants. This large number of plant varieties contrasts with the comparatively few domesticated in the Old World (Europe and Asia) – humans relied mainly on wheat and barley for carbohydrate, and peas and lentils for protein. On the other hand, the Old World countries domesticated a large number of animals, whereas the New World countries (the Americas) had comparatively few species suitable for domestication. The first animals to have been domesticated were sheep, in South-West Asia, about 11 000 years ago. Domestication of pigs, goats, cattle and other animals followed over the next two to three thousand years.

Early agricultural settlements were located in South-West Asia and around the eastern shores of the Mediterranean, a region often referred to as the 'fertile crescent' (see Figure 20.19). Farming was supplemented in these regions by fishing and hunting, and animals attracted by the crops were more than likely slaughtered for food. Surplus food could now be stored, as much of it was in the form of grain, which could be kept for much longer than meat. More people could be supported on an area of land than had been possible when they lived by hunting and gathering, and villages developed as small self-sufficient communities. With more food the birth-rate increased and villages gradually became larger. Settled life allowed the development of new tools and techniques: pottery, weaving and metallurgy all appeared around the time of the first villages.

Figure 20.19 The region of early settlement around the Persian Gulf and eastern Mediterranean, often referred to as the 'fertile crescent'

EXTENSION

Around 12 000 years ago a turning point was reached in the cultural evolution of humans – a transition was made from a nomadic hunting and gathering economy to one of farming. The transition must have taken hundreds, perhaps thousands, of years and it occurred at different times in different parts of the world. In some parts of the world these changes occurred much later. In others, such as Australia, farming never developed, perhaps because of the absence of naturally occurring grasses and animals suitable for domestication.

Use a range of research methods to find out when the transition to an agricultural way of life occurred on each of the continents.

Modern humans

Unlike the australopithecines and early *Homo*, who were restricted to living in favourable environments, modern humans are able to live comfortably anywhere on Earth. Technology has allowed us to modify the environment to suit ourselves, to travel easily from one place to another, to extend our life expectancy and so on. Our society is complex, with relatively few members involved in food production, while most are occupied in other pursuits.

With the reduced influence of selective agents such as environment and disease, natural selection will be of lesser importance in the future evolution of humans. It is likely that any future evolution of *Homo sapiens* will be driven by changes in culture and technology.

Human evolution
This website provides a comprehensive description of human evolution, narrated by noted anthropologist Donald Johanson. Click on 'Launch the documentary'.

Why study human origins?

> O Lord, what are human beings that you regard them?
>
> Or mortals, that you think of them?
>
> (Psalm 144)

The writer of this psalm from the Old Testament of the Bible, around 3000 years ago, was pondering the question 'What is a human?' This question still intrigues us today. Humans have the greatest curiosity of all animals and it is our curiosity that leads us to constantly search for answers to the question. Finding out how we came to be helps us to define what it is to be human.

For many people, curiosity and our thirst for knowledge are reasons enough for studying where we came from. For others it is an attempt to shed light on the present situation of the human species. The past influences the present and the future, and so an understanding of the forces and pathway that led to the evolution of *Homo sapiens* can help in our understanding of modern humans.

For more than 99% of the time that humans have lived on Earth they have led a nomadic existence as hunters and gatherers. It is only in relatively recent times that members of our species have lived in villages, towns and cities – in environments created by them. Because of this change we are not biologically suited to the way of life that we now lead. This has far-reaching implications in areas such as behaviour, health, diet and our relationships with one another. By studying our origins we can better understand some of the problems we have in adjusting to this relatively new way of life. Many problems faced by societies today, like poor physical fitness, being overweight, cardiovascular disease, mental illness, misuse of chemical substances and aggression, have their roots in our past.

Humans are continuing to evolve both biologically and culturally. We have no control over biological evolution. Nature selects the characteristics that are most suited to survival, and it is those characteristics that are passed on to future generations. For example, studies have shown that in populations exposed to malaria, resistance to malaria is slowly increasing. Cultural evolution is different because we can direct cultural evolution to solve problems. For example, people in many countries are now working towards a solution to the problem of climate change. Having a thorough appreciation of the past history of our species will help us to face, and solve, the problems of the future.

Cultural evolution of hominins

Science inquiry

ACTIVITY 20.1 Are humans unique?

Modern humans like to think of themselves as unique. We consider ourselves to be different from (and perhaps superior to) all other species of animals. But are we unique? What separates us from other animals, especially the other primates?

With a partner, try to draw up a list of features that are unique to humans. Consider all aspects of humanity in your discussion – physical characteristics, behaviour, human achievements and others. Do some of the features selected follow an evolutionary trend? Are these features likely to evolve further in the future?

Have a class discussion of the lists proposed by the various pairs in the class and try to agree on a class list. Be prepared to criticise others, but do so in a constructive way. It is more important to be involved in actively thinking about the topic than in arriving at a correct answer. In fact there may be very few points on which the whole class will agree.

ACTIVITY 20.2 Chimpanzees, Neanderthals and humans

This activity will enable you to use knowledge gained from previous chapters to examine the relationship between chimpanzees, Neanderthals and modern humans. Table 20.2 indicates the number of nucleotide differences between a region of mitochondrial DNA in two chimpanzees, a Neanderthal and two humans (see pages 219–20 for a discussion of mitochondrial DNA).

Table 20.2 Nucleotide differences in a region of mitochondrial DNA

	Human 2	Chimpanzee 1	Chimpanzee 2	Neanderthal
Human 1	15	77	76	20
Human 2		79	80	27
Chimpanzee 1			23	72
Chimpanzee 2				71

WHAT TO DO

Answer the questions below. As you answer the questions, refer to Table 20.2 and to previous chapters where necessary.

1. Based on the information in Table 20.2, which individual is most closely related to the Neanderthal and which is the least?
2. The Neanderthal mitochondrial DNA was extracted from a fossil 25 000 years old. What other information obtained from the fossil would be valuable in determining the evolutionary relationships of the Neanderthal with chimpanzees and humans?
3. What dating methods could be used to determine the absolute age of the Neanderthal fossil?
4. What methods could have been used to determine a relative age for the Neanderthal fossil?

Review questions

1 **a** What was the importance of meat eating to the future survival and evolution of the hominins?
b How did tool manufacture and use contribute to this survival?

2 *Homo erectus* (and the contemporaries of *H. erectus*) appears to be the first hominin to have used fire in a systematic way. List the ways in which fire could have improved their way of life, giving examples where appropriate.

3 Describe the significant cultural advance that occurred with the development of the Mousterian tool-making industry.

4 **a** It is known that the Denisovans were a distinct group of ancestors of modern humans but we do not know anything about their appearance or their culture. Explain why this is so.
b How is the Denisovan story an interesting reversal of the usual order of discoveries?

5 **a** Who were the Red Deer Cave people and where did they live?
b Only a few fossils of these people have been found. Why do experts believe they were a distinctive group of people?

6 Differentiate between the three tool-making traditions of the Cro-Magnons. List their age ranges and the tools that characterised them.

7 Why do scientists believe that the laurel-leaf blade may have been an ornament rather than a spear-point?

8 Cro-Magnon people appear to be among the world's first artists. Describe the two forms of art made by these people, and comment on the possible significance of art to their daily lives.

9 The hunter-gatherer way of life characteristic of the Cro-Magnon people was gradually replaced by an agricultural one.
a List the regions where agriculture is first thought to have developed.
b What factors contributed to the replacement of the hunter-gatherer way of life by an agricultural one?

10 Explain how the characteristics of the hybrid wheat emmer, and subsequent hybrids, enabled the development of agriculture.

11 Give two reasons for studying primate and hominin evolution.

Apply your knowledge

1 Australopithecines may have been the first hominins to manufacture tools for a specific purpose. Describe the significance of this development in food gathering for later hominin evolution.

2 For the past 100 000 years at least, hominins have adapted culturally to environmental change. Refer back to Chapter 14. Does natural selection affect cultural characteristics?

3 There is some speculation among scientists that the large brain of *Homo erectus* would have required offspring to be born at a very early stage to allow the passage of the large head through a relatively narrow birth canal. Discuss the implications that the care of helpless young would have had for the social behaviour of *Homo erectus*.

4 Briefly outline the technological advances in tool making from the early Oldowan industry to that of Magdalenian times.

5 Why would early humans have made portable art? Suggest possible reasons for this type of activity.

6 Useful cereal crops produce seed heads that do not break up in the wind. Outline the disadvantages of cereal crops with seeds that could be wind-dispersed, and the advantages of those with seed heads that stayed intact.

7 If you were living around 11 000 years ago, what characteristics would you have looked for in animals with a view to trying to domesticate them for meat production?

8 An article published in 2008 described how orang-utans could help each other get food by trading tokens. Read the article at the weblink and discuss whether this is an example of cultural evolution.

Orang-utans learn to trade favours

GLOSSARY

absolute date The actual age (in years) of a fossil or artefact

accelerator mass spectrometry (AMS) radiocarbon dating A technique used to give radiocarbon dates for very small samples of material

acetabulum The socket of the pelvis in which the head of the thigh bone fits

Acheulian tool A type of hand axe that was flaked all around the edges, first in one direction, and then in the other, until it formed a roughly two-faced lump, approximately teardrop in shape; associated with ***Homo erectus***

achromatopsia An inherited form of total colour blindness

acquired reflex A response to a stimulus that has been learned through practice

actinomycetes Bacteria that produce branching filaments from which streptomycin was extracted

action potential When sodium ions move into a nerve cell at a particular place on the membrane; this change is transmitted along the cell membrane as a nerve impulse

active immunity Immunity produced by the body manufacturing antibodies against a foreign antigen

adaptation A particular structure, physiological process or form of behaviour that makes an organism better able to survive and reproduce in a particular environment

adrenal cortex The outer portion of an adrenal gland; secretes the hormones aldosterone and cortisol

adrenal gland One of two endocrine glands, one immediately above each kidney; each consists of an inner adrenal medulla and an outer adrenal cortex

adrenal medulla The inner portion of an adrenal gland; secretes the hormones adrenaline and noradrenaline

adrenaline A hormone secreted from the adrenal medulla that prepares the body for the fight-or-flight responses; also acts as a neurotransmitter by transferring nervous impulses across the junction (synapse) between adjacent nerve cells; also called epinephrine

adrenocorticotropic hormone (ACTH) A hormone that controls the production and release of some of the hormones from the cortex of the adrenal glands

adrenocorticotropin An alternative name for adrenocorticotropic hormone

adult-onset diabetes A common form of diabetes that usually occurs in people over the age of 40 who are overweight; it can usually be controlled by diet; also known as type 2 diabetes

afferent division Part of the peripheral nervous system containing nerve fibres that carry impulses into the brain and spinal cord; also called sensory division

agglutination The clumping together of micro-organisms or blood cells

alarm reaction See **fight-or-flight response**

albinism An inherited condition marked by an inability to produce pigment in hair, skin and eyes

aldosterone A hormone that acts on the kidney to reduce the amount of sodium in the urine and increase the amount of potassium

alimentary canal The tube through which food passes; made up of mouth, oesophagus, stomach, intestines

allele An alternative form of a gene; an individual normally has only two alleles of each gene

allele frequencies How often each allele of a gene occurs in a population

all-or-none response A response of a constant size regardless of the strength of the stimulus; with respect to nerve cells, a nerve impulse is transmitted at full strength or not at all

alpha cell A type of cell in the islets of Langerhans in the pancreas that secretes the hormone glucagon

anaemia A condition in which there is a reduced amount of haemoglobin in the blood, or a reduced number of red blood cells

androgen Any of the male sex hormones produced by the testes; responsible for the development and maintenance of the male sex characteristics

aneuploidy A change in the chromosome number as a result of non-disjunction

annotation Identification of genes in a DNA sequence

antibiotic A chemical able to inhibit the growth of, or kill, micro-organisms, particularly bacteria

antibody A substance produced in response to a specific antigen; combines with the antigen to neutralise or destroy it

antibody-mediated immunity See **humoral response**

antidiuretic hormone (ADH) A hormone produced by the hypothalamus and released by the posterior lobe of the pituitary gland that stimulates the kidneys to remove water from urine, thus reducing urine production; also known as vasopressin

antigen Any substance capable of causing formation of antibodies when introduced into the tissues

antigen–antibody complex A compound formed when an antibody combines with an antigen

antiviral drug A drug used for the treatment of viral infections

aortic body The group of cells within the walls of the aortic arch that are sensitive to changes in the concentrations of oxygen and carbon dioxide in the blood and its pH

arboreal Living in trees; for example, as some monkeys do

arithmetic mean Often called the mean; the total measurements in a group divided by the total number of measurements

artefact (artifact) An object made or modified by humans

artificial immunity Immunity produced by giving a person an antigen, which triggers the immune response, or by giving a person antibodies to an infecting antigen

ascending tract Any of the sensory nerve fibres that carry impulses towards the brain

association area A part of the cerebral cortex concerned with intellectual and emotional processes such as memory, reasoning, judgement and personality

association neuron See **interneuron**

atrioventricular node (AV node) A compact mass of modified cardiac muscle cells between the heart's atria and ventricles that relay electrical impulses to the ventricles

attenuated Describes micro-organisms that have been reduced in virulence

Aurignacian tools The tool culture of stone, bone and antler associated with early Cro-Magnon people

australopithecine A general term used to refer to any species in the genus ***Australopithecus***

Australopithecus A genus of fossil ape-like primates found in rock layers dating to 3.6 million years ago

autonomic division The part of the efferent division of the peripheral nervous system that carries nerve impulses from the brain and spinal cord to internal organs; also called the autonomic nervous system (ANS)

autonomic nervous system See **autonomic division**

average The total measurements in a group divided by the total number of measurements

axon An extension of the body of a nerve cell; carries nerve impulses away from the cell body

bactericidal antibiotic A drug used to treat bacterial infections by killing the bacteria

bacteriophage A virus that infects bacteria

bacteriostatic antibiotic A drug used to treat bacterial infections; it does not kill the bacteria but stops them reproducing

basal ganglia The masses of grey matter inside each cerebral hemisphere

B-cell A type of lymphocyte that develops either into a plasma cell that produces antibodies or into a memory cell

beta cell A type of cell in the islets of the pancreas that secretes the hormone insulin

binomial system The system of naming organisms using the generic (genus) and specific (species) names to describe a species

bioinformatics The use of computers to describe the molecular components of living things

biotechnology The use of biological processes to produce useful products

bipedal locomotion Walking upright on two legs

bipolar neuron A neuron with two processes – one axon and one dendrite – arising from opposite sides of the cell body; these neurons are sensory, such as the neurons found in the retina of the eye

blood pressure The pressure of the blood on the walls of the blood vessels, especially the arteries

blunt end The end produced by a straight cut of a sequence of nucleotide bases

broad-spectrum antibiotic An antibiotic that affects many types of bacteria

brow ridge A ridge of bone above the eye sockets of the skull

carbon-14 The radioactive isotope of carbon

cardiac centre The part of the brain that regulates heartbeat; located in the medulla oblongata

cardiac output The volume of blood leaving one ventricle of the heart every minute

cardiovascular regulating centre See **cardiac centre**

carotid body The group of cells within the walls of the carotid arteries that are sensitive to changes in the concentrations of oxygen and carbon dioxide and the pH of the blood

carrying angle The arrangement of the thigh bones to form an angle to the vertical

case study An in-depth investigation of one particular person or situation

cell body The part of a neuron that contains the nucleus

cell-mediated response The part of the immune response in which T-cells attach to antigens to destroy them; also called cellular immunity

cell replacement therapy The replacement of damaged cells with healthy ones

central canal A hollow that runs through the centre of the spinal cord; filled with cerebrospinal fluid; also the central channel in an osteon of compact bone; may be called the Haversian canal

central nervous system (CNS) The part of the nervous system that consists of the brain and spinal cord

central thermoreceptor A thermoreceptor located in the hypothalamus

cephalosporin A type of antibiotic

cerebellum The part of the brain behind and below the cerebrum; concerned with coordination of movement

cerebral cortex The outer layer (grey matter) of the cerebrum

cerebral hemisphere One of the two halves of the cerebrum

cerebrospinal fluid (CSF) Fluid produced in the cavities of the brain; fills the brain cavities and surrounds the brain and spinal cord

cerebrum The largest part of the brain; made up of left and right hemispheres

cerumen Ear wax, secreted by special glands near the opening of the ear canal

chemoreceptor A receptor sensitive to particular chemicals

chromosomal mutation A change to the structure and/or number of chromosomes in an organism

chromosome A rod-like structure seen in the nucleus of a dividing cell; carries hereditary information; human body cells have 23 pairs of chromosomes

cilia Hair-like projections from a cell; they beat rhythmically to move material across a tissue surface; singular: cilium

clone A group of cells with the same genetic characteristics

cold receptor A receptor that is stimulated by low temperature

communicable disease A disease passed from one person to another by infection with micro-organisms; also called an infectious or transmissible disease

comparative genomics Comparison of genome sequences of different species

cone A receptor in the retina of the eye that is sensitive to bright light and to colour; also see **rod**

connector neuron See **interneuron**

contagious disease A disease passed on by direct contact

controlled experiment An experiment in which there are two almost identical set-ups; the only difference between them is the one variable being tested

controlled variable A factor kept the same for both the control and the experimental groups in an experiment

convolution A fold of the cerebral cortex of the brain; also called gyrus

corpus callosum A bundle of nerve fibres that links the two cerebral hemispheres

corticosteroid Any of a group of more than 20 hormones secreted by the adrenal cortex; the two main hormones are aldosterone and cortisol

cortisol A hormone that, along with related hormones, promotes normal metabolism

cranial capacity The volume of that part of the skull that is occupied by the brain

cranial nerve One of the 12 pairs of nerves that arise from the brain

cranium The part of the skull that contains the brain

cretinism A condition resulting from under-secretion of thyroxine in the mother during pregnancy

cri-du-chat syndrome A rare genetic disorder caused by a missing part of chromosome 5

Cro-Magnon people The first anatomically modern people found in Europe

crossing over The interchange of the parts of the chromatids of a homologous pair of chromosomes during the first stage of meiosis

cultural evolution Cultural development that occurs as a means of overcoming environmental and other challenges

culture Anything that is learned

cystic fibrosis (CF) A disorder controlled by a recessive allele carried on an autosome that is incurable but can be detected during foetal development; mucus-secreting glands, particularly in the lungs and pancreas, become fibrous and produce abnormally thick mucus, resulting in, among other things, chest infections

cytochrome C An iron-containing protein that can alternate between a reduced form and an oxidised form; important in the electron transport system in cellular respiration

cytoplasm The part of a cell between the outer membrane and the nucleus

cytosol The liquid part of the cytoplasm of a cell

dating Determining the age of excavated artefacts or fossils

deficiency disease A disease resulting from a dietary deficiency of a specific nutrient, especially a vitamin or mineral

dehydration Excessive loss of water and accompanying salts from the body; results when the body loses more fluid than it takes in

dendrite An extension of the body of a nerve cell; carries nerve impulses into the cell body

dendrochronology A method of determining the age of wood by counting the annual growth rings in the timber; also called tree-ring dating

dendrogram See **phylogenetic tree**

Denisovans A group of hominins that probably lived in east Asia around 40 000 years ago; DNA analysis of a finger bone showed them to be different from both Neanderthals and modern humans

dental arcade The shape of the pattern made by the teeth as they are set in the jaw

dental formula A formula that gives the number of each type of tooth in one-quarter of the jaw

dependent variable In an experiment, the factor that changes in response to changes made to the independent variable; also called the responding variable

depolarised Describes the membrane of a nerve cell when there is no difference in electrical charge between the inside and outside of the membrane

descending tract Any of the motor nerve fibres that carry impulses away from the brain

diabetes See **diabetes mellitus**

diabetes mellitus A group of diseases, all of which result in an abnormally high level of glucose in the blood and excretion of glucose in the urine; common name is diabetes

diastema A gap in a row of teeth; usually refers to a gap next to the canine teeth in primates with canine teeth that are much longer than the other teeth

disease Any condition in which normal functioning of the body is impaired

DNA fingerprint A technique that uses the banding patterns of DNA fragments as a means of identification; a DNA fingerprint is unique to a particular individual; also called DNA profile

DNA ligase An enzyme capable of combining two small components of single-strand DNA into one single structure

DNA profile See **DNA fingerprint**

DNA sequencing The determination of the precise order of nucleotides in a sample of DNA

dorsal root One of the two roots that link a spinal nerve to the spinal cord; located towards the back of the body and contains axons of sensory neurons

dorsal root ganglion A group of nerve cell bodies located in the dorsal root of a spinal nerve

Down syndrome See **trisomy 21**

Duchenne muscular dystrophy A genetic disease resulting in wasting of leg muscles and then arms, shoulders and chest

dynamic equilibrium A state reached when the rates of forward and reverse changes are equal; a stable, balanced or unchanging system results; frequently referred to as a steady state

effector A muscle or gland that carries out a response to a stimulus

effector neuron See **motor neuron**

efferent division Part of the peripheral nervous system containing nerve fibres that carry impulses out of the brain and spinal cord; also called motor division

electrochemical change The change in electrical voltage brought about by changes in the concentration of ions inside and outside the cell membrane of a neuron

electroencephalogram (EEG) A record of the electrical activity in the brain

electrophoresis A process in which charged molecules in solution are made to migrate and separate by passing an electric current through the solution

embryology The study of the early development of an organism; in humans, from fertilisation to the end of the eighth week of pregnancy

emmer A fertile hybrid of wild goat grass and wild wheat

emphysema A lung disease in which the walls of the alveoli break down, resulting in abnormally large air spaces

endocast An impression of the inside of the brain case, made of rock or some other solid material

endocrine gland A gland that secretes hormones directly into adjacent tissue; also called a ductless gland

endocrine system The body system involved in chemical communication between cells; made up of endocrine glands

endogenous retrovirus (ERV) A retrovirus that has become part of an organism's genome and exists in every cell of the body

enzyme An organic substance (usually a protein) that increases the speed of chemical changes without being altered or destroyed in the change; an organic catalyst

enzyme amplification A series of chemical reactions in which the product of one step is an enzyme that produces an even greater number of product molecules at the next step

epinephrine See **adrenaline**

erythropoietin (EPO) A hormone that stimulates production of red blood cells by the bone marrow

ethical behaviour Behaviour that follows a set of moral principles or values

ethics A set of moral principles or values

evolution The gradual change in the characteristics of a species

excretion Removal of the wastes of metabolism from the body

exocrine gland A gland that secretes into a duct that carries the secretion to the surface of the body cavities

extracellular fluid Fluid outside the body cells; includes tissue fluid and blood plasma

fair test See **controlled experiment**

feedback system A situation where the response to a stimulus changes the original stimulus

femur The thigh bone

fever An elevation of body temperature above the normal level of 37°C

fight-or-flight response A response preparing the body for increased activity; brought about by stimulation of the sympathetic division of the autonomic nervous system

fissure A deep downfold in the cerebral cortex of the brain

fluorine dating A method of determining the relative age of a fossil or artefact by measuring the amount of fluoride absorbed from the soil

follicle-stimulating hormone (FSH) A hormone that stimulates the development of a follicle in the ovary

foramen magnum The opening beneath the cranium through which the spinal cord passes

fossil Evidence of, or remains of, an organism that lived long ago

founder effect A type of genetic drift that occurs when a new population is formed by a small number of individuals; the small size of the sample can cause marked deviations in allele frequencies from the original population

frequency The number of times an event occurs

frequency distribution See **frequency table**

frequency table A summary of the data showing how often the variable in question occurs

friction ridge One of the many small ridges on the skin of the hands and feet of some primates; fingerprints

frontal lobe One of the four lobes of each cerebral hemisphere

ganglia Groups of nerve cell bodies outside the brain or spinal cord; singular: ganglion

gene The factor that determines a hereditary characteristic; part of a chromosome

gene flow The transfer of alleles from one population to another through migration

gene mutation An alteration to a single gene

gene pool The sum of all the alleles carried by the members of a population

gene therapy The treatment of disease by replacing, manipulating or supplementing non-functional genes in cells and tissues

genetic disease A state of ill health resulting from an individual's genes; usually refers to diseases that are inherited, but non-inherited forms result from mutation; also called hereditary disease or an inherited disorder

genetic engineering See **recombinant DNA technology**

geneticist A scientist who specialises in the study of genetics

genetics The study of inheritance

genome The complete set of genetic material in a cell; an organism's complete set of DNA

geographical barrier A feature of the landscape that prevents populations from interbreeding; includes oceans, mountain ranges, large lake systems, deserts and expansive ice sheets

germinal mutation See **germline mutation**

germline mutation A change in the hereditary material in the egg or sperm that becomes incorporated into the DNA of every cell in the body of the offspring

gestation The period of development of an organism in the uterus; the time between conception and birth

glucagon A hormone secreted by the pancreas that increases blood sugar level

gluconeogenesis The process of producing glucose molecules from fats and amino acids

glycogen A polysaccharide made up of thousands of glucose molecules bonded together in branching chains; functions as a store of glucose molecules in muscle and liver cells

glycogenesis The process whereby glucose molecules are chemically combined in long chains to form glycogen molecules

glycogenolysis The process of converting glycogen back to glucose

goitre A swelling of the neck caused by an enlargement of the thyroid gland

gonadotropins The hormones that affect the sex organs

gonads The testes and the ovaries

gracile Slender in form; used to refer to the body build of some human ancestors

graph A pictorial way of presenting numerical data; shows how changes in one variable affect another variable

Graves' disease A medical condition in which overactivity of the thyroid gland results in the secretion of excess amounts of the thyroid hormones

grey matter The part of the brain and spinal cord made up of nerve cell bodies and unmyelinated fibres

growth hormone (GH) A hormone that stimulates body cells to grow and multiply, especially the skeleton and skeletal muscles

gyrus An alternative name for a convolution of the cerebrum; plural: gyri

haemophilia A An inherited disorder in which a blood-clotting protein known as factor VIII is missing or in poor supply; also known as classic haemophilia

half-life The time required for half of any quantity of radioactive material to decay into stable non-radioactive material

heart rate The number of times the heart beats per minute

heat exhaustion The collapse of a person after exposure to heat, during which their body's heat-regulating mechanisms continue to function normally

heat receptor A receptor that is stimulated by high temperature

heat stroke The failure of a person's temperature-regulating mechanisms when exposed to excessive heat

helper T-cell A type of T-cell that, among other things, enhances antibody production by B-cells

heparin A substance that helps to prevent blood clotting

herd immunity A type of 'group' immunity that occurs when such a high proportion of people in a population are immunised that those who are not immune are protected

hereditary disease See **genetic disease**

histamine A substance released in response to injury to cells; it results in an increase in blood flow

home base A camp site to which prehistoric hunters brought back food for sharing with other members of their group

homeostasis The maintenance of a relatively constant internal environment despite fluctuations in the external environment

Homo The genus of hominin to which humans belong

Homo erectus A species of the genus ***Homo*** that lived between 300 000 and 1.8 million years ago

Homo habilis A species of the genus *Homo* that lived about 1.9 million years ago; believed to have lived alongside robust australopithecines

Homo neanderthalensis A regional population of hominins that existed in Europe during the last of the ice ages; recent evidence suggests that the Neanderthals may date back as far as 230 000 years ago

homologous organs Organs with similar structure but not necessarily similar function

hormone A chemical that is secreted by an endocrine gland and that affects the functioning of a cell or organ; often carried in the blood

human growth hormone (hGH) A hormone produced in the pituitary gland, responsible for normal growth and metabolism

humoral response A response triggered by foreign substances or micro-organisms entering the body

hyperglycaemia An abnormally high level of sugar in the blood; frequently found in people with diabetes mellitus

hypertension Abnormally high blood pressure

hyperthyroidism Overactivity of the thyroid gland resulting in abnormally high levels of thyroid hormones in the blood; see also **hypothyroidism**

hyperventilation Extremely rapid or deep breathing; may result in dizziness and even fainting due to the loss of carbon dioxide from the blood

hypophysis An alternative name for the pituitary gland

hypothalamus The part of the brain lying just below the thalamus; controls many homeostatic mechanisms, such as body temperature, water balance and heart rate

hypothermia Abnormally low body temperature; the temperature drops below the level required to maintain normal body functions

hypothyroidism Underactivity of the thyroid gland resulting in low levels of thyroid hormones in the blood; see also **hyperthyroidism**

immune response A response triggered by foreign substances or micro-organisms entering the body

immune system Different types of cells that occur in most organs of the body and that protect against foreign organisms, alien chemicals and abnormal cells

immunisation Programming the immune system so that the body can respond rapidly to infecting micro-organisms

immunity Resistance to infection from invading micro-organisms

immunoglobulin A particular group of proteins; antibodies are immunoglobulins

independent variable In an experiment, the factor being investigated; the factor deliberately changed to determine its effect; also called the experimental variable or the manipulated variable

index fossils Fossils or organisms that were on Earth for only a short period of time and are therefore useful in the relative dating of rock strata

infectious disease See **communicable disease**

inflammation The response to damage to a tissue; involves swelling, heat, pain and redness in the affected area

infundibulum The stalk-like structure that joins the pituitary gland to the hypothalamus

inhibiting factor A hormone that slows the release of another hormone

insula A part of the cerebrum that is buried deep inside the brain and considered a fifth lobe of each cerebral hemisphere

insulin A hormone, secreted by the pancreas, that decreases blood sugar level

insulin-dependent diabetes A form of diabetes that develops rapidly, usually before the age of 20; caused by a decline in insulin-producing cells of the pancreas; treated by injections of insulin at regular intervals; also known as type 1 diabetes

intercellular fluid Fluid between the body cells; also called interstitial fluid or tissue fluid

interneuron A nerve cell in the brain or spinal cord that carries messages between other nerve cells; also called association neuron or connector neuron

interstitial fluid See **intercellular fluid**

intracellular fluid The fluid found inside cells

islets of Langerhans Clusters of endocrine cells in the pancreas; secrete the hormones insulin and glucagon

isotope A form of an element with a particular number of neutrons in the nucleus of the atoms; the same element can have forms known as isotopes with different numbers of neutrons in the nucleus

kidney One of a pair of excretory organs responsible for maintaining a constant concentration of substances in the body fluids

killer T-cell A type of T-lymphocyte able to kill cells that are damaged or infected with viruses or bacteria; also called cytotoxic T-cell

Klinefelter's syndrome A genetic disorder resulting from inheritance of two X chromosomes and one Y chromosome

lactogenic hormone An alternative name for prolactin

lethal recessives Recessive alleles that, inherited in the homozygous condition, result in the death of the embryo, foetus or child

leucocyte A white blood cell; also spelt leukocyte

ligation The process of joining short strands of DNA during replication

literature review A survey of the material that has been written about a subject under consideration

longitudinal arch The arch of the bones of the foot, running from front to back

longitudinal fissure The longest fissure in the human brain; almost separates the cerebrum into two halves

longitudinal study A study conducted over a long period of time; may be carried out over years or even decades

lumbar Describes the lower region of the spinal column; lumbar vertebrae support the lower back

lung One of a pair of organs for gas exchange occupying the chest cavity

luteinising hormone (LH) A hormone that promotes final maturation of the ovarian follicle and the formation of the corpus luteum

lymphatic system A system of vessels that drain excess fluid from the tissues; also called the lymph system

lymphocyte A type of white blood cell; found in the lymph nodes and associated with the immune system

lymphoid tissue Tissue containing many lymphocytes and macrophages; found mostly in the lymph nodes but also in the bone marrow, tonsils, spleen and thymus

lysozyme An enzyme that kills bacteria; found in tears, saliva and perspiration

macrophage A phagocytic cell derived from a monocyte (a type of white blood cell)

Magdalenian culture A prehistoric culture known for a predominance of bone and antler over flint and stone tools, and for the works of art that were produced

mast cell A type of cell found in loose connective tissue; involved in the inflammatory response

mean See **arithmetic mean**

measurement error The difference between a measurement and the true value of what is being measured

median The mid-point of a set of numbers

medulla oblongata The part of the brain that joins the spinal cord

melatonin A hormone secreted by the pineal gland that is involved in regulation of sleep patterns

membrane potential The electrical voltage across the membrane of a cell (usually a nerve cell)

memory cell A type of cell that recognises an antigen to which the body has previously been exposed

meninges The membranes covering the brain and spinal cord

metabolic rate The rate at which energy is released to the body by the breakdown of food

metabolic water Water formed as a product of cellular respiration

metatarsals The bones of the foot between the toes and the ankle

mitochondria Structures in the cytoplasm of a cell in which the aerobic stage of respiration occurs; singular: mitochondrion

mitochondrial DNA (mtDNA) DNA found in the mitochondria of the cells rather than in the nucleus

model A simplified representation of an idea or a process; may be a diagram, flow chart, a simplified description of a complex situation or a physical model such as a model of a cell; examples are the stimulus–response model and the lock and key model for enzyme action

modulator A control centre responsible for processing information received from a receptor and for sending information to the effector

monosomy Where an individual has only one copy of a chromosome instead of two

motor area The part of the cerebral cortex that controls muscular movement

motor division See **efferent division**

motor fibre A fibre that carries impulses away from the central nervous system

motor neuron A nerve cell that carries messages from the brain or spinal cord to effector organs (muscles and glands); also called an effector neuron

Mousterian Describes a tool characterised by the careful preparation of a stone core from which a large number of flakes could be removed; associated with the Neanderthal people

multiple drug resistance Resistance of some strains of bacteria to most of the available antibiotics

multipolar neuron A nerve cell with one axon and many dendrites; the most common type of neuron

mural art Artwork on a permanent surface, such as the wall or roof of a cave

muscle tone The partial contraction of skeletal muscles

muscular dystrophy See **Duchenne muscular dystrophy**

mutagen See **mutagenic agent**

mutagenic agent An environmental agent that increases the rate of mutation

mutant An organism with a characteristic resulting from a mutation

mutation A change in a gene or chromosome leading to new characteristics in an organism

myelin White, fatty material that surrounds some nerve fibres

myelin sheath A white, fatty sheath that surrounds some nerve fibres

myelinated fibre A nerve fibre that has a myelin sheath

narrow-spectrum antibiotic An antibiotic that affects only a particular type of bacteria

Natufians The people of South-West Asia who formed the first known settled communities between 12 500 and 10 800 years ago

natural immunity Immunity that occurs without any human intervention

natural selection The process by which a species becomes better adapted to its environment; those individuals with favourable characteristics have a survival advantage and so pass those characteristics on to subsequent generations

negative feedback Feedback that reduces the effect of, or eliminates, the original stimulus

negative feedback system A situation in which feedback brings about a change opposite to, or reduces the effect of, the original stimulus

Neolithic Revolution The change from the nomadic to the village way of life; characterised by the domestication of plants and animals, and construction of permanent dwellings

nephron The functional unit of the kidney

nerve A bundle of nerve fibres

nerve fibre A projection from a nerve cell body with its associated coverings; usually refers to an axon

nerve impulse The electrochemical change that travels along the membrane of a nerve cell; the message carried by a nerve; see also **action potential**

nervous system The body system involved with control and coordination of the body

neurilemma A sheath surrounding a nerve fibre

neuromuscular junction The junction between branches of a motor nerve cell and a muscle fibre; also called the motor end plate

neuron A nerve cell; the basic structural and functional unit of the nervous system

neurotransmitter A molecule that carries a nerve impulse across the small gap between branches of adjacent nerve cells

nictitating membrane A transparent fold of skin (third eyelid) that protects the eyes of birds and reptiles; in humans it occurs as a vestigial organ in the corner of the eye

node of Ranvier A gap in the myelin sheath of a nerve fibre

non-disjunction When one or more chromosomes fails to separate during meiosis

non-self antigen Any compound foreign to the body that triggers an immune response

non-specific defences Defences of the body that act against all pathogens

noradrenaline A hormone secreted from the adrenal medulla that has effects similar to that of adrenaline; in particular, it increases the rate and force of the heartbeat; also called norepinephrine

norepinephrine See **noradrenaline**

nucleotide The basic structural unit of a nucleic acid, consisting of a simple sugar, a phosphate group and a nitrogen base

occipital lobe One of the four lobes of each cerebral hemisphere

oestrogen A female sex hormone; develops or maintains female reproductive structures and regulates menstrual cycle and pregnancy

Oldowan tool A very simple tool made by removing several flakes from a stone; the stone tool culture of *Homo habilis*

olfaction The sense of smell

opposability The ability to use the thumb to touch the tips of each of the other digits on the hand

orbit The bony cavity of the skull that holds the eyeball; the eye socket

order A category in the classification of organisms; the level of classification between class and family

organic compound A compound made up of large molecules that contain carbon

osmoreceptors Receptors sensitive to osmotic pressure of body fluids

outlier A measurement well beyond the range of the rest of the measurements in a set

oxytocin (OT) The hormone that stimulates contraction of the muscles of the uterus

pain receptor A receptor that is stimulated by damage to tissues

pancreas A gland that lies just below the stomach; both an endocrine and exocrine gland; secretes digestive enzymes from the exocrine cells, and the hormones insulin and glucagon from endocrine cells

pancreatic islets See **islets of Langerhans**

paracrine Any chemical secreted by a cell that diffuses to and affects adjacent cells; also called local hormone

parasympathetic division One of the two divisions of the autonomic nervous system; opposes the function of the sympathetic division; also called parasympathetic nervous system

parasympathetic nervous system See **parasympathetic division**

parathormone See **parathyroid hormone**

parathyroid gland One of four (usually) small glands about the size of a small pea embedded in the rear surface of the thyroid gland; secretes parathyroid hormone (PTH)

parathyroid hormone (PTH) A hormone that controls calcium and phosphate levels in the blood, also known as parathormone

parietal lobe One of the four lobes of each cerebral hemisphere

partial monosomy Where part of a pair of chromosomes is missing

passive immunity Immunity produced by the introduction of antibodies from another person

Patau syndrome A genetic disorder resulting from an extra copy of chromosome 13

pathogen A disease-causing organism; often referred to as a pathogenic organism

pebble tool A stone tool made by chipping flakes off a rounded pebble

pentadactyl Describes a limb with five fingers or toes

peripheral nervous system (PNS) The part of the nervous system that connects the central nervous system with the receptors, muscles and glands

peripheral thermoreceptor Temperature receptor in the skin and in some mucous membranes

pernicious anaemia A condition in which there is an insufficient production of red blood cells as a result of a deficiency of vitamin B_{12} in the diet

phage See **bacteriophage**

phagocytes Cells that are able to engulf micro-organisms and cell debris

phenylketonuria (PKU) An inherited disease resulting in damage to the growing brain and, thus, extreme mental deficiency, a tendency towards epileptic seizures, and failure to produce normal skin pigmentation

phylogenetic tree A diagram showing evolutionary relationships between related organisms; also called a dendrogram

phylum A category of biological classification; one of the principal divisions of a kingdom; consists of one or more classes; plural: phyla

pineal gland A small gland, about the size of a pea in children, found deep inside the brain; in adults it is just a tiny lump of fibrous tissue; the functions of the hormones it secretes have still not been identified

pituitary gland An endocrine gland located below the brain; joined to the hypothalamus by a stalk called the infundibulum

placenta The organ that supplies nutrients to, and removes wastes from, the foetus; also produces a number of hormones including oestrogens and progesterone

plasma cell A cell that develops from a B-cell and produces antibodies

plasmid In a bacterial cell, small circular strands of DNA distinct from the main bacterial genome; composed of only a few genes and able to replicate independently within cells

point mutation A change in just one of the bases in a DNA molecule

polarised Describes the situation when the inside of the membrane of a nerve cell has a negative electrical charge compared with the outside

polymerase chain reaction (PCR) A technique used in molecular biology for producing multiple copies of DNA from a sample; used in DNA fingerprinting and in identifying diseases

population A group of organisms of the same species living together in a particular place at a particular time

portable art Small decorative items that could be carried, such as carved figures

positive feedback Feedback that reinforces the original stimulus

potassium-argon dating A method of calculating the age of a fossil or artefact using the known rate of decay of radioactive potassium

potential difference Difference in electrical charge between two locations

precision grip The grasping of an object between thumb tip and fingertip, as in holding a pencil when writing

prehensile Grasping; refers to the digits of a hand or a foot that can grasp an object

prehensility Ability to grasp objects

pressoreceptors Receptors capable of responding to changes in blood pressure; often referred to as baroreceptors

primary response The response of the immune system to the first exposure to an antigen

primate A member of an order of mammals that includes the lemurs, lorises, tarsiers, monkeys, apes and humans

primer A strand of DNA or RNA that serves as a starting point for DNA replication

probability The likelihood that a particular event will occur

progesterone A female sex hormone produced by the ovaries; helps prepare the uterine lining for a fertilised egg; also prepares mammary glands for milk secretion

prognathism Having a protruding jaw

prolactin A hormone that promotes milk production during and after pregnancy

pus The thick fluid that results from inflammation; it contains dead phagocytes

qualitative data Observations that do not involve numbers or measurement

quantitative data Data expressed in numbers; usually involves measurement

radiocarbon dating The calculation of the age of a fossil or artefact using the known rate of decay of radioactive carbon

random assortment The random separation of maternal and paternal chromosomes during the first division of meiosis

random fertilisation The ability of any one sperm to fertilise any available egg

random genetic drift The occurrence of characteristics in a population as a result of chance rather than natural selection; occurs only in small populations; also called Sewall Wright effect

range The difference between the highest and lowest measurements in a group

rate A ratio that shows how long it takes to do something

ratio A numerical statement of how one variable relates to another; written as two numbers separated by a colon

receptor A structure that detects a stimulus

receptor neuron See **sensory neuron**

recognition site A specific sequence of nucleotides at which an enzyme cuts a strand of DNA

recombinant DNA Synthetic DNA; made by inserting genes from one source into a DNA molecule from a different source

recombinant DNA technology The procedures used to produce recombinant DNA; involve introducing DNA into a cell from a different type of organism or DNA that has been modified in some way

reflex A rapid, automatic response to a change in the external or internal environment; tries to restore homeostasis

reflex arc In a reflex, the pathway travelled by nerve impulses from receptor to effector

refractory period A short period following a stimulus during which a nerve cell or a muscle fibre cannot be stimulated again

relative date The age of a fossil or artefact relative to another fossil or artefact (i.e. whether older or younger)

relay neuron See **interneuron**

releasing factor A hormone whose purpose is to control the release of another hormone

reliability The extent to which an experiment gives the same result each time it is performed

repetition Doing the same experiment many times

replication 1. Having a number of identical experiments running together, or performing the experiment on a large number of subjects at the same time. 2. The process by which a DNA molecule forms an exact replica of itself

respiratory centre The part of the brain that regulates breathing rate; located in the medulla oblongata

resting membrane potential The membrane potential of unstimulated nerve cells

restriction enzyme An enzyme that cuts strands of DNA at a specific sequence of nucleotides

robust A term used to describe the heavy build of some human ancestors

rod A receptor in the retina of the eye that is sensitive to dim light; see also **cone**

saltatory conduction The conduction of a nerve impulse along a myelinated nerve fibre; the impulse seems to jump from one node of Ranvier to the next

scaffold A structure used in tissue engineering as a template for tissue growth

Schwann cell A cell that wraps around a nerve fibre, forming the myelin sheath

sebum An oily substance secreted by glands in the skin

secondary data Data collected by someone other than the person using the data

secondary response The response to a second or subsequent exposure to an antigen; the secondary response is faster and more intense than the primary response

selective agent Any factor that causes the death of organisms with certain characteristics but which has no effect on individuals without those characteristics

self-antigen Any large molecule produced in a person's own body; does not cause an immune response in that person

sense organ Receptors grouped into a discrete organ such as the eye

sensory area A part of the cerebral cortex that interprets impulses from receptors

sensory division See **afferent division**

sensory fibre A fibre that carries impulses into the central nervous system

sensory neuron A nerve cell that carries messages from receptors to the brain or spinal cord; also called a receptor neuron

set point In a feedback system, the level at which a variable is to be maintained

Sewall Wright effect See **random genetic drift**

shivering The involuntary contraction of a muscle; generates heat when body temperature begins to fall

sickle-cell anaemia An inherited disease causing early death; results from the inheritance of two alleles for sickle-cell anaemia

sickle-cell trait An inherited disease in which abnormal haemoglobin causes the red blood cells to become sickle-shaped when oxygen concentration is low

sinoatrial node (SA node) The heart's pacemaker; a group of cells in the wall of the right atrium of the heart that regulate the heartbeat

sociocultural barriers Barriers to interbreeding that are due to social and cultural factors

sodium–potassium pump A mechanism in the membrane of a nerve cell that transports sodium ions out of the cell and potassium ions into the cell

Solutrean culture The stone tool culture characterised by pressure flaking stones to produce beautifully made willow-leaf and laurel-leaf points; associated with the later Cro-Magnon people

somatic division The part of the efferent division of the peripheral nervous system that carries nerve impulses from the brain and spinal cord to skeletal muscles and skin; also called the somatic nervous system

somatic mutation A change occurring in a gene in a body cell (not in a gamete)

somatic nervous system See **somatic division**

somatic sensory neuron A nerve cell that carries messages from receptors in the skin, muscles, bones and joints into the brain and spinal cord

somatotropin See **growth hormone**

special creation The belief that a god created all species

speciation The process of new species developing

species The basic unit of biological classification; members of a species are capable of interbreeding and producing fertile offspring

specific defences Defences of the body that are directed against specific pathogens

spinal cord The nerve cord that extends from the brain to about waist level; enclosed in the vertebrae

spinal nerve One of the 31 pairs of nerves that arise from the spinal cord; joined to the spinal cord by dorsal and ventral roots

spinal reflex arc In a spinal reflex, the pathway travelled by a nerve impulse from receptor to effector

spinal reflex A reflex carried out by the spinal cord without involvement of the brain

staggered cut A cut produced when a restriction enzyme creates fragments of DNA with unpaired nucleotides that overhang at the break in the strands, called sticky ends

start codon The sequence AUG (adenine, uracil, guanine) is the codon for the amino acid methionine; when the ribosome reaches this codon, it starts making protein

steady state control system A negative feedback system that maintains homeostasis

steady state See **homeostasis**

stereoscopic vision A state where each eye sees a slightly different view of an object, so that depth as well as width and height can be seen; also called three-dimensional vision

sticky end The overhanging end produced by a staggered cut of a sequence of nucleotide bases; sometimes called cohesive end

stimulus Any change, internal or external, that causes a response

straight cut A cut produced when a restriction enzyme makes a clean break across the two strands of DNA so that the ends terminate in a base pair; called blunt ends

stratigraphy The study of the sequence of rock layers as a means of relative dating

streptomycin A type of antibiotic

striding gait A way of walking in which the hip and knee are fully extended

stroke volume The volume of blood forced from the left ventricle of the heart with each contraction

sub-unit vaccine A vaccine that contains only a fragment of the disease-causing micro-organism; for example, hepatitis B vaccine

sulci Downfolds between convolutions of the cerebral cortex; singular: sulcus

suppressor T-cell A type of T-cell that helps to slow down the immune response

survey The systematic collection, analysis and interpretation of information about a particular question or series of questions; usually designed so that data is collected from a large number of subjects

survival of the fittest A principle whereby organisms with favourable characteristics survive, but organisms with unfavourable characteristics die before they have a chance to reproduce

sweat The liquid produced by the sweat glands on the skin

sweat gland A gland in the skin that produces sweat

sweating The secretion of fluid by the sweat glands to help the body lose heat through evaporative cooling

sympathetic division One of the two divisions of the autonomic nervous system; opposes the function of the parasympathetic division; also called sympathetic nervous system

sympathetic nervous system See **sympathetic division**

synapse The junction between the branches of adjacent neurons

target cell A cell whose activity is affected by a particular hormone

target organ An organ whose activity is affected by a particular hormone

Tay-Sachs disease (TSD) A genetic disorder caused by a missing enzyme that results in fatty substances accumulating in the nervous system

T-cell A lymphocyte that can differentiate into a number of different kinds of cell, all of which are involved in cell-mediated immunity

temporal lobe One of the four lobes of each cerebral hemisphere

thalassaemia An inherited disease caused by a recessive allele, in which anaemia results from defects in the formation of haemoglobin

thermoreceptor A temperature receptor; located in the skin or the hypothalamus

thermoregulation The regulation of body temperature; the balance of heat gain and heat loss in order to maintain a constant internal body temperature independent of the environmental temperature

thymosin Any of a group of hormones secreted by the thymus that stimulate the immune system by helping the maturation of T-cells

thymus An endocrine gland located in the chest just above the heart and behind the sternum; secretes a group of hormones called thymosins

thyroid gland An endocrine gland, consisting of two lobes, located in the neck just below the larynx; secretes the hormone thyroxine

thyroid-stimulating hormone (TSH) A hormone that stimulates production and release of hormones from the thyroid gland; also known as thyrotropin

thyrotropin See **thyroid-stimulating hormone**

thyroxine A hormone secreted by the thyroid gland that regulates metabolism, growth and development

tissue engineering The rebuilding of damaged tissue by the use of biology, medicine and engineering

tissue fluid See **intercellular fluid**

tolerance limits Limits of factors such as temperature and fluid balance beyond which the body malfunctions

total drug resistance The resistance of some strains of bacteria to all antibiotics

touch receptor A receptor sensitive to touch

toxin Any poisonous substance produced by bacteria, plants or animals

toxoid An inactivated toxin

tract A bundle of nerve fibres in the central nervous system

transgenic organism An organism that has had DNA from another species introduced into it artificially

transverse arch The arch of the bones of the foot, running from side to side

trial and error A method of problem-solving in which one attempt to solve the problem is followed by another; each trial is recorded and the results allow the investigator to gradually home in on the solution

tribe A level of biological classification that occurs between subfamily and genus; usually contains several genera, for example the tribe Hominini includes modern humans and their extinct ancestors

tri-iodothyronine A hormone secreted by the thyroid gland; contains iodine and is the most powerful of the thyroid hormones; affects many body processes including body temperature, growth and heart rate

trisomy 21 A genetic disorder resulting from an extra copy of chromosome 21 or an extra part of chromosome 21; also called Down syndrome

Turner's syndrome A genetic disorder resulting from inheritance of one X chromosome and no other sex chromosome

type 1 diabetes See **insulin-dependent diabetes**

type 2 diabetes See **adult-onset diabetes**; also see **diabetes mellitus**

ubiquitous protein One of a group of proteins that appears to be in all species from bacteria to humans; the small protein called ubiquitin was so-named because it is present in all types of cells

uncontrolled variable A variable that could not be kept the same for the control and the experimental groups in an experiment

unipolar neuron A neuron with a single process, an axon; the cell body is to one side of the axon; in humans such neurons are sensory and carry messages to the spinal cord

unmyelinated fibre A nerve fibre that has no myelin sheath

ureter The tube that leaves each kidney and drains into the urinary bladder

urethra The tube that empties the bladder to the outside; in males it also carries sperm

urinary bladder A hollow, muscular organ near the base of the abdominal cavity; collects urine from the two ureters

uterus The hollow, pear-shaped organ in which a fertilised egg grows into a baby, situated between the urinary bladder and the rectum; also called the womb

vaccination The introduction of antigens to a person so that they acquire immunity without suffering from the illness

vaccine An antigen preparation used in immunisation

valid Describes an experiment that tests what it is supposed to test

variable Any factor that may change during an experiment

variation The differences that exist between individuals or populations of a species

vasoconstriction A decrease in the diameter of blood vessels, restricting the flow of blood through them

vasodilation An increase in the diameter of blood vessels, increasing the flow of blood through them

vasomotor centre The part of the brain that regulates the diameter of blood vessels; located in the medulla oblongata

vasopressin See **antidiuretic hormone**

vector 1. An agent such as an insect capable of transferring a disease-causing organism from one person to another.
2. A bacterial plasmid, viral phage or other such agent used to transfer genetic material from one cell to another

ventral root One of the two roots that link a spinal nerve to the spinal cord; located towards the front of the body; contains axons of motor neurons

vertebral canal The opening in the vertebrae through which the spinal cord passes

vestigial organ A structure of reduced size that appears to have no function; for example, the ear muscles of humans

virulence The disease-producing power of a micro-organism

virus An infectious agent, too small to be seen with a light microscope, consisting of a protein sheath surrounding a core of nucleic acid; viruses are totally dependent on living cells for reproduction

visceral sensory neuron A neuron that takes impulses from the internal organs to the central nervous system

water intoxication A potentially life-threatening condition caused by drinking too much water when the amount of salt (and other electrolytes) in the body is low; commonly caused by long bouts of intensive exercise during which electrolytes are not replenished and large amounts of water are consumed

white matter The part of the brain and spinal cord made up of myelinated fibres

INDEX

A

B

C

D

E

F

G

H

I

Q

R

S

T

U

V

W

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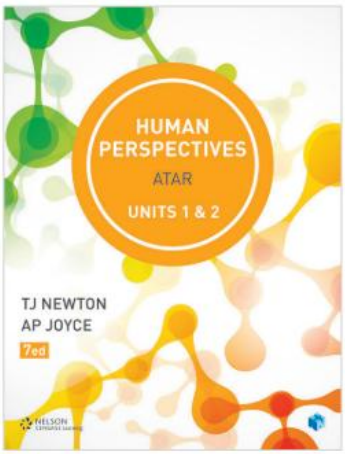

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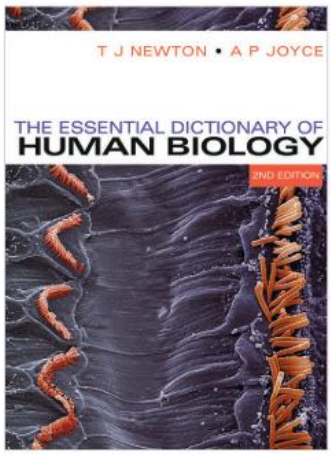

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