STANDARD LEVEL

Biology

for the IB Diploma Programme

3rd Edition

ALAN DAMON
RANDY McGONEGAL
WILLIAM WARD

Pearson

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Biology

for the IB Diploma Programme

Alan Damon, Randy McGonegal, William Ward

Published by Pearson Education Limited, 80 Strand, London, WC2R 0RL.

www.pearson.com/international-schools

Text © Pearson Education Limited 2023
Development edited by Judith Head and Jess White
Copy edited by Eva Fairnell
Proofread by Eva Fairnell
Indexed by Georgie Bowden
Designed by Pearson Education Limited
Typeset by Tech-Set ltd
Picture research by Integra
Original illustrations © Pearson Education Limited 2023
Cover design © Pearson Education Limited 2023

First published 2023

25 24 23
10 9 8 7 6 5 4 3 2 1

British Library Cataloguing in Publication Data
A catalogue record for this book is available from the British Library

ISBN 978 1 29242 773 7

Printed in Slovakia by Neografia

Acknowledgements

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Theme C

C2.1 is not included as it is for HL students only.

Theme D

D2.2 is not included as it is for HL students only.

D Continuity and change – Ecosystems 508

Syllabus roadmap

The aim of the syllabus is to integrate concepts, topic content and the nature of Science through inquiry. Students and teachers are encouraged to personalize their approach to the syllabus to best fit their interests.

Theme	Level of organization			
	1. Molecules	**2. Cells**	**3. Organisms**	**4. Ecosystems**
A **Unity and diversity**	Common ancestry has given living organisms many shared features while evolution has resulted in the rich biodiversity of life on Earth.			
	A1.1 Water **A1.2** Nucleic acids	**A2.2** Cell structure	**A3.1** Diversity of organisms	**A4.1** Evolution and speciation **A4.2** Conservation of biodiversity
B **Form and function**	Adaptations are forms that correspond to function. These adaptations persist from generation to generation because they increase the chances of survival.			
	B1.1 Carbohydrates and lipids **B1.2** Proteins	**B2.1** Membranes and membrane transport **B2.2** Organelles and compartmentalization **B2.3** Cell specialization	**B3.1** Gas exchange **B3.2** Transport	**B4.1** Adaptation to environment **B4.2** Ecological niches
C **Interaction and interdependence**	Systems are based on interactions, interdependence and integration of components. Systems result in emergence of new properties at each level of biological organization.			
	C1.1 Enzymes and metabolism **C1.2** Cell respiration **C1.3** Photosynthesis	**C2.2** Neural signalling	**C3.1** Integration of body systems **C3.2** Defence against disease	**C4.1** Populations and communities **C4.2** Transfers of energy and matter
D **Continuity and chance**	Living things have mechanisms for maintaining equilibrium and for bringing about transformation. Environmental change is a driver of evolution by natural selection.			
	D1.1 DNA replication **D1.2** Protein synthesis **D1.3** Mutations and gene editing	**D2.1** Cell and nuclear division **D2.3** Water potential	**D3.1** Reproduction **D3.2** Inheritance **D3.3** Homeostasis	**D4.1** Natural selection **D4.2** Stability and change **D4.3** Climate change

Authors' introduction to the third edition

Welcome to your study of IB Diploma Programme (DP) biology. This is the third edition of Pearson's highly successful Standard Level (SL) biology book, first published in 2007. It has been rewritten to match the specifications of the new IB biology curriculum for first assessments in 2025 and provides comprehensive coverage of the course. It is our intention as authors of this textbook to open a door to biological knowledge that will provide a pathway towards an ever-present curiosity of life, the factors that affect it today, and the factors that may affect it in the future.

While there is much new and updated material in this textbook, we have kept and refined the features that made the previous editions so successful and effective. We hope our knowledge and enthusiasm for biology as well as our understanding of the IB biology requirements will be passed onto you.

Content

This book covers the content that is set out in the IB DP biology subject guide for first assessments in 2025. It utilizes the overarching theme of Nature of Science (NOS) to provide the means for you to accomplish the following aims:

1. to develop conceptual understanding that allows connections to be made between different areas of the subject, and to other DP science subjects
2. to acquire and apply a body of knowledge, methods, tools and techniques that characterize science
3. to develop the ability to analyse, evaluate and synthesize scientific information and claims
4. to develop the ability to approach unfamiliar situations with creativity and resilience
5. to design and model solutions to local and global problems in a scientific context
6. to develop an appreciation of the possibilities and limitations of science
7. to develop technology skills in a scientific context
8. to develop the ability to communicate and collaborate effectively
9. to develop awareness of the ethical, environmental, economic, cultural and social impact of science.

Chapters are presented in the same sequence as provided in the subject guide. There are four main themes:

A. Unity and diversity
B. Form and function
C. Interaction and interdependence
D. Continuity and change

Each theme is then discussed at four different levels of organization. They are:

1. Molecules
2. Cells
3. Organisms
4. Ecosystems

Each topic begins with an introductory image and caption supplying a brief entry point into its content. Guiding Questions are then presented for further clarification of chapter content.

Guiding Questions

What plausible hypothesis could account for the origin of life?

What intermediate stages could there have been between non-living matter and the first living cells?

The text covers the course content with all scientific terms explained. We have been careful to apply the same terminology you will see in IB assessments.

Linking Questions that relate topics to one another can be found in each chapter. When encountered, Linking Questions should be considered in order to understand how other concepts from within the course relate to those currently being discussed. When used effectively, Linking Questions can provide an excellent tool for revision.

For what reasons is heredity an essential feature of living things?

Each chapter concludes with Guiding Questions revisited and a summary of the chapter. The summary presents key points from the chapter you should be especially aware of.

Guiding Question revisited

How can viruses exist with so few genes?

Nature of Science

Throughout the course you are encouraged to think about the nature of scientific knowledge and the scientific process as it applies to biology. Examples are given of the evolution of biological theories as new information is gained, the use of models to conceptualize our understandings, and the ways in which experimental work is enhanced by modern technologies. Ethical considerations, environmental impacts, the importance of objectivity, and the responsibilities regarding scientists' code of conduct are also considered here. The emphasis is on appreciating the broader conceptual themes in context. We recommend that you familiarize yourself with these examples to enrich your understanding of biology.

Throughout the book you will find NOS themes and questions emerging across different topics. We hope they help you to develop your own skills in scientific literacy.

Nature of Science

Science has progressed and continues to progress with the development of new study techniques. Not only has the microscope increased our knowledge of the cell, but ultracentrifuges and fractionation of cells have also greatly enhanced our understanding of the cell and its organelles.

Key to feature boxes

A popular feature of our past editions is maintained in this book, that is the different coloured boxes interspersed throughout each chapter. These boxes can be used to enhance your learning.

Global context

The impact of the study of biology is global, and includes environmental, political and socio-economic considerations. Examples of these are given to help you see the importance of biology in an international context. These examples also illustrate some of the innovative and cutting-edge aspects of research in biology.

Thanks to modern communication technologies, it is possible for scientists working all over the world to collaborate and contribute to a scientific endeavour such as sequencing the genome of plants that help feed the world. Rice is one example: biologists from 10 countries contributed to sequencing the first rice genome.

Surface area-to-volume ratio. Full details on how to carry out this activity with a worksheet are available in the eBook.

Skills in the study of biology

These boxes indicate links to the skills section of the course, including ideas for laboratory work and experiments that will support your learning and help you prepare for the Internal Assessment. These link to further resources in the eBook (look out for the grey icon).

When you study the action of sarcomeres, how much is your knowledge limited by two-dimensional models, such as Figure 3?

Theory of Knowledge

These questions, which are mostly from the Theory of Knowledge (TOK) guide, stimulate thought and consideration of knowledge issues as they arise in context. The questions are open-ended and will help trigger critical thinking and discussion.

The sequence of nitrogenous bases in DNA, later transcribed into RNA, forms the basis of the genetic code.

Key fact

Key facts are drawn out of the main text and highlighted in bold. These boxes will help you to identify the core learning points within each section. They also act as a quick summary for review.

You are not required to know all the names of the intermediate molecules of the respiration process. However, you must understand the steps and the overall products.

Hint for success

These boxes give hints on how to approach questions, and suggest approaches that examiners like to see. They also identify common pitfalls in understanding, and omissions made in answering questions.

Challenge yourself

These boxes contain probing questions that encourage you to think about the topic in more depth, and may take you beyond the syllabus content. They are designed to be challenging and to make you think.

Challenge yourself

1. Using Figure 8, showing the DNA profiles from six suspects, can you identify which one matches the DNA profile of the blood stain found at the crime scene?

Interesting fact

These give background information that will add to your wider knowledge of the topic and make links with other topics and subjects. Aspects such as historic notes on the life of scientists and origins of names are included here.

Where does the term gene knockout come from? In contact sports such as boxing, a knockout marks the end of the combat, because the boxer who has been knocked out is no longer able to stand and fight. A gene that has been knocked out will no longer be able to make the protein that produced the original effect or trait

Questions

There are three types of question in this book.

1. Worked examples with solutions

Worked examples appear at intervals in the text and are used to illustrate the concepts covered. They are followed by the solution, which shows the thinking and the steps used in solving the problem.

Worked example

The length of an image you are looking at is 50 mm. If the actual length of the subject of the image is 5 µm, what is the magnification of the image?

Solution

Magnification = 50 mm/5 µm = 50,000 µm/5 µm = 10,000×

Or

Magnification = 50 mm/5 µm = 50×10^{-3} m/1×10^{-6} m = 10,000×

2. Exercises

These questions are found at the end of each chapter. They allow you to apply your knowledge to test your understanding of what you have just been reading. The answers to these are accessed via icons on the first page of each chapter in the eBook. Exercise answers can also be found at the back of the eBook.

Exercises

Q1. Explain why the obligate parasitism shown by viruses may have been a major factor in convergent evolution within the group.

3. Practice questions

These questions are found at the end of each group of chapters displaying a common theme and level of organization. The significance of these questions is that they are IB exam-style questions. The mark schemes used by examiners when marking these questions are accessed via icons in the eBook next to the questions. These questions and mark schemes are essential in providing insight into the depth of comprehension necessary to achieve success in an IB exam.

A2 Practice questions

1. **(a)** An organelle is a discrete structure within a cell with a specific function. In the table below, identify the missing organelles and outline the missing functions.

Name of organelle	Structure of organelle	Function of organelle
Nucleus	Region of the cell containing chromosomes, surrounded by a double membrane, in which there are pores.	Storage and protection of chromosomes.
Ribosome	Small spherical structures, consisting of two subunits.	
	Spherical organelles, surrounded by a single membrane and containing hydrolytic enzymes.	Digestion of structures that are not needed within cells.
	Organelles surrounded by two membranes, the inner of which is folded inwards.	

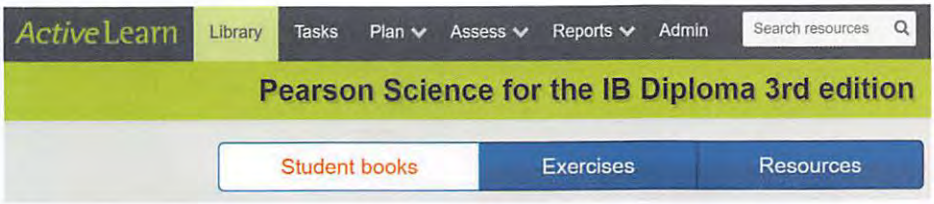
(4)

(b) The table above shows some of the organelles found in a particular cell. Discuss what type of cell this could be. (2)

(Total 6 marks)

eBook

In your eBook you will find more information on the Skills section of the course, including detailed suggestions for laboratory work, and the answers to the exercises and practice questions found in the text. You will also find links to videos and command term worksheets in the Resources tab of your eBook account. In addition, there are auto-marked quizzes in the Exercises tab of your eBook account (see screenshot below).



We truly hope that this book and the accompanying online resources help you enjoy the fascinating subject of IB biology. We wish you success in your studies.

Alan Damon, Randy McGonegal and William Ward

THEME

A Unity and diversity

1 Molecules

This is DNA, one of the molecules classified as a nucleic acid and a molecule that is integral to life on Earth. The molecules that are important to life are diverse and complex. Yet their basic structures are largely consistent from species to species. This allows us to study the fundamental structures and functions of these molecules and apply that knowledge to all living organisms. In this chapter, you will first study the solvent of all biochemically important molecules, water. Later, you will consider the structure of nucleic acids.

A1.1 Water

Guiding Questions

What physical and chemical properties of water make it essential for life?

What are the challenges and opportunities of water as a habitat?

What makes water essential for living organisms? What physical and chemical properties does water have that provide essential benefits to aquatic, marine and terrestrial organisms? What opportunities and challenges does water pose for life? These are not questions designed to be answered in one or more short statements. They are questions that deserve to be explored. A portion of this chapter will attempt to begin that exploration.

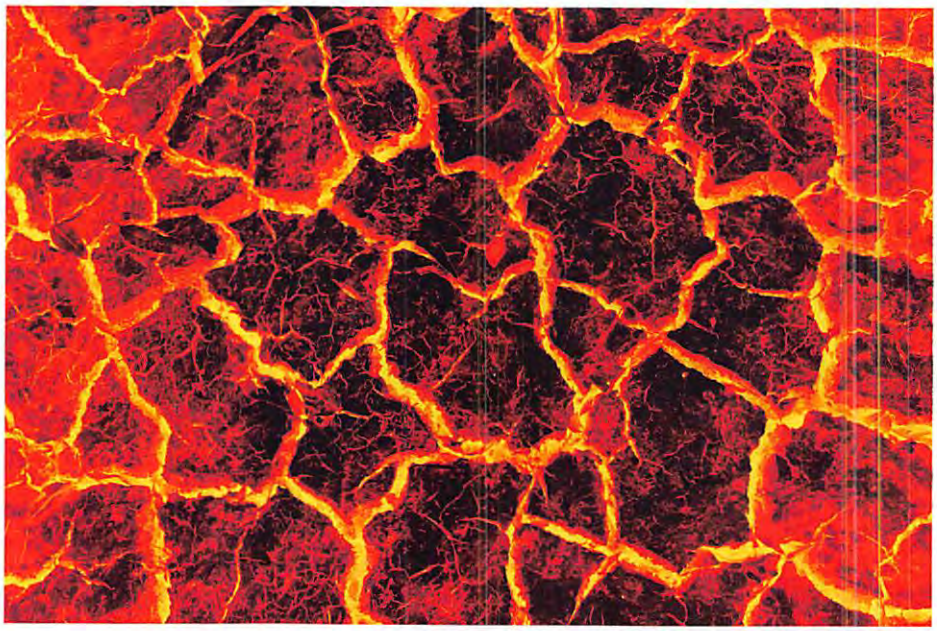
Life first evolved in water and all living things are still dependent on this amazing molecule. Fortunately, we live on a planet where water exists in all three states: there is abundant liquid water, water vapour and ice. Water, as a polar molecule, is an excellent solvent for the vast majority of elements and compounds necessary for life. Water molecules are found inside and outside cells, and chemical communication in and out of cells must occur in a water environment.

Water has both advantages and disadvantages for the aquatic and marine organisms that use it as a habitat. Advantages include the fact that water provides buoyancy and stable thermal properties for these organisms. Disadvantages include its relatively high viscosity compared to air. This means that many organisms living in water have adapted their body shape and propulsion mechanisms in order to move easily through an aquatic environment.

A1.1.1 – The medium of life

A1.1.1 – Water as the medium for life
Students should appreciate that the first cells originated in water and that water remains the medium in which most processes of life occur.

Life on Earth has never been possible without water. Imagine a primordial planet slowly cooling from its original molten mass. That primitive Earth would not have had any water because of the extremely high temperatures at its centre *and* on its surface.



The surface of the Earth may have looked like this early in its history, with magma giving off tremendous heat at the surface.

Approximately 70% of our planet's surface is covered by water. The deepest parts of the Pacific Ocean are deeper than the height of the highest land peaks.

The origin and evolution of the first cells could not begin until temperatures cooled enough for water to form and, later, for the water cycle to begin. We take for granted the changes that water makes as it goes between its solid, liquid and gaseous phases. Earth's varied temperatures allow these changes. That was not the case in our planet's early history.

It is thought that the first cells formed and slowly evolved in the oceans. Cells require a complex series of biochemical reactions. This means a **solvent** is needed for reactions to occur. Ocean water provided the source for that solvent. The first cells evolved a membrane to separate the water in the cytoplasm from the "ocean water".

Every solution where water is the solvent is called an aqueous solution. Thus, cytoplasm, rivers, blood and oceans are all aqueous solutions.

When most people think of water, their first thoughts are about the water they drink and bathe or swim in. But water is more widespread than that. Below are a few examples of where the importance of water as a solvent is vital to living organisms.

Water is the solvent that:

- makes up the fluid (cytoplasm) in all cells where all cellular reactions occur
- makes up the fluid inside all organelles in cells
- is found between cells of multicellular organisms (intercellular or tissue fluid)
- permits transport of substances into and out of cells
- is essential to blood and many other body fluids in humans and other organisms
- provides the medium in which all organisms in oceans, lakes and rivers live.

Challenger Deep (the lowest known portion of the Mariana Trench) is 10,984 m below the surface of the Pacific Ocean. Mount Everest (the tallest known land mass) is 8,848 m above sea level. The difference between those points is over 19 km or 12 miles.

Nature of Science

Measurements in science often change over time. If you research the world's deepest and tallest points you may find slightly different numbers (meters below and above sea level). There are various possible reasons including: how recently the data point was taken; what method was used to obtain the data; whether or not the data change over time due to natural causes. Can you think of other reasons for the data to vary?

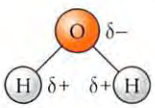
A1.1.2 – The structure and polarity of water molecules

A1.1.2 – Hydrogen bonds as a consequence of the polar covalent bonds within water molecules

Students should understand that polarity of covalent bonding within water molecules is due to unequal sharing of electrons and that hydrogen bonding due to this polarity occurs between water molecules.

Students should be able to represent two or more water molecules and hydrogen bonds between them with the notation shown below to indicate polarity.

To understand the properties of water and its importance to living organisms, it is necessary to understand the molecular structure of water molecules.



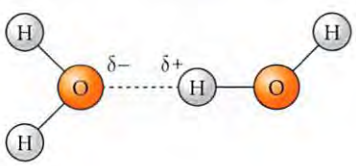
A1.1 Figure 1 This image shows the covalent bonds in a water molecule. Each of two hydrogen atoms is bonded at an angle to a single oxygen atom. Remember that each of the two covalent bonds is a pair of shared electrons.

The covalent bonds between the oxygen atom and the two hydrogen atoms of a water molecule are categorized as **polar covalent bonds**.

You may remember from fundamental chemistry that covalent bonds form when two atoms share electrons. Electrons are negatively charged and the nucleus of an atom is positively charged (because of the protons). So, any equally shared electrons create a **non-polar covalent bond**. This is because neither of the atoms has a higher density of electrons than the other. Good examples of non-polar covalent bonds include the covalent bond between two carbons and the covalent bond between two hydrogens.

Polar covalent bonding results from an unequal sharing of electrons. In water, the single oxygen atom is bonded to two different hydrogen atoms. Each oxygen–hydrogen bond is a polar covalent bond. This results in a slight negative charge at the oxygen end of the molecule and a slight positive charge at the end with the two hydrogens.

Because of the open triangular shape of a water molecule, the two "ends" of each molecule have opposite charges. The oxygen side is slightly negative and the hydrogen side is slightly positive. This is why water is a polar molecule: it has different charges at each end. Because of this, water molecules interact with each other and other molecules in very interesting ways. Many of these interactions are explained by the usually short-lived (ephemeral) attractions between either two water molecules or between a water molecule and another type of charged atom (or ion). These ephemeral attractions are called **hydrogen bonds** and will be explained further in the following sections.



A1.1 Figure 2 Two water molecules showing a single hydrogen bond between them. The bonding force of each hydrogen bond (indicated by the dotted line) is weak. In liquid water, the bond is ephemeral because the water molecules continue to move around.

You may be used to seeing the Greek symbol Δ called delta. Δ is the capital letter symbol and δ is the corresponding small case letter symbol for delta.

The electrons being shared to create the covalent bonds within a water molecule are not being shared equally between the two atoms. In Figure 1, you see the symbols δ^+ and δ^- (delta positive and delta negative). These symbols represent areas of low or high electron density in the sharing of electrons to create a covalent bond. Each hydrogen atom is assigned a δ^+ because that is an area of lesser electron density (thus a small positive charge due to the single proton of the hydrogen atom). The oxygen atom is assigned a δ^- charge due to its high electron density.

SKILLS

Practise sketching from memory a diagram similar to the one shown in Figure 2. Include the hydrogen bond and the delta symbols and charges as shown. Practise adding a third and fourth water molecule with the same symbolism and orientation.

A1.1.3 – Cohesion of water molecules

A1.1.3 – Cohesion of water molecules due to hydrogen bonding and consequences for organisms

Include transport of water under tension in xylem and the use of water surfaces as habitats due to the effect known as surface tension.

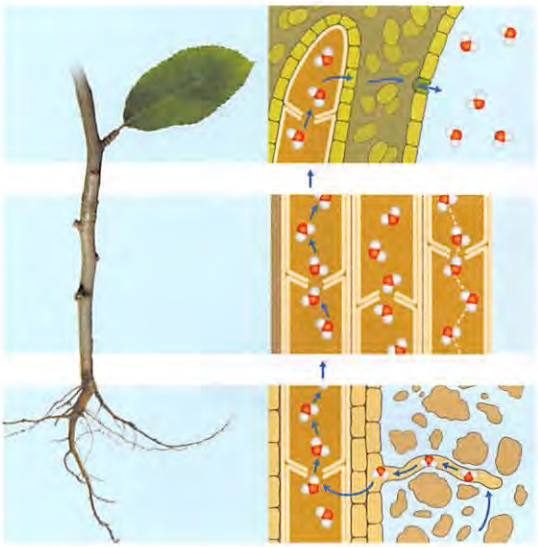
Water molecules are highly cohesive. **Cohesion** occurs when *molecules of the same type* are attracted to each other. As you have seen, water molecules have a slightly positive end and a slightly negative end. Whenever two water molecules are near each other, the positive end of one attracts the negative end of another – this is hydrogen bonding. When water cools below its freezing point, the molecular motion of the water molecules slows to the point where the hydrogen bonds become locked into place and an ice crystal forms. Liquid water has molecules with a faster molecular motion, and the water molecules are able to influence each other, but not to the point where molecules stop their motion. This influence is highly important and leads to many of the physical and chemical properties of water. The ephemeral hydrogen bonding between liquid water molecules explains a variety of events, including the following.

- Why water has a **surface tension**. Surface tension is due to the fact that the layer of water molecules at the surface of a body of water does not have molecules of water above it. Because of this, the water molecules show a relatively strong cohesive force to the molecules immediately around and below them (no molecules are pulling upwards). This surface tension must be broken in order for an object to move through the surface from above. It is surface tension that causes you pain when you do a "belly flop" into a body of water. It is also surface tension that creates a habitat for some animals such as water striders and basilisk lizards.

i You can float a paperclip on water because of the surface tension of the water. Make sure you maximize the surface area of the paperclip on the water if you try this.

A green basilisk (*Basiliscus plumifrons*) (found in Central America) running across the surface of water. Aided by its webbed feet to increase the surface area in contact with the water, the lizard must keep running in order to not break through the surface tension.

- How water is able to move as a "water column" in the vascular tissues of plants. The majority of water moving upwards in a plant moves within small tubes called **xylem**. Think of xylem as being similar to numerous tiny straws. When water evaporates from a leaf (in a process called transpiration) the water that evaporates in order to exit the leaf has cohesion to the water in a xylem tube that adjoins the exit point. The evaporation with corresponding cohesion creates a low pressure in this area called **tension**. This tension pulls on the other water molecules in the xylem tube so they all move upwards towards the leaf. The molecules are all cohesive to each other and all move up collectively. This evaporation occurs in small, controlled openings called stomata, which are usually found on the underside of leaves. The water that transpires from the leaf is replaced in the xylem in the root system of the plant.



An example of the importance of cohesion. At the top, water is evaporating from a stoma (singular of stomata). Stomata are very small openings that can be opened or closed and are found primarily on the under surface of leaves. The evaporation of water from open stomata is called transpiration. The water is provided to the leaf by many xylem tubes. The transpiration of water creates tension (a low-pressure area in the leaf and xylem tube) and the polarity of water molecules pulls the entire water column to move towards the low-pressure area. The xylem tube within the leaf is continuous with the xylem in the stem and root. The water moving upwards is replaced by ground water moving into the root system.

Think of a xylem tube and the upwards movement of water as being similar to what happens when you use a straw in a drink. The suction you provide creates tension (low-pressure area at the top of the straw) and the fluid is moved upwards along the straw. The bottom of the straw in your drink is similar to the bottom of the xylem tubes found in the root system of a plant.

A1.1.4 – Adhesion between water and other polar substances

A1.1.4 – Adhesion of water to materials that are polar or charged and impacts for organisms
Include capillary action in soil and in plant cell walls.

Water molecules are certainly not the only molecules in nature that exhibit polarity. An attraction between two *unlike* molecules due to hydrogen bonding is called **adhesion**. When water molecules are attracted to cellulose molecules by hydrogen bonding, the attraction is an example of adhesion because the hydrogen bonding is between two different kinds of molecule. Where is this important in nature?

- Water within the xylem. Cohesion and adhesion are both at work in this example. When the column of water is "pulled up", cohesion moves each molecule up; when the column is not being "pulled up", adhesion keeps the entire column from dropping down within the tube. The same phenomenon occurs when water is placed in a capillary tube – you can think of the xylem tissue in plants as being biological capillary tubes.

Cohesion and adhesion are both a result of the polarity of water molecules. Cohesion is an attraction between two water molecules and adhesion is an attraction between a water molecule and another polar molecule that is not water.

A capillary tube is a glass tube (similar to a straw) that has a very narrow inside opening. In this photo, a capillary tube has been inserted into a vessel filled with water with a red dye. The liquid will spontaneously climb upwards into the capillary tube due to adhesion and remain in a fixed position within the tube. The adhesion is the attraction between the inside surface of the glass tube and water molecules.

How do the various intermolecular forces of attraction affect biological systems?

- Capillary action in soil. Even soil that appears to be dry contains water in microscopic channels. These small channels act in a similar way to capillary tubes. Water molecules adhere to the polar molecules making up the soil and other water molecules are then sometimes moved by cohesion. The small root hairs of plants intrude into the water-filled spaces and water is taken into the root.

A1.1.5 – The solvent properties of water

A1.1.5 – Solvent properties of water linked to its role as a medium for metabolism and for transport in plants and animals
Emphasize that a wide variety of hydrophilic molecules dissolve in water and that most enzymes catalyse reactions in aqueous solution. Students should also understand that the functions of some molecules in cells depend on them being hydrophobic and insoluble.

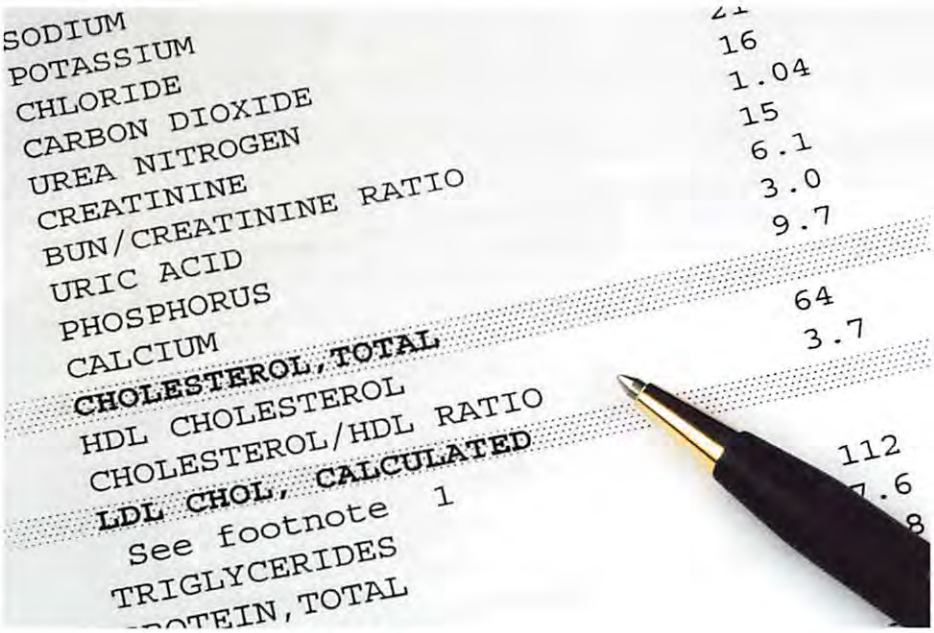
As you have seen, water is a polar molecule and thus a polar solvent. In nature, water is almost always found as a solvent carrying one or more of a wide variety of other substances as solutes. Any solution that has water as the solvent is called an **aqueous solution**. Any substance that dissolves readily in water is described as **hydrophilic** (water loving) and any substance that does not dissolve easily is called **hydrophobic** (water fearing).

Hydrophilic molecules

The cytoplasm of a cell is a good example of an aqueous solution and contains a wide variety of water-soluble substances. These hydrophilic solutes include (among others) glucose, ions, amino acids and proteins. Some of the dissolved proteins in cells are the biological catalysts called enzymes. Reactions within the cytoplasm depend on enzymes to proceed at a rate necessary for life and at a temperature tolerated by that type of cell.

Water is an excellent medium for transporting dissolved substances. The water contained in xylem vessels of plants is not pure water. It is an aqueous solution that transports inorganic ions such as sodium, potassium and calcium. These and many other essential substances are hydrophilic; they dissolve easily in water and are transported upwards from the root system to the leaves.

The blood of many animals, including humans, is also an aqueous solution. The red and white blood cells are suspended in plasma. Plasma is an aqueous solution of an incredible array of molecules. Anyone looking at the results of a typical medical blood test can see the variety of solutes in this solution.



A small section of the results of a human blood test showing some of the dissolved substances in the aqueous portion of blood called plasma.

The biochemistry of a cell occurs in its cytoplasm and also within membrane-bound organelles such as the nucleus and mitochondria. The fluids of these cellular environments use water as a solvent because most biochemically active molecules are polar and dissolve easily in an aqueous solvent.

Hydrophobic molecules

Some non-polar (insoluble) molecules found in nature are important to living organisms. Here are some examples.

- Steroid hormones, such as oestradiol and testosterone, are able to pass directly through the plasma membrane and nuclear membrane of a cell. Steroid hormones can do this because they are hydrophobic and are able to pass directly through the hydrophobic layers of cell membranes.
- Many proteins have some sections that are hydrophilic and other sections that are hydrophobic. Membrane-bound proteins may use one or more hydrophobic areas to embed into the hydrophobic layers of a membrane while their hydrophilic section(s) extends into either the intercellular fluid or cytoplasm. This enables the protein to stay attached to the membrane but still interact with soluble substances in the surrounding cell fluids.

- The epidermal cells of leaves are capable of secreting a wax that is used to coat the leaves and is called the **cuticle**. This wax cuticle is hydrophobic and acts as a barrier to water entering and especially exiting the leaf by evaporation. Without this cuticle, leaves would quickly dehydrate because their function requires a thin, broad surface area exposed to the Sun.

A1.1.6 – The physical properties of water

A1.1.6 – Physical properties of water and the consequences for animals in aquatic habitats

Include buoyancy, viscosity, thermal conductivity and specific heat. Contrast the physical properties of water with those of air and illustrate the consequences using examples of animals that live in water and in air or on land, such as the black-throated loon (*Gavia arctica*) and the ringed seal (*Pusa hispida*).

Note: When students are referring to an organism in an examination, either the common name or the scientific name is acceptable.

Table 1 outlines the important physical properties of water compared with air.

Property	Water	Air
Buoyancy or buoyant force (an upwards force exerted on an object placed in the medium – either water or air)	Buoyant force equals the weight of the water displaced by the object. The buoyant force is upwards because there is more pressure from below (in the water) than above (in the air).	An object placed in air has an almost insignificant buoyant force. This force is equal to the weight of the air displaced by the object.
Viscosity	Water's resistance to an object moving through it.	Air's resistance to an object moving through it. Since air is far less dense than water, air's viscosity is far less.
Thermal conductivity	The ability of a substance to transfer heat. Water has a high thermal conductivity.	The thermal conductivity of air is very low compared to water.
Specific heat capacity	In simplest terms, water can absorb or give off a great deal of heat without changing temperature very much. Think of a body of water on a very cold night: even though the air may be very cold, a nearby body of water is relatively stable in temperature.	Air's ability to absorb or give off heat without changing temperature is very low compared to that of water. The temperature of the air changes easily and rapidly due to weather events.

▲ **A1.1 Table 1** Physical properties of water

The physical properties of water have important consequences for animals that live in aquatic habitats, such as the black-throated loon (*Gavia arctica*) and the ringed seal (*Pusa hispida*).

The black-throated loon is a beautiful bird that lives primarily in very cold regions of the Northern Hemisphere. As with most aquatic birds, the loon transfers regularly between land (for nesting), water (for feeding) and air (for flying). Even though this bird is capable of diving for food, it spends much of its time in water on the surface relying on the buoyant force of the water to float. The bird requires energy to overcome the viscosity of water to move across the water surface and even more when it dives for fish and other food sources below the surface. Webbed feet and efficient, streamlined body shape aid the loon in this movement. When the bird is in water, the high thermal conductivity of the water would cause the loon to lose more body heat than when it is in the air. Like many waterbirds, loons use an adaptation to prevent this. They have an oil gland near their tail and they use their beaks to rub this oil over their feathers to make them waterproof. When the air is very cold (below 1°C) the surrounding water is likely to be warmer than the air because the high specific heat of water allows its temperature to remain relatively stable in comparison to air.

Black-throated loon (*Gavia arctica*)

The ringed seal is another animal that is common in cold environments of the Northern Hemisphere. This small seal is buoyant, although not as buoyant as a loon – less of its body is above the surface of the water when resting. It is buoyant enough to keep its snout above water easily and thus has an easily available supply of air. Seals spend a great deal of time swimming in and under the water to catch food (fish and invertebrates) and occasionally to escape a predator such as an orca. Their streamlined shape and paddle-like feet are great assets in overcoming the viscosity of water. But water has high thermal conductivity compared to air, so ringed seals need to minimize body heat loss. They do this by having a thick blubber under their skin. The blubber is insulation and reduces heat loss from the seals' internal organs. Like the black-throated loon, ringed seals are protected from very low air temperatures by the relatively high temperature of arctic water (compared to arctic air) which is due to the high specific heat of water.

You are not required to memorize the scientific names (genus and species) of example organisms.

Melting sea ice due to global warming is threatening many species, including seals, because their habitats are fundamentally changing in a very short period of time. No one country by itself can solve the problem of global warming.

What biological processes only happen at or near surfaces?

Ringed seal (*Pusa hispida*)

Guiding Question revisited

What physical and chemical properties of water make it essential for life?

In this chapter we have described how and why water has:

- polar covalent bonds due to an unequal sharing of electrons between oxygen and hydrogen
- cohesive forces attracting one molecule of water to another
- adhesive forces attracting molecules of water to other types of polar molecules
- excellent solvent properties for other polar molecules (solutes)
- properties making water the "solvent of life" as exhibited by cytoplasm, intercellular fluids, blood and many other solutions that are vital to living organisms.

Guiding Question revisited

What are the challenges and opportunities of water as a habitat?

In this chapter we have investigated:

- physical and chemical properties of water that provide both opportunities and challenges for living organisms
  - buoyancy – important to all aquatic and semi-aquatic organisms to keep them at or near the water surface
  - viscosity – the body shape and propulsion mechanisms of animals have become adapted to overcome this resistance that water has for objects moving through it
  - thermal conductivity – organisms living in cold-water environments must have either a physiology adapted for that water temperature or a means of insulation from the cold because water readily conducts heat away from an organism's body
  - specific heat – water in oceans, lakes and rivers has a very high specific heat that protects many aquatic organisms from much colder surrounding air temperatures.

Exercises

Q1. Describe how a polar covalent bond differs from a non-polar covalent bond.

Q2. Describe the pathway and the forces involved in getting water from the soil surrounding a large tree to a leaf in one of the uppermost branches of that tree (hint: start with the leaf).

Q3. State:

(a) an example of a molecule that is soluble in the cytoplasm of a cell

(b) the function of that same molecule.

Q4. State:

(a) an example of a molecule that is insoluble in the cytoplasm of a cell

(b) the function of that same molecule.

Q5. Describe two adaptations that the black-throated loon (*Gavia arctica*) has evolved for overcoming the viscosity of water.

A1.2 Nucleic acids

Guiding Questions

How does the structure of nucleic acids allow hereditary information to be stored?

How does the structure of DNA facilitate accurate replication?

The organisms alive on Earth today have a long history and a very long family tree. Living things do not just appear, rather they are descended from previous generations. This is based on genetics. The information that is being passed from one generation to the next is in the form of DNA. Humans have 46 DNA molecules in each cell in the form of chromosomes. Written in the genetic code of DNA is information that makes a blue whale what it is and makes you what you are.

Along the length of DNA molecules there are chemical messages that code for specific proteins. Most of these protein messages are common to a species, but a few are individual to one single individual of that species. Thus, each living organism is unique. Preceding every cell division, the DNA replicates in an amazingly accurate series of steps that produces two DNA molecules where there was once one. Life has continued in this way for millions of years.

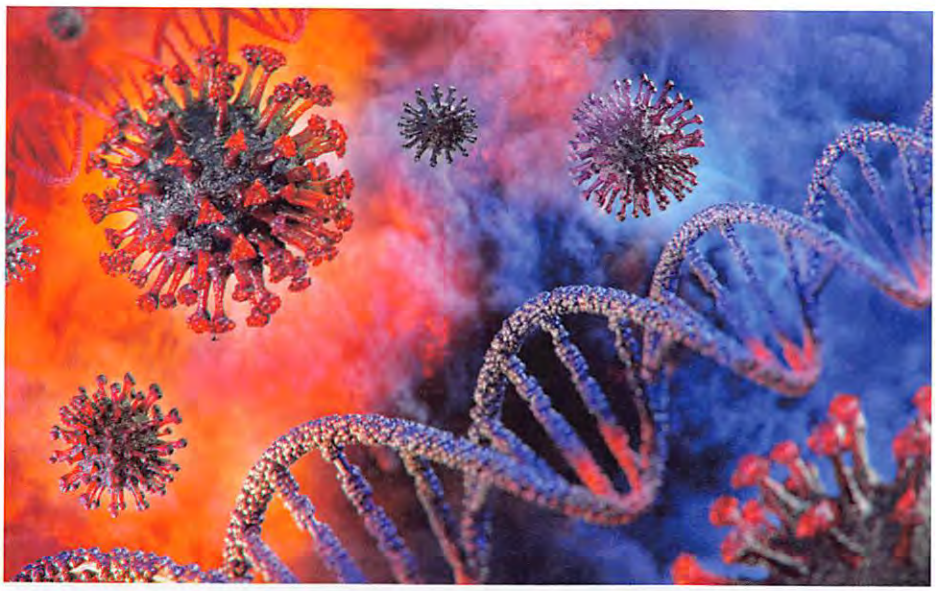
This chapter will introduce you to DNA and other molecules termed nucleic acids. Nucleic acids include DNA and three types of RNA that are all involved in the synthesis of proteins in cells.

A1.2.1 – DNA is the universal genetic material

A1.2.1 – DNA as the genetic material of all living organisms
Some viruses use RNA as their genetic material but viruses are not considered to be living.

Deoxyribonucleic acid (DNA) is the molecule that provides the long-term stored genetic information for all organisms on Earth. When mutations occur that influence evolution, they happen within DNA and are passed on to the next generation. The fact that DNA is universal to all living organisms is evidence of our common ancestry, even back to when the most complex life forms were single cells living in the oceans.

In addition to sugars and phosphate groups acting as a structural framework, DNA has within it four **nitrogenous bases**: adenine, thymine, cytosine and guanine, which are found along the length of the very long molecule. These four bases can be combined in a tremendous variety of orders and lengths. The sequences of nitrogenous bases are the genetic messages or **genes**. The messages are codes for **amino acids**. Amino acids are the "building blocks" of proteins, and a cell's identity and function is determined by the proteins it is able to synthesize. Every cell in a multicellular organism has the same DNA, but each different type of cell only uses the genetic information that is appropriate for that cell.

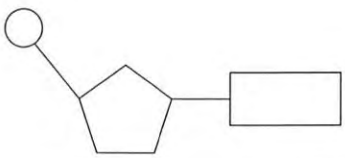


An artist's rendering of the interior of a cell showing viral particles and a DNA molecule. The spikes on the viral particles are modified proteins that attach to the cells of an organism they infect. Inside each of the viruses is a nucleic acid, either DNA or RNA (ribonucleic acid), that may undergo one or more mutations upon every replication cycle. Some mutations may alter the proteins on the spikes and change how well the protein spikes attach to the host cells.

Viruses are not living organisms. Some viruses contain RNA as their genetic information and some contain DNA. No matter which nucleic acid acts as the genetic code for viral proteins, viruses are not considered to be alive because they cannot survive without a cell of a living organism, and they have no internal biochemistry when they exist as a separate particle. Only when they infect a cell will their nucleic acid (RNA or DNA) become active and use the internal biological components of the cell for their own uses. A virus has absolutely no other function other than to reproduce itself: viruses exist to reproduce. Sometimes that reproduction damages cells to the point of causing great harm to the host organism.

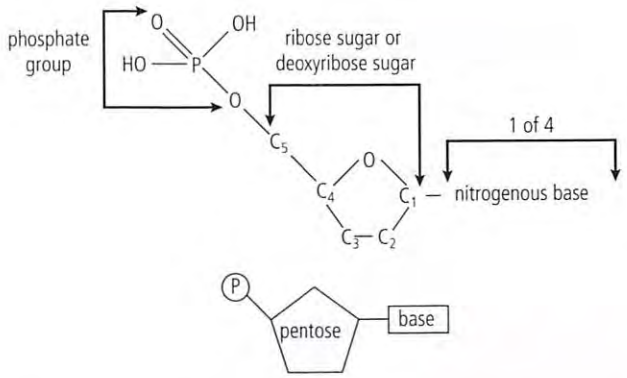
A1.2.2 – The structure of nucleotides

A1.2.2 – Components of a nucleotide
In diagrams of nucleotides use circles, pentagons and rectangles to represent relative positions of phosphates, pentose sugars and bases.



Both DNA and RNA are **polymers** of **nucleotides**. This means that both DNA and RNA have repeating units called nucleotides within the much larger molecule. So, in order to understand the structure of these two molecules important to life, we must first start with the structure of the nucleotides. Individual nucleotides consist of three major parts: one phosphate group, one five-carbon monosaccharide (also called a pentose sugar) and a nitrogenous base. Covalent bonds occur at specific locations in order to produce a functional unit.

It is important to note that in Figure 1 a circle is used to represent a phosphate, a pentagon is used to represent a pentose sugar, and a rectangle is used to represent a nitrogenous base.

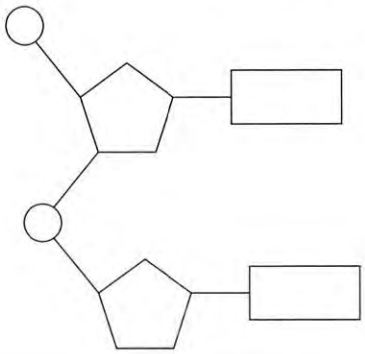


A1.2 Figure 1 Two representations of a single nucleotide are shown in the diagram. The upper drawing shows more detail, although not every atom and bond are shown of the pentose sugar and only a bonding location is shown for a nitrogenous base. The lower drawing shows the level of detail the IB requires you to draw from memory.

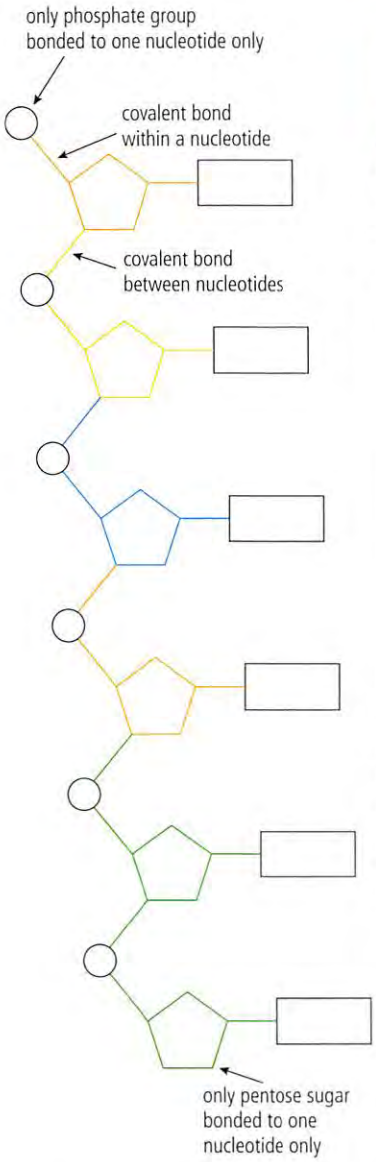
A1.2.3 – Sugar to phosphate "backbone" of DNA and RNA

A1.2.3 – Sugar–phosphate bonding and the sugar–phosphate "backbone" of DNA and RNA

Sugar–phosphate bonding makes a continuous chain of covalently bonded atoms in each strand of DNA or RNA nucleotides, which forms a strong "backbone" in the molecule.



Nucleotides in both DNA and RNA bond together to produce long chains or polymers. In order to form a chain of nucleotides, the pentose sugar of one nucleotide is covalently bonded to the phosphate group of the next nucleotide. This means that there will always be one phosphate group with only one bond to a sugar at one end of the nucleic acid polymer, and a pentose sugar with only one bond to a single phosphate at the other end.



A1.2 Figure 2 Some nucleic acids are formed from a single chain of nucleotides.

Challenge yourself

Examine Figure 1 on the previous page. Notice that the carbons of the pentose sugar are numbered. Now look at Figure 2, showing six nucleotides bonded together as a single-stranded polymer. Answer the following.

1. Within the polymer of six nucleotides, which *sugar* carbons are bonded to phosphate groups? (Do not consider the first nucleotide.)
2. Within a *single* nucleotide, what number carbon is always attached to the phosphate group?
3. Which carbon number is always attached to the nitrogenous base?

Nucleotides bond to one another to form a chain or polymer as a result of **condensation reactions** forming covalent bonds between the sugar of one nucleotide and the phosphate group of the next nucleotide. The fact that covalent bonds hold the chain together is important as covalent bonds are relatively strong (require a great deal of energy to break) and thus a nucleic acid polymer made of nucleotides is quite stable.

A1.2.4 – Nitrogenous bases within nucleic acids

A1.2.4 – Bases in each nucleic acid that form the basis of a code
Students should know the names of the nitrogenous bases.

In total, there are five possible **nitrogenous bases** in RNA and DNA. Four are found within RNA, and four are found in DNA. Only one of the bases differs in the two types of polymers, as shown in Table 1.

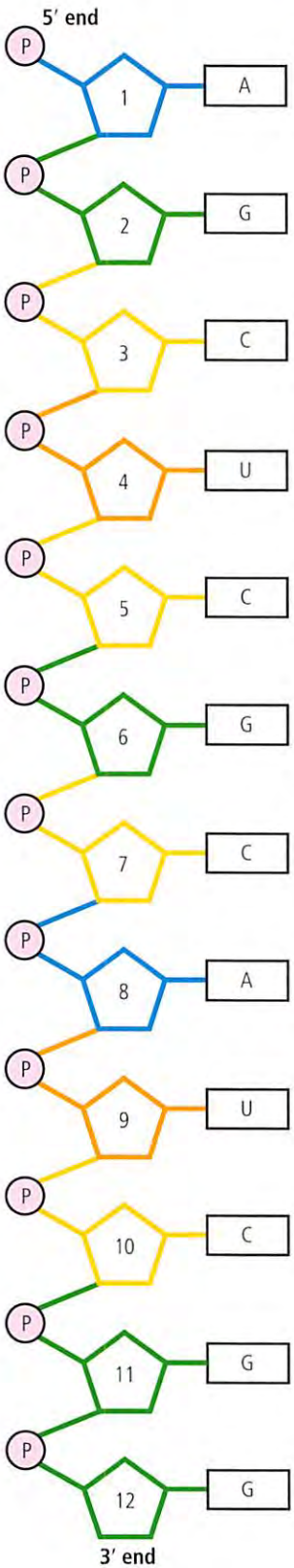
RNA nitrogenous bases	DNA nitrogenous bases
Adenine (A)	Adenine (A)
Uracil (U)	Thymine (T)
Cytosine (C)	Cytosine (C)
Guanine (G)	Guanine (G)

A1.2 Table 1 The five nitrogenous bases found in RNA and DNA

It may look like some of the nucleotides found in RNA and DNA are identical, for example because they both contain the base adenine. However, they are not identical because all the nucleotides found in RNA contain ribose as their pentose sugar, and all the nucleotides in DNA contain deoxyribose. In addition, the base uracil only occurs in RNA, not DNA, and the base thymine only occurs in DNA, not RNA. Thus, there are eight different nucleotides in total. When drawing nucleotides, it is common practice to put the capitalized first letter of the base inside the rectangle, as used by the IB.

Make sure you know the names of the five nitrogenous bases found in RNA and DNA, and do not just rely on the abbreviated form of a capital letter.

The sequence of nitrogenous bases in DNA, later transcribed into RNA, forms the basis of the genetic code.



Challenge yourself

4. Use the geometric symbols required by the IB (see Figure 1) to represent all the possible separate nucleotides of DNA. Once you have sketched the four for DNA, do the same for RNA. To remind yourself of the fundamental pentose sugar difference between RNA and DNA nucleotides, you might want to put the letter "R", for ribose, inside the pentose shape of all RNA nucleotides. Then put "DR", for deoxyribose, inside all of the four DNA nucleotides. Make sure you end up with eight different nucleotides in total, one containing uracil and one containing thymine.

A1.2.5 – The structure of RNA

A1.2.5 – RNA as a polymer formed by condensation of nucleotide monomers
Students should be able to draw and recognize diagrams of the structure of single nucleotides and RNA polymers.

RNA is formed when nucleotides become bonded together in very specific sequences. The nucleotides are joined together by a **condensation reaction** between the pentose sugar of one nucleotide and the phosphate group of the next nucleotide. This reaction releases a water molecule (which is why this is called a "condensation" reaction). If an RNA molecule contains 322 nucleotides, 321 molecules of water would have been produced during its **synthesis**, as it would have required 321 condensation reactions to form.

Challenge yourself

5. How many water molecules would have been produced when the condensation reactions occurred that produced the 12 nucleotide RNA sequence shown in Figure 3?

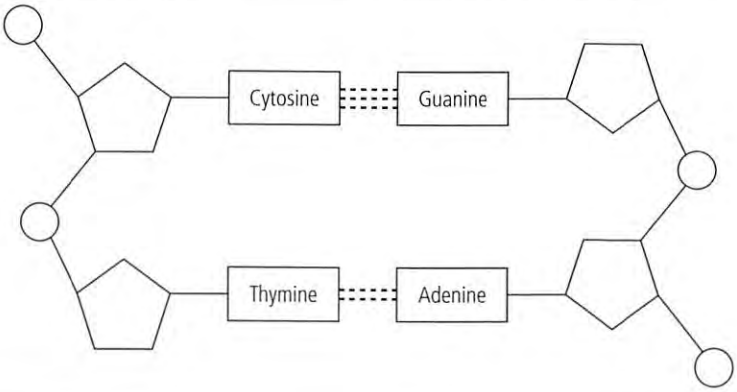
i Even though the RNA depiction in Figure 3 has only 12 nucleotides shown, the actual RNA may have as many as a few thousand nucleotides.

A1.2 Figure 3 Twelve nucleotides bonded to form a very small section of a strand of RNA. The molecule is recognized readily as RNA because of the presence of uracil and because it is a single strand. Each adjoining nucleotide has been drawn in a different colour to emphasize the nucleotide structures. Notice that the chain has an alternating pentose-phosphate backbone, with the nitrogenous bases extending outwards from the backbone.

A1.2.6 – The structure of DNA

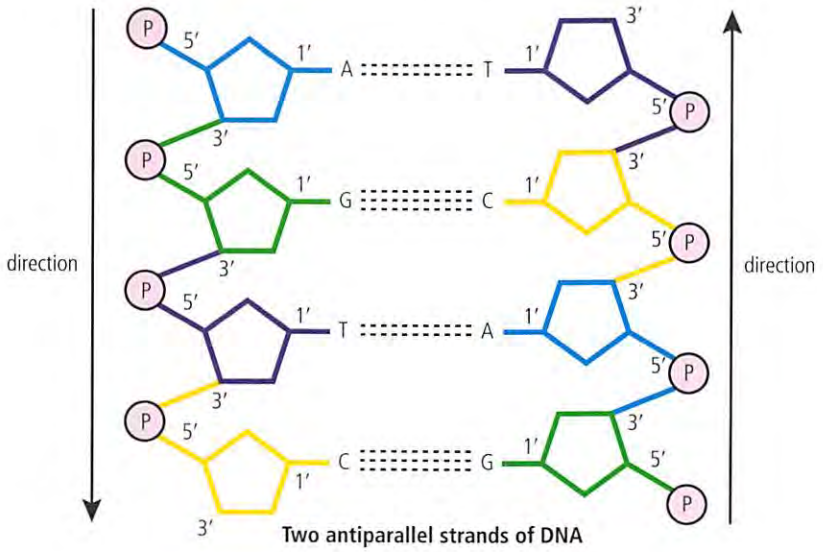
A1.2.6 – DNA as a double helix made of two antiparallel strands of nucleotides with two strands linked by hydrogen bonding between complementary base pairs

In diagrams of DNA structure, students should draw the two strands antiparallel, but are not required to draw the helical shape. Students should show adenine (A) paired with thymine (T), and guanine (G) paired with cytosine (C). Students are not required to memorize the relative lengths of the purine and pyrimidine bases, or the numbers of hydrogen bonds.



RNA is composed of a single chain or strand of nucleotides, while DNA consists of two chains or strands of nucleotides connected to one another by hydrogen bonds. The strands of both DNA and RNA may involve very large numbers of nucleotides. To visualize DNA, imagine the double-stranded molecule as a ladder (see Figure 4). The two sides of the ladder are made up of the phosphate and deoxyribose sugars. The rungs of the ladder (what you step on) are made up of the nitrogenous bases. Because the ladder has two sides, there are two bases making up each rung. The two bases making up one rung are said to be complementary to each other. Notice that the base pairs are always adenine (A) bonded to thymine (T) and cytosine (C) bonded to guanine (G). There are no exceptions to this in DNA, and these base pairings are known as the **complementary base pairs**. Because the two strands are upside down in comparison to each other, but parallel, they are said to be **antiparallel** to each other.

The nitrogenous bases adenine and thymine are always paired with each other in the double-stranded DNA molecule. Likewise, cytosine and guanine are always paired. These pairings are called the complementary base pairs.

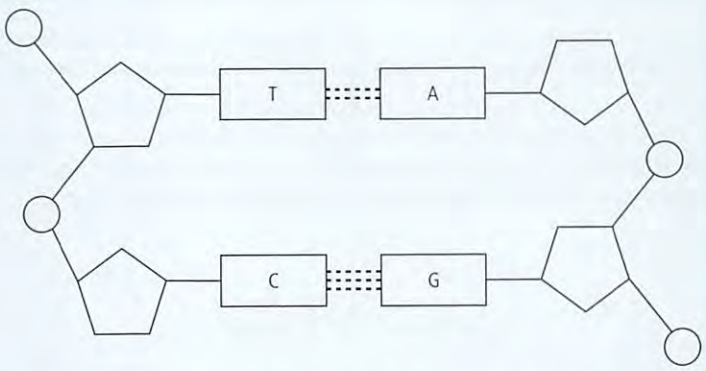


Two antiparallel strands of DNA

A1.2 Figure 4 A small section of a double-stranded DNA molecule showing hydrogen bonds (dotted lines) between complementary base pairs. This type of representation of DNA is known as a "ladder diagram" and does not attempt to show the helical shape of the molecule.

Always attempt to view DNA and RNA molecules as chains of nucleotides. Identify the first nucleotide with its own phosphate, sugar and nitrogenous base and then visually move to the next, and so on. In Figure 4 you would visually start in the upper left corner for the left strand, and you would start in the lower right corner for the right strand.

Challenge yourself



6. On your own paper and using the figure above as a guide, sketch and label the geometric shapes as shown to represent this four-nucleotide section of DNA.
7. Add four more nucleotides to each side by adding to the bottom of your sketch so that you end up with a 12-nucleotide section of antiparallel DNA. Remember to use complementary base pairs, although you can choose the base sequence.
8. Circle two *complete* nucleotides of your *added* nucleotides, one on each side, but do not circle any of the nucleotides in the corners of the figure. Check to make sure that your circles include one phosphate group, one deoxyribose sugar and one nitrogenous base, and that there are no uncircled nucleotides that are incomplete.

A1.2.7 – Distinguishing between DNA and RNA

A1.2.7 – **Differences between DNA and RNA**
Include the number of strands present, the types of nitrogenous bases and the type of pentose sugar.
Students should be able to sketch the difference between ribose and deoxyribose. Students should be familiar with examples of nucleic acids.

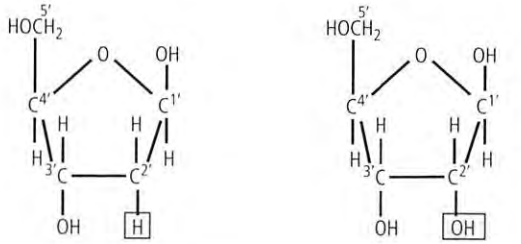
DNA and RNA are both linear polymers, consisting of sugars, phosphates and bases, but there are some important differences between the two molecules. Table 2 summarizes these differences.

DNA	RNA
Double-stranded molecule	Single-stranded molecule
All nucleotides contain deoxyribose sugar	All nucleotides contain ribose sugar
Thymine is one of the four nitrogenous bases	Uracil is one of the four nitrogenous bases
Shaped into a double helix	Variety of shapes depending on type of RNA
Acts as the permanent genetic code of a cell/organism	Does not contain a permanent genetic code, except in RNA viruses

▲ **A1.2 Table 2** A comparison of DNA and RNA molecules

Distinguishing between deoxyribose and ribose

Ribose has a molecular formula of $C_5H_{10}O_5$, whereas deoxyribose has a formula of $C_5H_{10}O_4$. Notice that the only difference in the molecular (chemical) formulas is that ribose has one more oxygen compared to deoxyribose. A side-by-side comparison shows where the difference occurs (see Figure 5). In organic chemistry an –OH group bonded to a carbon is called an **alcohol** or **hydroxyl group**. If you remove the oxygen from the hydroxyl group, it simply leaves a hydrogen. This may not look like much, but it is the common difference in all nucleotides of RNA versus DNA.



A1.2 Figure 5 A molecular sketch showing the deoxyribose sugar of DNA compared to the ribose sugar found in RNA molecules. Notice the difference in the lower right corners of the two molecules. Ribose has one more oxygen in its structure compared to deoxyribose.

SKILLS

Practise sketching each of the two molecules shown in Figure 5. Learn the pattern that is common to both molecules and then modify for the single difference between deoxyribose and ribose.

i

The single "missing" oxygen in the pentose sugar of DNA leads to the name *deoxy*ribose within the full name for DNA (deoxyribose nucleic acid). The full name of RNA is ribonucleic acid.

Specific examples of nucleic acids

All living organisms use DNA as their long-term hereditary storage molecule. DNA stores genetic information as genes, but for that information to become useful to a cell there must be other nucleic acids at work. Here are four of the other nucleic acids as examples.

- **Messenger RNA (mRNA)** – This is an RNA molecule that is synthesized from an area of DNA called a **gene**. In a cell with a nucleus, the mRNA then leaves the nucleus and represents the genetic information necessary to make a protein. This is where it gets its name "messenger" RNA.
- **Transfer RNA (tRNA)** – Special genes of DNA code for tRNA molecules. When a specific protein is synthesized, specific amino acids must be added to the amino acid chain in a specific order. The function of tRNA is to transfer the correct amino acid into a growing chain of amino acids. This is the reason for its name "transfer" RNA.
- **Ribosomal RNA (rRNA)** – Again, special genes of DNA code for rRNA molecules. Along with some previously synthesized proteins, rRNA is used to create an organelle in cells called ribosomes. Cells typically have many thousands of ribosomes, and they are the cellular location where proteins are synthesized.
- **Adenosine triphosphate (ATP)** – This is a single-nucleotide nucleic acid. There are many other single-nucleotide nucleic acids in cells, but we are going to use this one as an example. ATP is used in cells as a type of chemical energy. When a muscle contracts, many ATP molecules are used as an energy source for the movement. The ultimate purpose of cellular respiration is to convert the energy contained within food molecules into the energy of ATP.

!

Do not concern yourself at this point with the details of these examples of nucleic acid molecules, beyond what is summarized in this section. The function of each of these molecules is explained in much greater detail in other chapters.

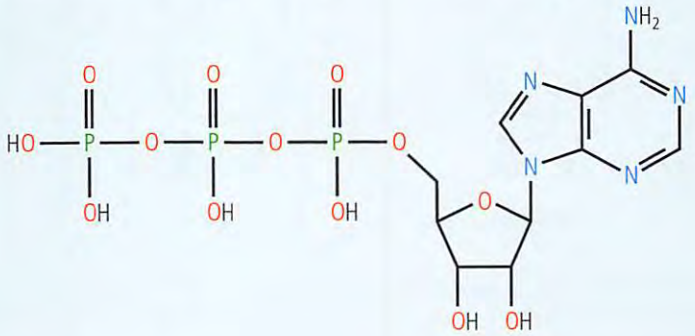
Challenge yourself

The figure below shows a molecular diagram of an ATP molecule. You do not need to memorize it, but based on what you have read earlier in this chapter you should be able to look at the diagram and answer the following questions.

9. Why is this molecule called a "triphosphate"?

10. Is the pentose sugar in this molecule ribose or deoxyribose?

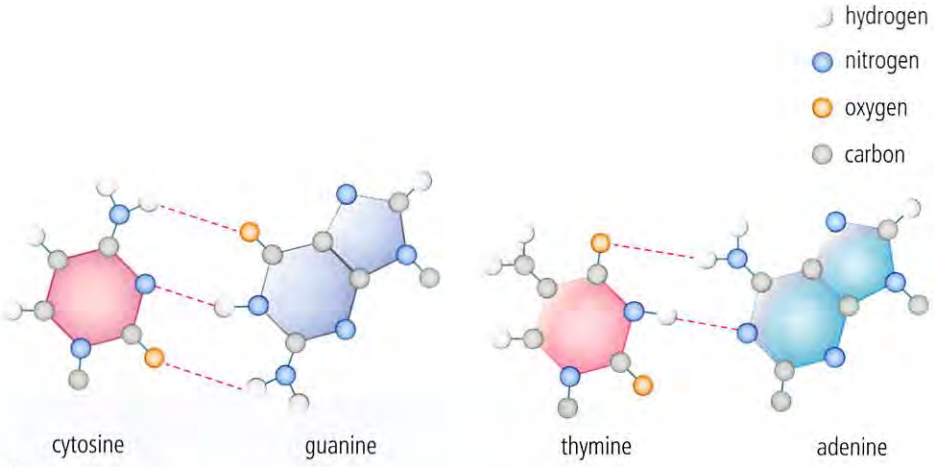
11. The "adenosine" portion of the molecule's name comes from the nitrogenous base bonded to the pentose sugar. What is that nitrogenous base?



A1.2.8 – The importance of complementary base pairing

A1.2.8 – Role of complementary base pairing in allowing genetic information to be replicated and expressed
Students should understand that complementarity is based on hydrogen bonding.

As you recall, adenine and thymine are complementary to each other in DNA, and cytosine and guanine are complementary as well. This complementarity is based on hydrogen bonding. Adenine and thymine only form hydrogen bonds with each other; adenine does not form hydrogen bonds with any other DNA nucleotide. The same is true for cytosine and guanine.



▲ Hydrogen bonding (shown in dotted red lines) between the complementary base pairs within DNA. It is this hydrogen bonding that holds the two antiparallel strands together and ultimately results in the double helix shape.

Complementary base pairing is important in DNA replication. Imagine that an area of DNA has been unzipped (opened up into two single strands). If free-floating individual nucleotides in solution begin pairing with the unmatched nucleotides, an exact copy of the original molecule can be made. In fact, if both sides of the original DNA are used as a template, then two molecules of DNA can be synthesized, each a duplicate of the original. In a simplified form, this is how DNA replication occurs.

A1.2.9 – Storage of genetic information

A1.2.9 – Diversity of possible DNA base sequences and the limitless capacity of DNA for storing information
Explain that diversity by any length of DNA molecule and any base sequence is possible. Emphasize the enormous capacity of DNA for storing data with great economy.

DNA stores genetic information in its sequence of nitrogenous bases. Every three bases represents a meaningful piece of information called a triplet or, more specifically, a **triplet codon**. Many triplets within DNA code for one of the 20 amino acids. There are four different DNA nucleotides that can be arranged as sequenced triplets. So, what are the odds of DNA containing any one triplet in any one gene location? Consider the odds of having G–G–G in one triplet area of DNA. If it was by random chance (although it is not) the odds would be:

$$\frac{1}{4} \times \frac{1}{4} \times \frac{1}{4} = \frac{1}{64}$$

Why? Because there is a one in four chance of the nitrogenous base being guanine, and it occurs in our example three times.

This computation also means that there are 64 combinations of nucleotides within the triplet code system. All of those 64 combinations are used in the genetic code for some purpose, most of them coding for amino acids.

Researchers are working on ways to store data (text files, photos, books, maps) within artificially created DNA molecules. DNA stores information using the very efficient code of four nitrogenous bases, compared to the less efficient 0 and 1 binary code used by computers.

Think about all the ways that the four nitrogenous bases of DNA can be grouped. If DNA was a short molecule (say around 1,000 nucleotides), the number of groupings would be large, but still not unlimited. Now consider that the length of DNA (the number of nucleotides in one strand) is only limited by the amount that will fit efficiently into a cell. The shortest DNA molecule in the human genome is about 50 million base pairs, and the longest about 260 million base pairs.

As you can see, the likelihood that two DNA molecules are identical as a result of random chance approaches zero. DNA can contain a nearly limitless amount of genetic information.

How can polymerization result in emergent properties?

A1.2.10 – Genetic uniqueness

A1.2.10 – Conservation of the genetic code across all life forms as evidence of universal common ancestry
Students are not required to memorize any specific examples.

Identical twins develop when a single fertilized egg or early embryo splits into two portions. Each grows to become a separate person and shares exactly the same DNA sequences.

Imagine a section of DNA that contains the triplet code C–G–A. If that triplet code is used to synthesize a protein, the amino acid that will be produced will be alanine. If the triplet code is A–G–A, the amino acid is serine. A chart listing the triplet codes can provide this information.

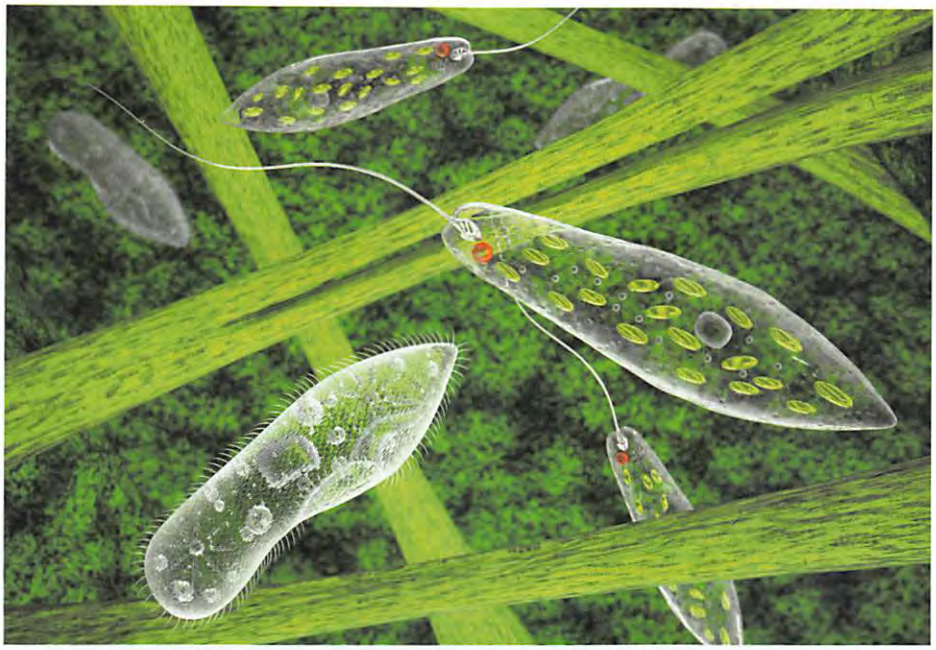
It does not matter whether the organism is a species of fungus, an oak tree, or a human being. All living organisms use the same genetic code. The genetic code is therefore said to be universal.

So why are organisms different from each other? The answer to that is the DNA base sequences are different even though the code to read the sequences is the same. Your best friend, although not directly related to you, is related to you by evolution. The two of you share more than 99% of the same gene sequences. If it was 100%, you would not be the unique and different people you are.

A conserved genetic code

What makes RNA more likely to have been the first genetic material, rather than DNA?

Why has the genetic code remained unchanged? The answer to this question lies in the process of evolution. The evolution of living organisms has been occurring for over 3.5 billion years. If you could go back in time far enough you would probably not see any organisms that you recognize today, although some of the organisms you would see will be the ancestors of today's organisms. If you were to keep moving back through time, the organisms would become even less familiar, and eventually they would be nothing more than single-celled organisms living in water.



Bacteria and protists were some of the first organisms on Earth to evolve, and thus hold the origin of the genetic code used by all organisms today. Humans and other life forms still have genes in common with these evolutionary pioneers.

These single-celled organisms are the ancestors of all life on Earth today. This is also postulated to be the time period in which the biochemistry of DNA and RNA evolved. All life forms from that point on used DNA to store their genetic information, and RNA to transfer that information to the order of amino acids in their proteins. Evolution changes the DNA sequences slowly, but it always has continued to use the same mechanisms of genetic coding.

Nature of Science

The theory of evolution by natural selection as proposed by Charles Darwin and independently by Alfred Wallace was based primarily on their observations of physical traits. It appeared to them that organisms developed adaptations to fit different ecological niches in the area that they lived in. In 1859, when Darwin published his famous book *On the Origin of Species*, there was absolutely no knowledge of DNA or the molecular basis of heredity and evolution. Scientific ideas that originate in one form can be corroborated by later scientific work if the ideas are sound. Today there is a mountain of evidence supporting evolutionary principles, including a vast amount of information from **molecular genetics**.

Guiding Question revisited

How does the structure of nucleic acids allow hereditary information to be stored?

In this chapter we have described how RNA and DNA are structured:

- each is composed of subunits called nucleotides
- nucleotides exist in eight types, four types in RNA and four types in DNA
- each nucleotide contains one of five possible nitrogenous base, adenine, thymine, cytosine, guanine and uracil

- in DNA, the two strands are held together by complementary base pairing between the nitrogenous bases
- the sequence of the nucleotides in sections of DNA called genes allows long-term storage of the genetic code
- RNA molecules are complementary copies of genes of DNA transcribed by using RNA nucleotides.

Guiding Question revisited

How does the structure of DNA facilitate accurate replication?

In this chapter we have described how:

- DNA exists as a double-stranded molecule
- DNA makes copies of itself
- this unwinding allows the nitrogenous bases to make new complementary pairings using the exposed nitrogenous bases as a template
- the pairings are adenine with thymine, and cytosine with guanine
- two DNA molecules are created from one during DNA replication, although neither is completely "new".

Exercises

Q1. State how many nucleotide types exist within the structures of DNA and RNA.

Q2. Suggest a reason why researchers often give DNA information:

(a) as the sequence of nitrogenous bases without indicating the presence of the phosphate group and sugar component of each nucleotide (for example 5′ATTCCGTGTACGT3′)

(b) from one strand of DNA only.

Q3. You are visualizing a single sequence of nitrogenous bases and you see multiple uracil bases. What does that tell you about the molecule?

Q4. Which of these is not a nucleic acid?

A DNA **B** ATP **C** PCR **D** RNA

Q5. A measurement of a sample of DNA showed that 22% of the nitrogenous bases were cytosine. Calculate the expected percentage of the following nitrogenous bases:

(a) guanine

(b) adenine

(c) thymine.

A1 Practice questions

1. Describe the importance of water to living organisms.

(Total 5 marks)

2. Draw a labelled diagram showing the structure of three water molecules and how they interact.

(Total 4 marks)

3. Draw a labelled diagram of a section of DNA showing four nucleotides.

(Total 5 marks)

4. Distinguish between the structures of DNA and RNA.

(Total 3 marks)

5. Where do hydrogen bonds form?

   A Between the slight negative charge of hydrogen and the slight positive charge of oxygen within a water molecule.

   B Between the slight positive charge of hydrogen and the slight negative charge of oxygen within a water molecule.

   C Between the slight positive charge of hydrogen and the slight negative charge of oxygen in different water molecules.

   D Between the slight negative charge of hydrogen and the slight positive charge of oxygen in different water molecules.

(Total 1 mark)

THEME

A Unity and diversity

2 Cells

Early Earth provided an environment that was extremely inhospitable to life as we know it today. Yet, over long periods of time, conditions changed allowing the building blocks of life to form. Once the building blocks were in place, a slow but steady development occurred. Ultimately, the complexity of life has led to the estimated 8.7 million different species that exist today.

A2.1 is not included as it is for HL students only.

A2.2 Cell structure

Guiding Questions

What are the features common to all cells and the features that differ?

How is microscopy used to investigate cell structure?

In the 1660s, Antonie van Leeuwenhoek became interested in the early microscopes being developed by Robert Hooke. The Dutch businessman and scientist used mostly blown-glass lenses to produce his own microscopes, which opened a completely new world to all. His powers of observation led to the first recorded descriptions of bacteria and protozoa. From van Leeuwenhoek's work the science of microbiology took form.

Countless improvements in microscopy since these simple beginnings have led to an understanding of the features common to all cells. We have also learned of the tremendous diversity that exists not only in cells but in all life.

A2.2.1 – Cells and the functions of life

A2.2.1 – Cells as the basic structural unit of all living organisms
NOS: Students should be aware that deductive reason can be used to generate predictions from theories. Based on cell theory, a newly discovered organism can be predicted to consist of one or more cells.

Whether organisms are extremely small or extremely large, understanding their smallest functional units is imperative. These units are known as cells. Organisms range in size from a single cell upwards to trillions of cells. To better understand all the organisms around us we must study their cells.

Cytology is the branch of biology that studies all facets of the cell. As our understanding of the cell has increased, so has our ability to understand all forms of life and diseases that occur on planet Earth. This area of research is extremely active in laboratories all over the world.

The cell theory states:

- all organisms are composed of one or more cells
- cells are the smallest units of life
- all cells come from pre-existing cells.

What are the features of a compelling theory?

Nature of Science

Inductive reasoning utilizes specific observations to arrive at broader generalizations. Deductive reasoning works in the opposite direction. It allows you to make an inference using widely accepted facts or premises. Using deductive reasoning, a newly discovered organism can be predicted to carry out the functions of life and demonstrate the principles of cell theory.

A2.2.2 – Cells and the microscope

A2.2.2 – Microscopy skills

Application of skills: Students should have experience of making temporary mounts of cells and tissues, staining, measuring sizes using an eyepiece graticule, focusing with coarse and fine adjustments, calculating actual size and magnification, producing a scale bar and taking photographs.

NOS: Students should appreciate that measurement using instruments is a form of quantitative observation.

Cells are made up of many different subunits. These subunits are often of a particular size, but most are microscopically small.

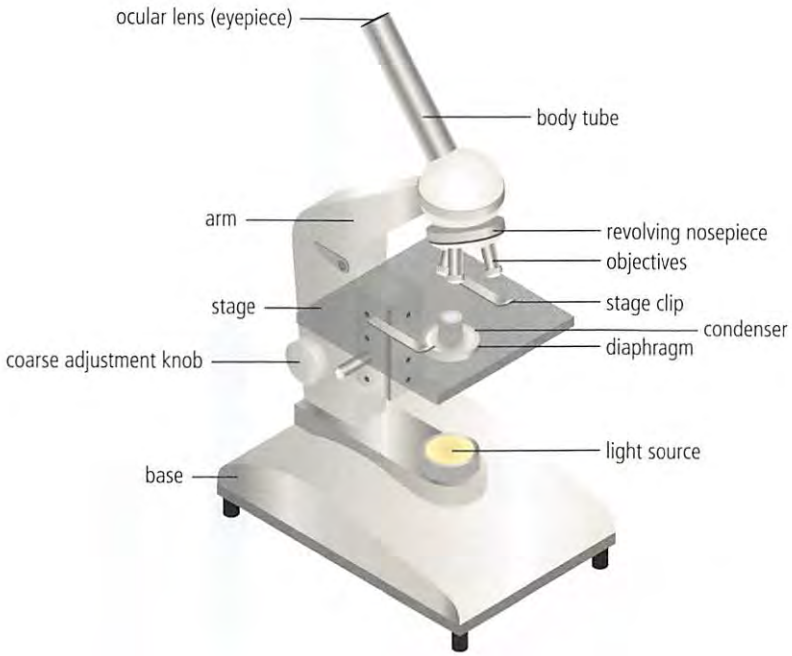
Unit	Equivalent measurement
1 metre (m)	100 cm = 1,000 mm
1 centimetre (cm)	10^{-2} m (0.01 m)
1 millimetre (mm)	10^{-3} m (0.001 m)
1 micrometre (μm)	10^{-6} m (0.000001 m)
1 nanometre (nm)	10^{-9} m (0.000000001 m)

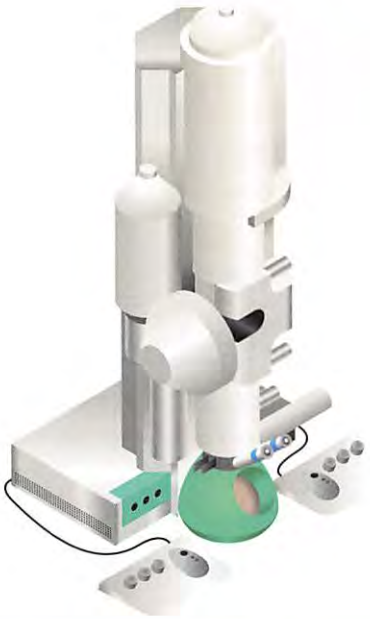
▲ Commonly used microscope metric equivalents

Microscopes with a high **magnification** and **resolution** are needed to observe cells and especially their subunits. Magnification is the increase in an object's image size compared to its actual size. Pictures or drawings of an image from a microscope include the number of times larger than the actual object they are, for example 500× or 100,000×.

Resolution refers to the minimal distance between two points or objects at which they can still be distinguished as two. As the resolution of a microscope increases, the greater the detail that microscope will reveal. Some like to explain resolution in terms of clarity, with greater resolution providing greater clarity.

Light microscopes use light, passing through living or dead specimens, to form an image. Stains may be used to improve the visibility of structures. **Electron microscopes (EMs)** provide the greatest magnification (over 100,000×) and resolution. These use electrons passing through a specimen to form an image.



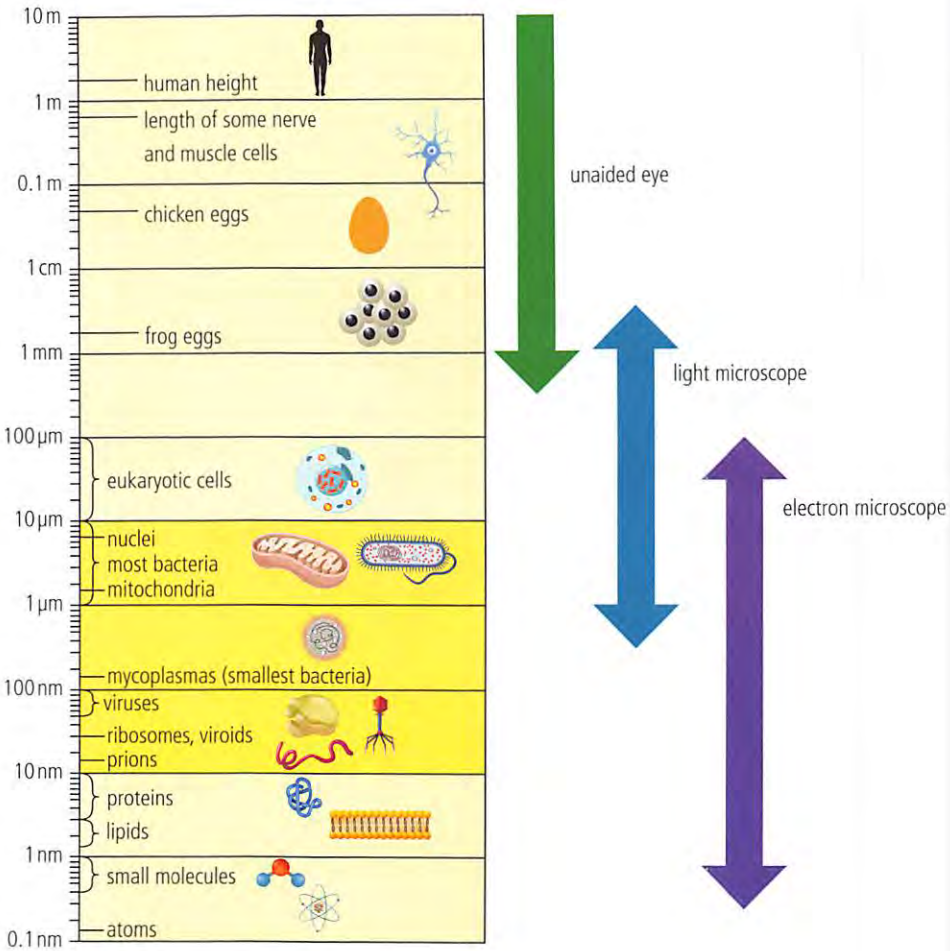


A light microscope (above) and an electron microscope (below).

Light microscope	Electron microscope
Inexpensive to purchase and operate	Expensive to purchase and operate
Simple and easy specimen preparation	Complex and lengthy specimen preparation
Magnifies up to 2,000×	Magnifies over 500,000×
Specimens may be living or dead	Specimens are dead, and must be fixed in a plastic material

▲ A comparison of the light microscope and the electron microscope

Most cells can be up to 100 micrometres (100 µm) in size. Organelles are up to 10 µm in size. Bacteria are between 1 and 10 µm in size. Viruses are up to 100 nanometres (nm) in size. Cell membranes are 10 nm thick, while molecules are about 1 nm in size. All these structures are three-dimensional.



A representation of what can be used to visualize various structures important in biology.

Cells and their subunits are so small they are hard to visualize, so it is important to appreciate relative sizes. Cells are relatively large, and then in decreasing order of size are:

- organelles
- bacteria (some bacteria cells are as large as organelles)
- viruses
- membranes
- molecules.

If you want to calculate the actual size of a specimen seen with a microscope, you need to know the diameter of the microscope's **field of vision**, also called the **field of view**. The field of vision is the total area visible when looking through a microscope's **ocular** or eyepiece, and the diameter can be calculated using special **micrometers**. There are two general types of micrometers: ocular and stage. The **ocular micrometer**, also called a **graticule**, is located in the eyepiece and is engraved with equal units. It is important to note that the units on this micrometer are arbitrary. They are calibrated using a **stage micrometer**. This calibration is often done using a simple ruler or a special slide with defined units, usually millimetres. By comparing the units of the graticule to the known unit size of the stage micrometer, you can determine the size

of the image being examined. The ocular micrometer has to be calibrated in this way with each objective power of the microscope. The size of the specimen can then be calculated.

A simple formula can be used to calculate the magnification being used:

$$\text{magnification} = \frac{\text{measured size of image}}{\text{actual size of specimen}}$$

Scale bars are often used with a micrograph or drawing so that the actual size can be determined. Scale bars and magnification will be addressed in more detail in a later practical activity.

Worked example

The length of an image you are looking at is 50 mm. If the actual length of the subject of the image is 5 µm, what is the magnification of the image?

Solution

Magnification = 50 mm/5 µm = 50,000 µm/5 µm = 10,000×

Or

Magnification = 50 mm/5 µm = 50×10^{-3} m/1×10^{-6} m = 10,000×

SKILLS

Use of a light microscope to investigate cells and cell structure sizes. Full details of how to carry out this activity with a worksheet are available in the eBook.

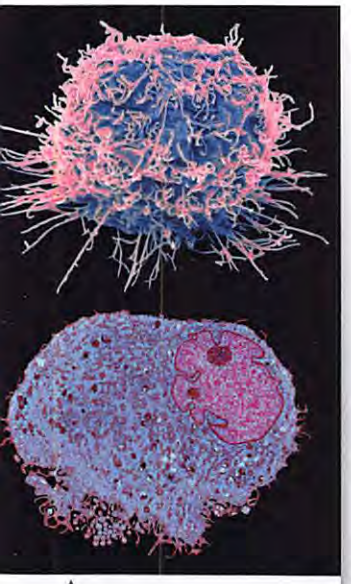
Nature of Science

Scientists need to accumulate data when conducting experiments using scientific methods. Two types of data can be collected. Qualitative data is non-numerical but descriptive. It includes attributes such as colour, presence of a structure or feature (or not) or sex. Quantitative data involves numerical values collected by a specific type of instrument. Examples of quantitative data are mass measured by a laboratory balance or length measured by a ruler. These two types of data, when collected properly, allow meaningful conclusions to be made.

A2.2.3 – Advanced microscopy

A2.2.3 – Developments in microscopy
Include the advantages of electron microscopy, freeze fracture, cryogenic electron microscopy, and the use of fluorescent stains and immunofluorescence in light microscopy.

The microscope has undergone tremendous advancement since the one used by Robert Hooke in 1665. Early microscopes were pivotal in the development of the cell theory, even though they were extremely simple by today's standards. Scientists have also perfected many new techniques in the preparation of materials for study involving the microscope. In this section we will examine some of these developments and techniques.



The top image of a leukaemia cell is from a scanning electron microscope (SEM). The bottom image is of the same cell but from a transmission electron microscope (TEM).

One significant advancement in microscopy was the development of the electron microscope (EM). The EM utilizes a beam of electrons rather than a beam of light, which the light microscope uses. Electrons have a much shorter wavelength than light. The benefits of the shorter wavelength include a 1,000 times greater resolving power than the light microscope, and the ability to magnify objects over 500,000× compared to the maximum magnification of 2,000× for a light microscope.

There are two general types of EMs – the **scanning electron microscope (SEM)** and **transmission electron microscope (TEM)**. The SEM uses a beam of electrons to scan the surface of a specimen. The TEM aims a beam of electrons through a very thin section of a specimen, allowing its inner structure to be viewed. Both SEM and TEM images provide essential information in cytology investigations.

Techniques employed when working with an EM include **freeze fracture** and **cryogenic electron microscopy**. Freeze fracture is a process of preparing a sample for observation with an EM. It involves the rapid freezing of a biological specimen followed by physically breaking the specimen apart (fracturing). This technique reveals a plane through the sample that can then be examined. Our understanding of the cell membrane has been greatly enhanced using this technique.

Cryogenic electron microscopy is a recent advancement in EM that has furthered our knowledge of structural biology. It enables an image to be formed using computer enhancement that shows the three-dimensional framework of proteins involved with the function of a cell. It utilizes low temperatures to freeze specimens in ice. Many advances in our understanding of virus composition and structure, cell membrane components and their arrangement, cellular protein synthesis, and even hereditary expression and regulation, are the result of using this technique. New applications of cryogenic electron microscopy are being developed at an amazing pace with enlightening results.

It is obvious that the EM offers tremendous advantages over the light microscope in the study of cells and their structures. However, it is important to note that EMs are expensive, require extensive training to operate, and involve non-living specimens embedded in some sort of matrix such as plastic. Often, structural features called **artifacts** are seen in the pictures produced by an EM. These artifacts do not actually exist in the cell but are produced during the preparation of the samples for an EM.

Both fluorescent staining and immunofluorescence have been extensively used in the study of severe acute respiratory syndrome coronavirus 2 (SARS-CoV-2) and related viruses. They have provided valuable information about the life cycle of the virus as it attacks living cells.

When living samples are to be studied, the light microscope must be used. Two preparation techniques developed recently for the study of cells using light microscopy involve the use of **fluorescent stains** and **immunofluorescence**. Fluorescent stains are substances or dyes that combine with specific cellular components. When these living samples are then irradiated with ultraviolet or violet-blue light, the parts that accepted the dye will fluoresce. When fluorescence occurs, assorted colours are produced, allowing more detailed visibility. Immunofluorescence also allows greater visibility of living tissue. Immunofluorescence involves antibodies that have dyes already combined with them. Specific antibodies combined with unique coloured dyes recognize and combine with target molecules. This allows the target, usually a protein, to be detected. This technique is often used to detect viral proteins that have infected cells.

Fluorescence-based methods have recently been developed to target RNA. We are now able to visualize single RNA molecules within single cells and viruses.

The light microscope has gone through many developments to improve its ability to produce images of living cells and their internal structures. One area of development has involved the part of the microscope called the **condenser**. The condenser is located between the stage and the light source. It possesses a lens that directs light rays from the light source through the specimen. From the specimen, the light rays pass through the objective lens to the ocular lens, where the image is viewed by the researcher. By changing the capabilities of the condenser, we now have some microscope types with unique and valuable features.

Type of microscope	Feature
Brightfield	Visible light is used; the specimen is viewed against a light background; it is the most common and easy to use light microscope
Darkfield	A special opaque lens is used in the condenser, that blocks direct light from entering the specimen; the specimen appears light against a dark background
Phase-contrast	A special condenser with a circular diaphragm and a modified objective lens are used to reveal detailed images of specimens without staining

▲ Types of light microscope

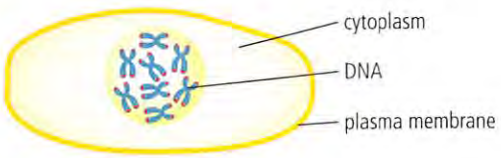
Each advance of the microscope, whether light or electron, leads to a corresponding increase in our understanding of the cell's structures and functions.

A2.2.4 – Structures common to all cells

A2.2.4 – Structures common to cells in all living organisms
Typical cells have DNA as genetic material and a cytoplasm composed mainly of water, which is enclosed by a plasma membrane composed of lipids. Students should understand the reasons for these structures.

As all organisms are composed of one or more cells and demonstrate common functions, all cells possess certain common structures. These include:

- DNA, as their genetic material
- a cytoplasm, composed of mainly water
- a plasma membrane, composed of lipids that surrounds the cytoplasm.



◀ All cells possess three common structures: DNA, cytoplasm and a plasma membrane. Cells usually demonstrate greater complexity than this, with many more structures. However, greater complexity is not required for a cell to carry out the functions of life.

For new cells to be formed from pre-existing cells, there must be a means to store and transfer information. DNA fulfils this role because of its ability to form large molecules from small building blocks called **nucleotides**. Four different nucleotides make up DNA. It is the specific sequence of these unique nucleotides, and their ability to combine to form huge chains, that results in the production of the exact proteins

essential for passing on distinctive characteristics from cell to cell and even from organism to organism. DNA also controls the production of enzymes within an organism, which serve a controlling role in chemical reactions.

A matrix is an unstructured semi-fluid region within a boundary. The cytosol is a matrix with a gel-like consistency in which other cell structures may be suspended.

The cytoplasm is found within the boundary of a cell. This region of a cell consists of a matrix composed mainly of water called **cytosol.** Cytosol contains all the ingredients necessary for a cell to conduct its day-to-day activities. These ingredients include many different carbon compounds, as well as **ions,** which are atoms with a charge, and other inorganic compounds. The cytoplasm of a cell is the location where most chemical reactions take place.

The plasma membrane encloses the cell and protects its contents from the surrounding environment. Its major component is two layers of lipids combined as a **bilayer**. Proteins and the element phosphorus are also associated with this bilayer. The membrane controls interactions between a cell's contents and the exterior. Materials needed by the cell are transported into the cell through the membrane, while waste material is transported out of the cell. Membrane proteins provide identity properties to the cell, which is especially important in multicellular organisms. The membrane proteins in multicellular organisms also engage in communication and transport between cells.

What explains the use of certain molecular building blocks in all living cells?

Two types of organism, bacteria (members of the domain Eubacteria) and archaea (members of the domain Archaea), are made up of prokaryotic cells and are called prokaryotes. Most of these organisms do not cause disease and are not pathogenic (disease-causing). They are an extremely diverse group occupying air, water and soil environments. Prokaryotes are a very successful group of organisms.

A2.2.5 – The prokaryote cell

A2.2.5 – Prokaryote cell structure
Include these cell components: cell wall, plasma membrane, cytoplasm, naked DNA in a loop and 70S ribosomes. The type of prokaryotic cell structure required is that of Gram-positive eubacteria such as *Bacillus* and *Staphylococcus*. Students should appreciate that prokaryote cell structure varies. However, students are not required to know details of the variations such as the lack of cell walls in phytoplasmas and mycoplasmas.

What is a prokaryotic cell?

After extensive studies of cells, it has become apparent that all cells use some common molecular mechanisms. There are huge differences between forms of life, but cells are the basic unit and different cells have many characteristics in common. Cells are often divided into groups based on major characteristics. One such division separates cells into **prokaryotic** and **eukaryotic cells**. Prokaryotic cells are much smaller and simpler than eukaryotic cells. In fact, most prokaryotic cells are less than 1 μm in diameter. As bacteria are prokaryotic cells, you can see that such cells play a large role in the world today.

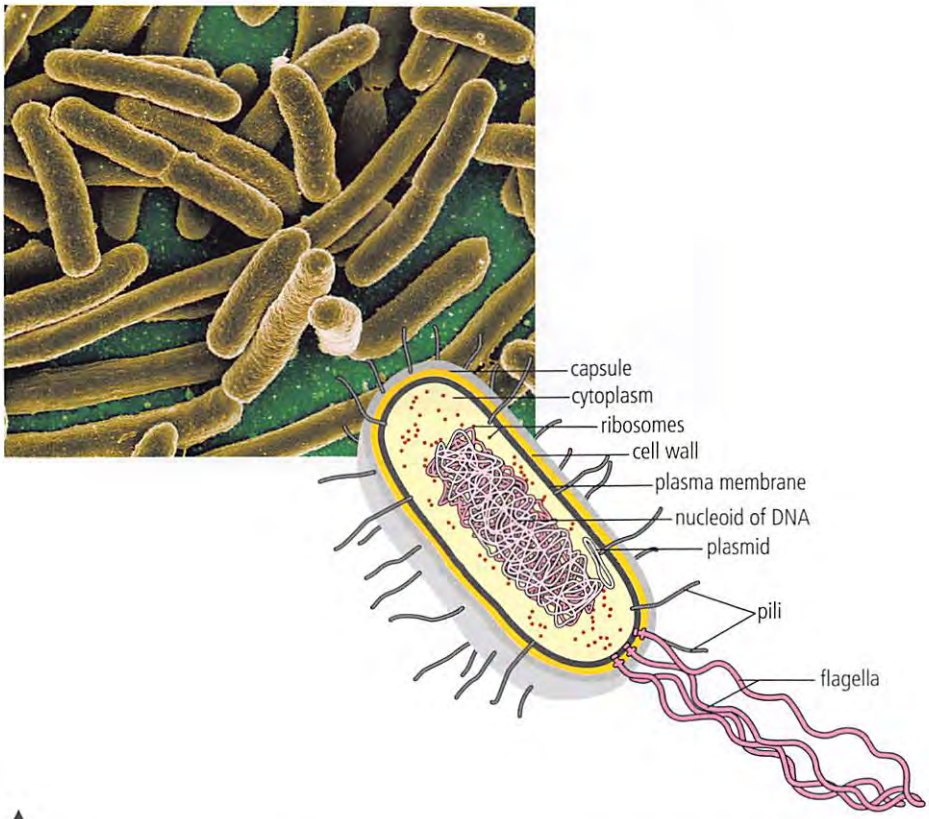
A domain is the highest classification rank of all organisms. Three domains of life are recognized. They are the Eubacteria, the Archaea, and the Eukarya.

Prokaryotic organisms include bacteria and archaea. Bacteria and archaea appear to have followed different branches to eukaryotes (in the domain Eukarya) in the evolution of life. Prokaryotes are mostly small and unicellular. There are thousands of distinct types differentiated by many factors, including nutritional requirements, sources of energy, chemical composition and morphology (shape).

Features of prokaryotic cells

Study the diagram of a prokaryotic cell (Figure 1) and make sure you can identify:

- the cell wall
- the plasma membrane
- flagella
- pili
- ribosomes
- the nucleoid (a region containing free DNA).



A2.2 Figure 1 A false-colour scanning electron micrograph (SEM) of the bacterium *Escherichia coli*. Below it is a drawing of a prokaryotic cell.

Cell wall and plasma membrane

The prokaryotic cell wall protects and maintains the shape of the cell. It also keeps the bacterial cell from rupturing when water pressure is greater inside the cell than outside. In most prokaryotic cells this wall is composed of a carbohydrate–protein complex called **peptidoglycan**. Some bacteria have an additional layer of a type of polysaccharide outside the cell wall. This layer, called the **capsule**, makes it possible for some bacteria to adhere to structures such as teeth, skin and food.

The plasma membrane is found just inside the cell wall and is similar in composition to the membranes of eukaryotic cells. To a considerable extent, the plasma membrane controls the movement of materials into and out of the cell, and it plays a role in binary fission of the prokaryotic cell.

Becoming familiar with common prefixes, suffixes and word roots will help you understand biological terms. For example, the word prokaryotic is from the Greek word "pro", which means "before", and "karyon" which means "kernel", referring to the nucleus.

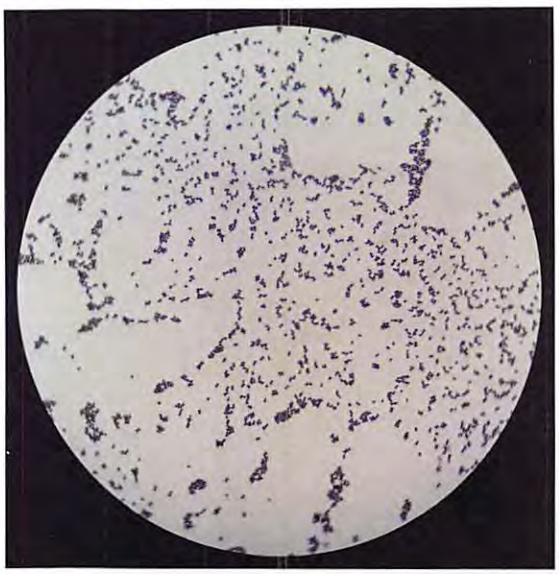
Antibiotics used to treat infections caused by bacteria can attack two areas of the bacterial cell. They may interfere with the proper development of the cell wall, resulting in a weakened outer protective wall. They may also act on ribosomes, to prevent the synthesis of the cell's required proteins. These same antibiotics do not act on eukaryote cell walls or ribosomes, so they can be used to successfully treat bacterially caused infections without harming the cells of the affected eukaryotic organism.

Gram staining is important in medicine as it provides evidence not only of a bacterial infection but also of the type of bacteria causing the infection. This helps in determining a proper treatment plan.

One major way to classify bacteria is by their ability to retain a dye called crystal violet. Bacteria that are "Gram-positive" have cell walls that, when exposed to crystal violet, take on a violet or blue appearance. "Gram-negative" bacteria do not retain this dye and do not appear violet or blue when examined with a microscope. *Bacillus* and *Staphylococcus* are examples of Gram-positive bacteria.

Follow the Gram-staining procedure accessed from this page of your eBook.

SKILLS



▲ A transmission electron micrograph (TEM) of *Bacillus subtilis* bacteria. Notice the violet-blue colour indicating that this bacterium is Gram-positive. Had this bacterium been Gram-negative, there would be a pink colour present because of the addition of Gram's safranin, as mentioned in the Gram-staining procedure.

Pili and flagella

Some bacterial cells contain hair-like growths on the outside of the cell wall. These structures are called **pili** and can be used for attachment. However, their main function is in joining bacterial cells in preparation for the transfer of DNA from one cell to another (sexual reproduction).

Some bacteria have flagella (plural) or a flagellum (singular), which are always longer than pili. Flagella allow a cell to move and are anchored to the cell wall and plasma membrane.

▲ A scanning electron micrograph (SEM) of a bacterial cell with a single flagellum. When flagella are present on a bacterial cell, they are usually involved in movement. Many bacteria have more than one flagellum attached.

Cytoplasm

The cytoplasm occupies the complete interior of the cell. Using a microscope capable of high magnification, the most visible structure of the cytoplasm is the chromosome or a molecule of DNA. There are no specialized areas within the cytoplasm because internal membranes do not exist. All the cellular processes taking place within prokaryotic cells occur within the cytoplasm, without the existence of specialized compartments.

Because there are no specialized areas within prokaryotic cells, chemical reactions are not isolated from one another. This may limit the cell's development and efficiency because of possible interference between the reactions. It is interesting that without this separation of specialized areas, prokaryotes have the most diverse metabolic reactions of all organisms. When areas within a cell take on specific functions and are separated from the surrounding cytoplasm, the cell is said to show compartmentalization. Compartmentalization was a major development as prokaryotic cells gave rise to eukaryotic cells.

Ribosomes

Ribosomes occur in all prokaryotic cells, and they function as sites of protein synthesis. These small structures occur in large numbers in cells that produce a substantial amount of protein, and, when numerous, they give a granular appearance to a TEM of a prokaryotic cell. Ribosomes are composed of two subunits, a protein and a type of RNA called ribosomal RNA. The structure of prokaryotic ribosomes will be explained further in the context of eukaryotic cell structures (Section A2.2.6).

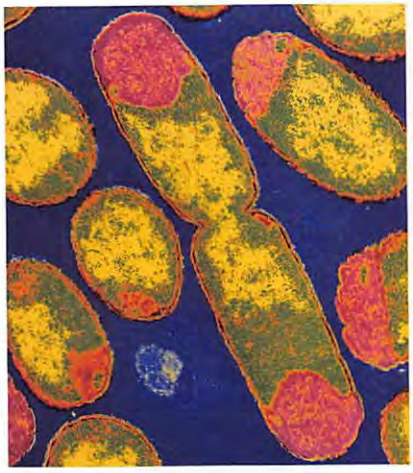
The nucleoid region

The nucleoid region of a bacterial cell is non-compartmentalized and contains a single, long, continuous, circular thread of DNA, the bacterial chromosome. The nucleoid region is not surrounded by a membrane. Prokaryotic cell DNA is not associated with proteins called histones, as the DNA of eukaryotes is; hence bacterial chromosomes can be described as naked loops. This nucleoid region is involved with cell control and reproduction.

In addition to the bacterial chromosome, bacteria may also contain **plasmids**. These small, circular, DNA molecules are not connected to the main bacterial chromosome. The plasmids replicate independently of the chromosomal DNA. Plasmid DNA is not required by the cell under normal conditions, but it can help the cell adapt to unusual circumstances.

Binary fission

Prokaryotic cells divide by a very simple process called **binary fission**. During this process, the DNA is copied, resulting in two daughter chromosomes. These daughter chromosomes become attached to different regions on the plasma membrane, and the cell divides into two genetically identical daughter cells. This divisional process includes an elongation of the cell and a partitioning of the newly produced DNA by specialized fibres.



A false-colour transmission electron micrograph (TEM) showing *Escherichia coli* dividing by binary fission.

Challenge yourself

1. Prepare a drawing of the ultrastructure of a prokaryotic cell based on electron micrographs. Remember to use a sharp pencil; use simple, narrow lines, and do not use shading. Label each of the structures, including their function.

i Plasmids have especially important roles to play in some techniques involving genetic engineering/modification. Current research into genetic modification is progressing rapidly with the use of a recently discovered biological scalpel called CRISPR. It is hoped that CRISPR will provide a future cure for some genetic diseases.

i Some types of bacteria go through binary fission every 20 minutes when conditions are ideal. This results in huge populations and greater potential for infections. Refrigeration of foods is often used to reduce ideal conditions for bacteria, resulting in lower bacteria counts in our food and less chance of infection/food poisoning.

A2.2.6 – The eukaryote cell

A2.2.6 – Eukaryote cell structure

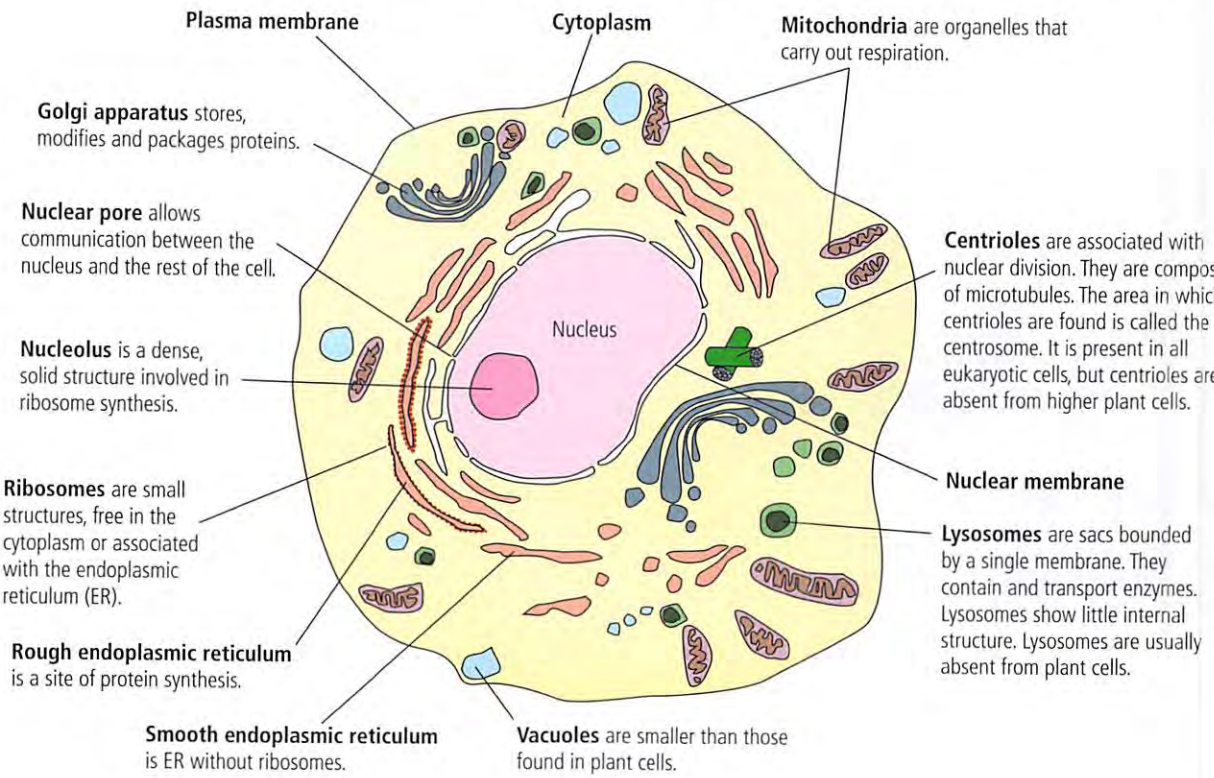
Students should be familiar with features common to eukaryote cells: a plasma membrane enclosing a compartmentalized cytoplasm with 80S ribosomes; a nucleus with chromosomes made of DNA bound to histones, contained in a double membrane with pores; membrane-bound cytoplasmic organelles including mitochondria, endoplasmic reticulum, Golgi apparatus and a variety of vesicles or vacuoles including lysosomes; and a cytoskeleton of microtubules and microfilaments.

What is a eukaryotic cell?

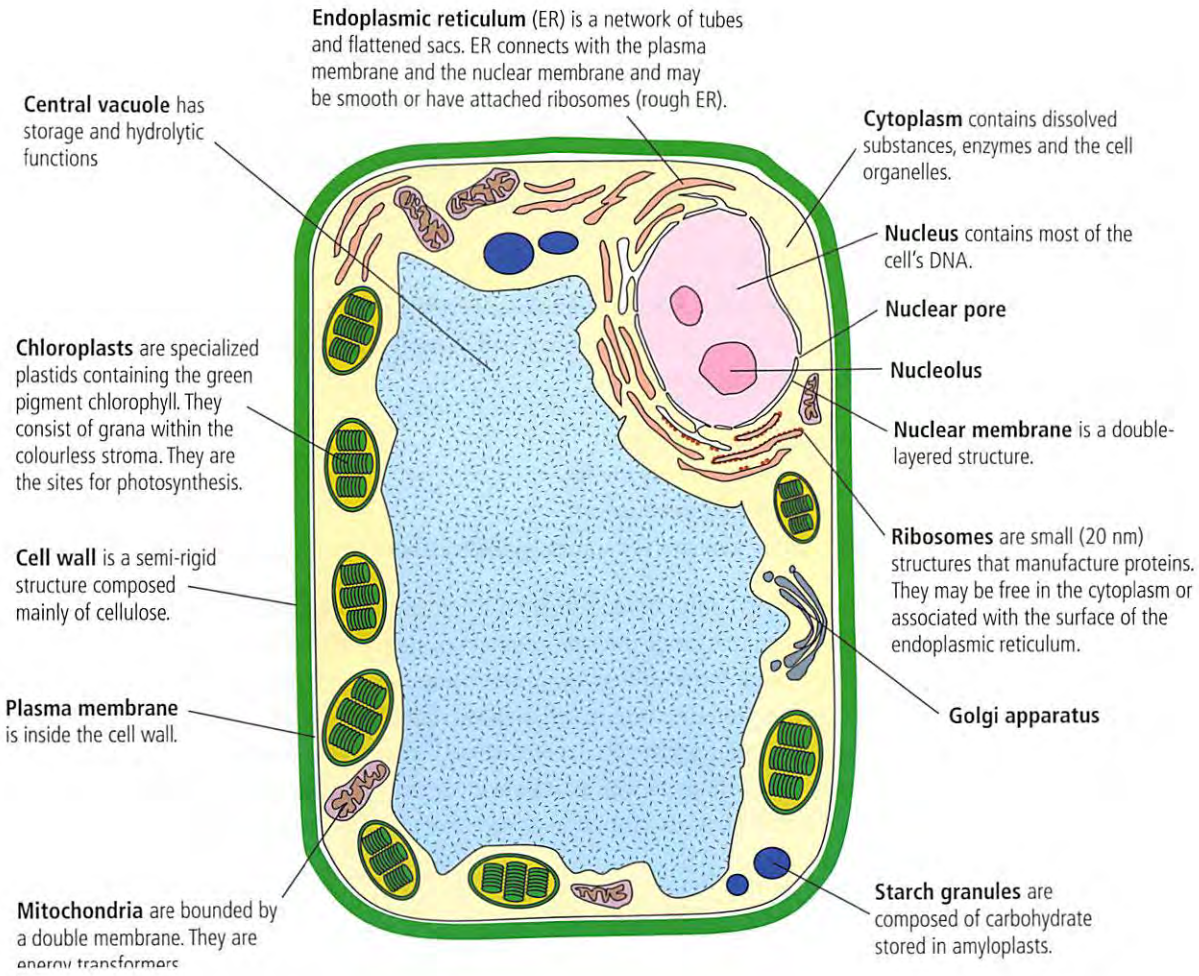
The term "eukaryote" comes from the Greek words meaning "true kernel" or nucleus.

Whereas prokaryotic cells occur in bacteria and archaea, eukaryotic cells occur in organisms such as algae, protozoa, fungi, plants and animals. Eukaryotic cells range in diameter from 5 to 100 μm. A "kernel" or nucleus is usually noticeable in the cytoplasm. Other **organelles** may be visible within the cell if you have a microscope with a high enough magnification and resolution. Organelles are non-cellular structures that carry out specific functions (a bit like organs in multicellular organisms); different types of cells may have different organelles. These structures enable compartmentalization in eukaryotic cells, which is not a characteristic of prokaryotic cells. Compartmentalization enables different chemical reactions to be separated, which is especially important when adjacent chemical reactions are incompatible. Compartmentalization also allows chemicals for specific reactions to be isolated; this isolation results in increased efficiency.

Examine Figures 2 and 3, illustrating typical animal and plant eukaryotic cells.



A2.2 Figure 2 Look at this drawing of a typical animal cell and compare it with Figure 3.



A2.2 Figure 3 What is different and what is similar between this typical plant cell and the animal cell in Figure 2?

As you read about the organelles of eukaryotic cells, refer to Figures 2 and 3.

Organelles of eukaryotic cells

Common organelles include the following (see Figures 2 and 3):

- endoplasmic reticulum
- ribosomes
- lysosomes (not usually found in plant cells)
- Golgi apparatus
- mitochondria
- nucleus
- chloroplasts (only in plant and algal cells)
- centrosomes (present in all eukaryotic cells, but centrioles are not found in most plant and fungal cells)
- vacuoles.

The microscope has given us an insight into the structure and function of eukaryotic cell organelles and characteristics.

Microscopes have a rich history of international development. Glass lenses were used in the 1st century by the Romans to magnify objects. Savino D'Armate, an Italian, made a magnifying eyeglass in the 13th century to be used with one eye. In the 1590s, two Dutch eyeglass makers, Hans Jansen and his son Zacharias Jansen, produced the first compound microscope by putting two lenses together. Antonie van Leeuwenhoek, also Dutch, improved the Jansen compound microscope in the 1600s. Since this beginning, many individuals in many different countries of the world have contributed to making the present-day microscope extremely effective in the study of the cell and other small structures. Modern technology allowing extensive communication has also been extremely important in the continual improvement of the current microscope.

Cytoplasm

All eukaryotic cells have a region called the **cytoplasm** that occurs inside the plasma membrane and outside the nucleus. It is in this region that the organelles are found. The fluid portion of the cytoplasm around the organelles is called the **cytosol**. Eukaryotic cytoplasm includes small fibres and rods called a cytoskeleton, which creates a complex internal structure. Prokaryotic cytoplasm lacks a cytoskeleton.

Cytoskeleton

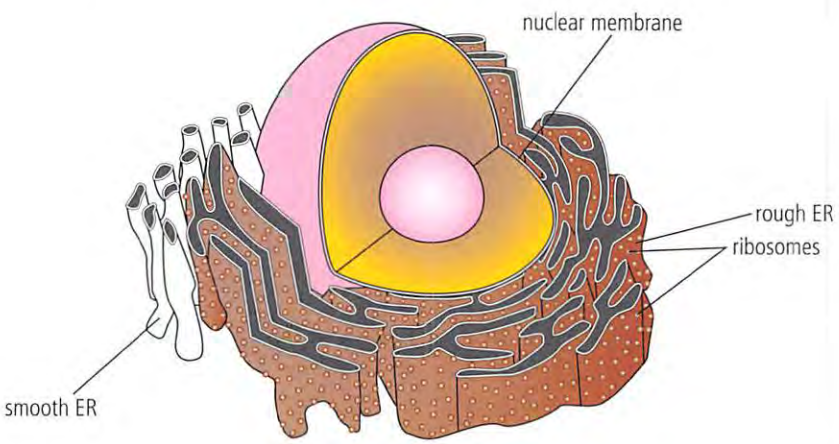
The eukaryotic cell cytoplasm contains a network of fibres collectively called the **cytoskeleton**. These fibres are composed of protein and provide the following functions within the cell:

- maintaining cell shape
- anchoring some organelles
- aiding cellular movements
- providing a means for some organelles to move within the cell.

The cytoskeleton contains actin filaments, intermediate filaments and microtubules. These fibres can rearrange their protein components so that the cell can respond to changes in both internal and external environments. Actin filaments are also called microfilaments, and function in cell division and cell movement, especially involving contractions, as in muscle cells. Intermediate filaments are found in most animal cells and reinforce cell shape as well as anchoring some organelles. Microtubules shape and support the cell. They also function as movement paths or tracks through the cell for some organelles.

Endoplasmic reticulum

The **endoplasmic reticulum (ER)** is an extensive network of tubules or channels that extends most everywhere in the cell, from the nucleus to the plasma membrane. Its structure enables its function, which is the transportation of materials throughout the internal region of the cell. There are two general types of ER: **smooth ER** and **rough ER**. Smooth ER does not have any of the organelles called ribosomes on its exterior surface. Rough ER has ribosomes on its exterior.



Smooth endoplasmic reticulum (ER) and rough endoplasmic reticulum (ER).

Smooth ER has many unique enzymes embedded on its surface. Its functions include:

- the production of membrane phospholipids and cellular lipids
- the production of sex hormones such as testosterone and oestradiol
- detoxification of drugs in the liver
- the storage of calcium ions in muscle cells, needed for contraction
- transportation of lipid-based compounds
- helping the liver to release glucose into the bloodstream when needed.

Rough ER has ribosomes on the exterior of its channels. The ribosomes participate in protein synthesis, so this type of ER engages in protein development and transport. These proteins may become parts of membranes, enzymes or even messengers between cells. Most cells contain both types of ER, with the rough ER being closer to the nuclear membrane.

Ribosomes

Ribosomes are unique structures that do not have an exterior membrane. They conduct protein synthesis within the cell. These structures may be found free in the cytoplasm, or they may be attached to the surface of ER. They are always composed of a type of RNA and protein. You will recall that prokaryotic cells also contain ribosomes. However, the ribosomes of eukaryotic cells are larger and denser than those of prokaryotic cells. Ribosomes are composed of two subunits. In eukaryotic cells these subunits together equal 80S. The ribosomes in prokaryotic cells are also of two subunits, but they only equal 70S.

The letter S used in the measurement of ribosomes refers to Svedberg units, which indicate the relative rate of sedimentation during high-speed centrifugation. The higher the S value, the quicker the structure will become part of the sediment and the more mass it will have.

Lysosomes

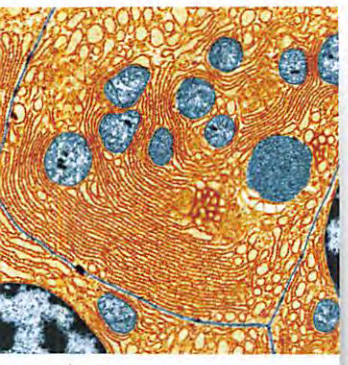
Lysosomes are intracellular digestive centres that arise from the Golgi apparatus. A lysosome does not have any internal structures. Lysosomes are **vesicles** (sacs) bounded by a single membrane that contains as many as 40 different enzymes. The enzymes are all **hydrolytic** and catalyse the breakdown of proteins, nucleic acids, lipids and carbohydrates. Lysosomes fuse with old or damaged organelles within the cell to break them down, so that recycling of the components can occur. Lysosomes are also involved in the breakdown of material that is brought into the cell by **phagocytosis**. Phagocytosis is a type of **endocytosis** and is a means by which materials can enter a cell.

Endocytosis is the uptake of new materials into the cell by invagination of the plasma membrane. If the material entering the cells is solid, the process is known as phagocytosis. When liquid containing dissolved materials enters the cell, it is known as pinocytosis.

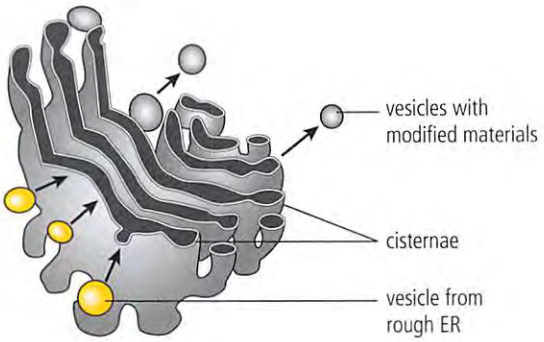
The interior environment of a functioning lysosome is acidic; acidic conditions are necessary for the enzymes to hydrolyse large molecules. When **hydrolysis** occurs, large molecules are broken down with the addition of water.

Golgi apparatus

The **Golgi apparatus** consists of flattened sacs called **cisternae**, which are stacked one on top of another. This organelle functions in the collection, packaging, modification and distribution of materials synthesized in the cell. One side of the apparatus is near the rough ER, called the ***cis*** side. It receives products from the ER. These products then move into the cisternae of the Golgi apparatus. They continue to move to the discharging or opposite side, the ***trans*** side. Small sacs called **vesicles** can then be seen coming off the trans side. Lysosomes are an important example of vesicles produced by the Golgi apparatus. The vesicles carry modified materials to wherever they are needed inside or outside the cell. The Golgi apparatus is especially prevalent in glandular cells, such as those in the pancreas, which manufacture and secrete substances.



A transmission electron micrograph (TEM) of a pancreatic exocrine cell. Can you tell that this is an animal cell? Locate as many of the structures of an animal cell as you can. How do the structures of this cell reflect the overall functions of the pancreas?



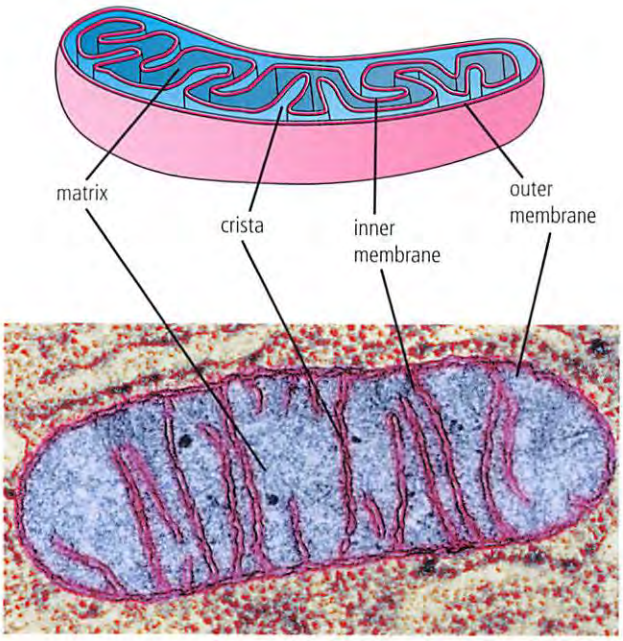
In this drawing of the Golgi apparatus, the movement of the vesicles is shown by arrows. Can you identify which side is the *cis* side and which is the *trans* side?

Mitochondria

Mitochondria (singular mitochondrion) are rod-shaped organelles that appear throughout the cytoplasm. They are close in size to a bacterial cell. Mitochondria have their own DNA, a circular chromosome like that in bacterial cells, allowing them some independence within the cell. They have a double membrane: the outer membrane is smooth, but the inner membrane is folded into **cristae** (singular crista). Inside the inner membrane is a semi-fluid substance called the **matrix.** An area called the **inner membrane space** lies between the two membranes.

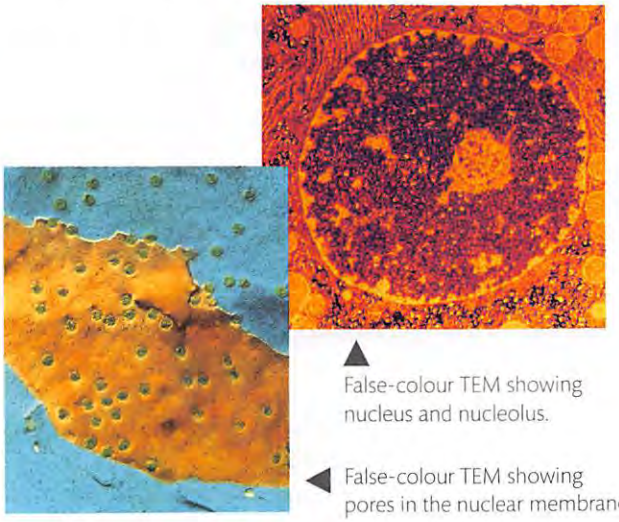
The cristae provide a huge surface area within which the chemical reactions characteristic of mitochondria occur. Most mitochondrial reactions involve the production of usable cellular energy called **adenosine triphosphate (ATP)**. Because of this, the mitochondria are often called the powerhouse of a cell. This organelle also produces and contains its own ribosomes. These ribosomes are of the 70S type. Cells that have high energy requirements, such as muscle cells, have large numbers of mitochondria.

Compare this drawing of a mitochondrion with the corresponding false-colour transmission electron micrograph (TEM) below it.



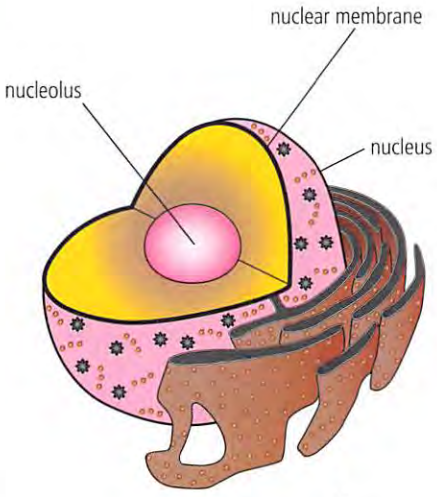
Nucleus

The **nucleus** in eukaryotic cells is an isolated region where DNA resides. It is bordered by a double membrane referred to as the **nuclear envelope**. This membrane allows compartmentalization of the eukaryotic DNA, thus providing an area where DNA can conduct its functions without being affected by processes occurring in other parts of the cell. The nuclear membrane does not result in complete isolation, because it has numerous pores that allow communication with the cell's cytoplasm.



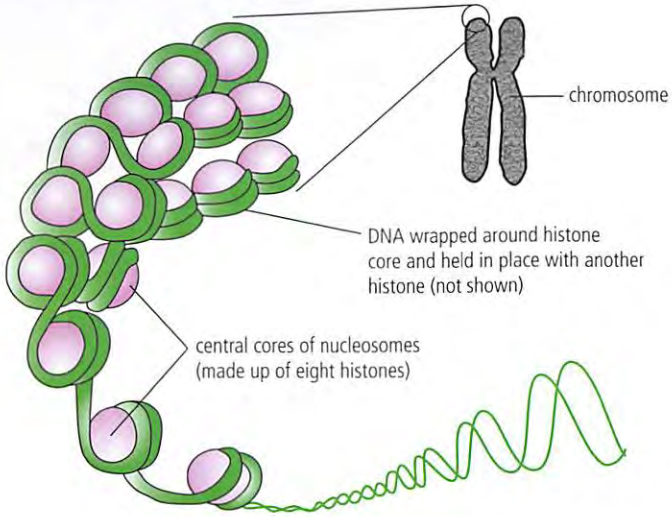
False-colour TEM showing nucleus and nucleolus.

False-colour TEM showing pores in the nuclear membrane.



The nucleus has a double membrane with pores and contains a nucleolus.

The DNA of a eukaryotic cell often occurs in the form of chromosomes; chromosomes vary in number depending on the species. Chromosomes carry all the information that is necessary for the cell to exist, thus allowing an organism to survive, whether it is unicellular or multicellular. The DNA is the genetic material of the cell. It enables certain traits to be passed on to the next generation. When the cell is not in the process of dividing, the chromosomes are not present as visible structures. During this phase, the cell's DNA is in the form of **chromatin.** Chromatin is formed of strands of DNA and proteins called **histones.** The DNA and histone combination often results in structures called a **nucleosome.** A nucleosome consists of eight spherical histones with a strand of DNA wrapped around them and secured with a ninth histone. This produces a structure that resembles a string of beads. A chromosome is a highly coiled structure of many nucleosomes.



This drawing shows how DNA is packaged into chromosomes.

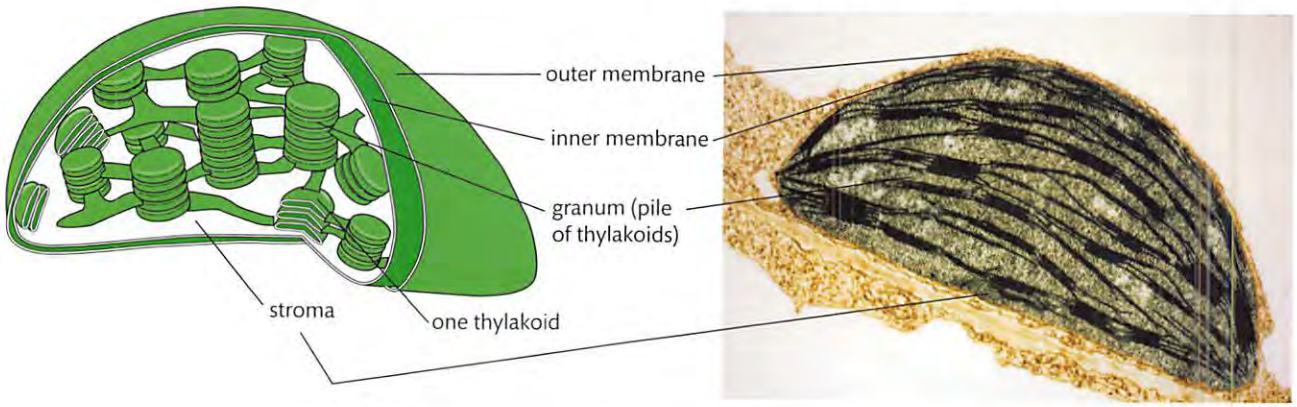
The nucleus is often located centrally within the cell's cytoplasm, although in some cell types it is pushed to one side or the other. The side position is characteristic of plant cells, because these cells often have a large central vacuole. Most eukaryotic cells possess a single nucleus, but some do not have a nucleus at all, and others have multiple nuclei. Without a nucleus, cells cannot reproduce. The loss of reproductive ability is often paired with increased specialization to carry out certain functions. For example, human red blood cells do not have nuclei: they are specialized to transport respiratory gases. Most nuclei also include one or more dark areas called **nucleoli** (singular nucleolus). Ribosome molecules are manufactured in nucleoli. The molecules pass through the nuclear envelope before assembling as ribosomes.

Chloroplasts

Chloroplasts occur only in algae and plant cells. The chloroplast contains a double membrane and is about the same size as a bacterial cell. Like the mitochondrion, a chloroplast contains its own DNA and 70S ribosomes. The DNA of the chloroplast takes the form of a ring.

You should note all the characteristics that chloroplasts and mitochondria have in common with prokaryotic cells.

As well as DNA and ribosomes, the interior of the chloroplast includes **grana** (singular granum), **thylakoids** and the **stroma**, which are labelled in Figure 4. A granum is made up of numerous thylakoids stacked like a pile of coins. The thylakoids are flattened membrane sacs with components necessary for the absorption of light. Absorption of light is the first step in **photosynthesis**. Photosynthesis is a process that converts light energy into chemical energy. The chemical energy is then stored in sugars made from carbon dioxide. The fluid stroma is like the cytoplasm of the cell. It occurs outside the grana but within the double membrane. The stroma contains many enzymes and chemicals necessary to complete the process of photosynthesis. Like mitochondria, chloroplasts can reproduce independently of the cell.

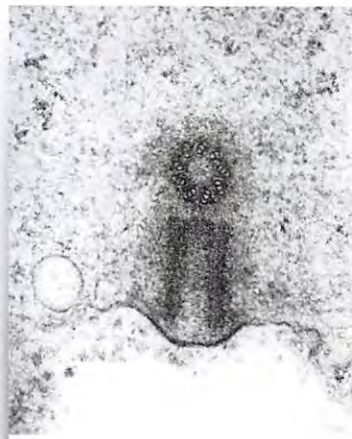


A2.2 Figure 4 Compare the drawing of a chloroplast with the corresponding transmission electron micrograph (TEM) of a chloroplast.

Centrosome

The **centrosome** occurs in all eukaryotic cells. In animal cells it consists of a pair of **centrioles** that are often at right angles to one another. The centrioles are involved with the assembly of **microtubules**, which are important to a cell because they provide structure and allow movement. Microtubules are also important for cell division. Plant and fungal cells do not have centrioles. However, they are able to produce microtubules from their centrosome-like regions, which suggests that centrioles are not necessary for producing microtubules.

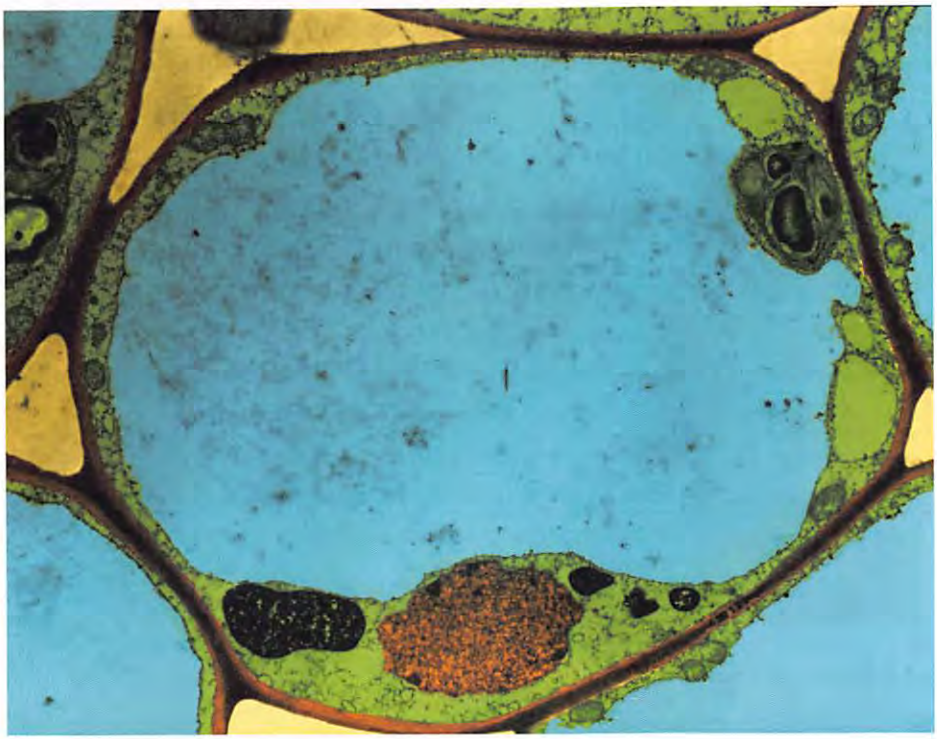
The centrosome is located at one end of the cell, close to the nucleus. **Basal bodies** are structures related to the centrosome of eukaryotic cells and are located at the base of cilia and flagella. Not all eukaryotic cells have cilia or flagella, therefore not all eukaryotic cells have basal bodies. The basal bodies are thought to direct the assembly of microtubules within the associated cilia or flagella. When present, centrioles appear to produce basal bodies.



A transmission electron micrograph (TEM) showing the two centrioles of a centrosome. The presence of centrioles indicates that the micrograph is of a eukaryotic cell, but not a plant or fungal cell.

Vacuoles

Vacuoles are storage organelles that are usually formed from the Golgi apparatus. They are membrane-bound and have many possible functions. They occupy a very large space inside the cells of most plants. In animal cells, vacuoles are small and may be numerous. Vacuoles may store several different substances, including potential food (to provide nutrition, as in plant cells), metabolic waste and toxins (to be expelled from the cell) and water. Vacuoles enable cells to have higher surface area-to-volume ratios even at larger sizes. In plants, they allow an uptake of water, which provides rigidity to the organism. When a large vacuole occurs in the central area of a plant cell, it is called a **central vacuole**. Vacuoles are like vesicles except that they are larger.



A coloured transmission electron micrograph (TEM) of a plant cell that has a central vacuole filled with water. Note the central location of the vacuole, with the cytoplasm and all the other organelles pushed to the cell margins.

When comparing items, be certain to state the characteristic for each type of item, as shown in Table 1 for prokaryotic and eukaryotic cells.

A comparison of prokaryotic and eukaryotic cells

A table is an effective way of summarizing the differences between prokaryotic and eukaryotic cells.

Prokaryotic cells	Eukaryotic cells
DNA in a ring form without protein	DNA with proteins as chromosomes/chromatin
DNA free in the cytoplasm (nucleoid region)	DNA enclosed within a nuclear envelope (nucleus)
No mitochondria	Mitochondria present
70S ribosomes	80S ribosomes
No internal compartmentalization to form organelles	Internal compartmentalization present, forming many types of organelles
Size less than 10 μm	Size more than 10 μm

A2.2 Table 1 Comparing prokaryotic and eukaryotic cells

If asked to state the similarities between the two types of cells, make sure you include the following:

- both types of cells have some outside boundary that always involves a plasma membrane
- both types of cells conduct all the functions of life
- DNA is present in both cell types.

A2.2.7 – Unicellular organisms

A2.2.7 – Processes of life in unicellular organisms
Include these functions: homeostasis, metabolism, nutrition, movement, excretion, growth, response to stimuli and reproduction.

All organisms, whether unicellular or multicellular, carry out all the functions of life. The functions of life are summarized in Table 2.

Metabolism	The sum of all the chemical reactions that occur within an organism
Growth	The development of an organism
Reproduction	The ability to produce offspring
Response to stimuli	As the environment changes, the organism adapts
Homeostasis	Maintenance of a constant internal environment
Nutrition	The ability to acquire the energy and materials needed to maintain life
Excretion	The ability to release materials not needed or harmful into the surrounding environment
Movement	The ability to move or change position

A2.2 Table 2 The functions of life

It is important to note that if the functions of life are evident, then life is said to be present.

Unicellular organisms have unique ways of carrying out the life functions compared to **multicellular** organisms.

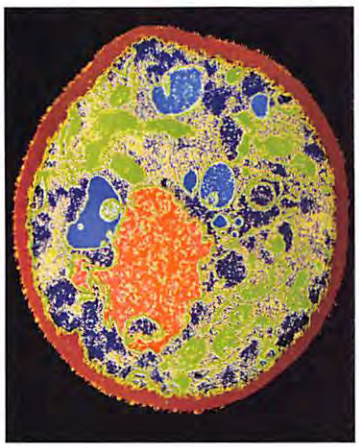
- The cell membrane controls the movement of materials in and out of the cell, to help maintain homeostasis.
- Vacuoles isolate and store waste so that it does not harm the organism.
- Cells often possess cilia or flagella that allow movement in response to changes in the environment.
- Vacuoles carry out digestion, to provide nutrition for the organism.
- Mitochondria or areas of enzymes allow energy production to continue for all the functions of life.
- Ribosomes provide the building blocks for growth and repair.

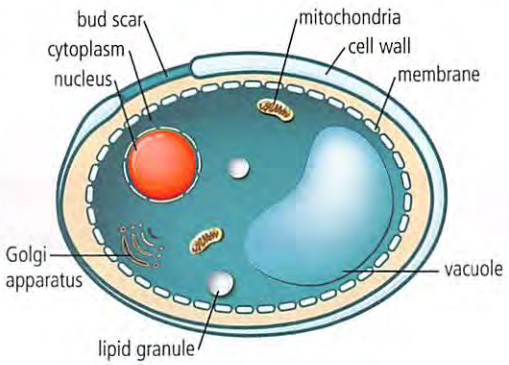
Multicellular organisms often have whole groups of cells called **organs** carrying out these functions.

A2.2.8 – Different types of eukaryotic cells

A2.2.8 – Differences in eukaryotic cell structure between animals, fungi and plants
Include presence and composition of cell walls, differences in size and function of vacuoles, presence of chloroplasts and other plastids, and presence of centrioles, cilia and flagella.

The eukaryotic cells of different types of organisms can vary. Three types of organisms with eukaryotic cells are plant cells, animal cells and fungal cells. There are over 14,000 species of fungi, and it is believed that they were the first eukaryotes to live on land.





This drawing of a yeast cell illustrates some of the major cell organelles common to fungi.

This transmission electron micrograph (TEM) of a yeast cell represents one of the many species of fungi. From our previous work with organelles, identify as many as possible.

Fungi can be unicellular or multicellular. They include yeasts, mushrooms, truffles and bread moulds, plus many more. No fungus can produce its food. Fungi secrete (release into the surrounding environment) digestive enzymes and then absorb the externally digested nutrients as their source of energy. They have major roles in our planet, including decomposing organic debris to enable the recycling of nutrients, being a source of food, being used in medicines, and even controlling many harmful insects.

Most believe fungi are more closely related to animals than to plants. Table 3 summarizes the differences between plant, animal and fungal eukaryotic cells. However, do not forget the similarities between these three cell types as well.

Plant cells	Animal cells	Fungal cells
Exterior of cell includes an outer cell wall composed of cellulose, with a plasma membrane just inside	Exterior of cell includes a plasma membrane. There is no cell wall	Exterior of cell includes an outer cell wall composed of chitin, with a plasma membrane just inside
Chloroplasts are present in the cytoplasm area, enabling the production of carbohydrates	There are no chloroplasts for carbohydrate production	There are no chloroplasts for carbohydrate production
Possess large centrally located vacuoles for the storage of carbohydrates	Vacuoles are generally small and numerous, when present, with many unique functions	Vacuoles are generally small and numerous, with many unique functions
Store carbohydrates as starch	Store carbohydrates as glycogen	Store carbohydrates as glycogen
Usually do not contain cilia, flagella or basal bodies	May have cilia or flagella, with associated basal bodies	May have cilia or flagella, but do not have associated basal bodies
Because a rigid cell wall is present, this cell type has a fixed, often angular, shape	Without a cell wall, this cell is flexible and more likely to be a rounded shape	The cell wall allows a degree of flexibility, along with support for the cell; the cell shape may vary
Possess centrosomes but no centrioles	Possess both centrosomes and centrioles	Possess centrosomes but no centrioles

▲ **A2.2 Table 3** Differences between plant, animal and fungal cells

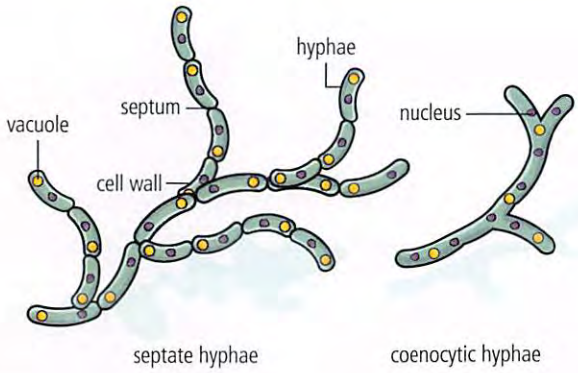
Most of the organelles discussed are present in all eukaryotic cells. When an organelle is present in each of the eukaryotic cell types, it usually has the same structure and function. For example, all three cell types contain mitochondria that possess cristae, a matrix and a double membrane. Also, in all three cell types, the mitochondria function in the production of ATP for use by the cell.

A2.2.9 – Atypical eukaryotes

A2.2.9 – Atypical cell structure in eukaryotes
Use numbers of nuclei to illustrate one type of atypical cell structure in aseptate fungal hyphae, skeletal muscle, red blood cells and phloem sieve tube elements.

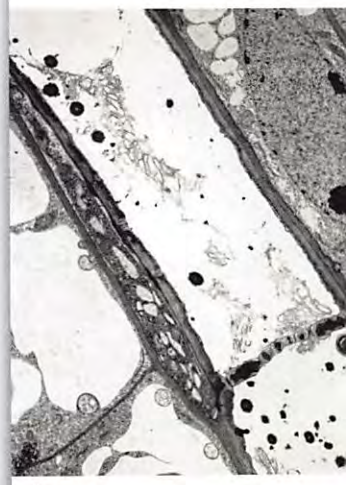
The structure of some eukaryotic cells is unique or atypical, which allows them to carry out specialized functions. One example of this atypical structure involves cell nuclei.

Some multicellular fungi produce filaments called **hyphae**. Most of these hyphae consist of chains separated by cross-walls that have pores to allow various organelles and cytoplasm to flow from cell to cell. However, some fungi produce hyphae that lack cross-walls. The result of this is a single mass of cytoplasm (one cell) with more than one nucleus.



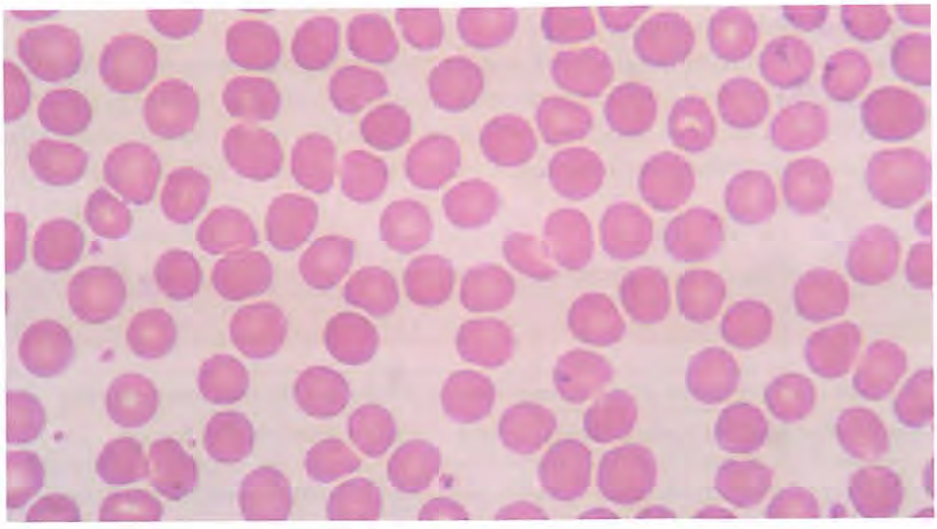
Notice the two types of hyphae shown in this image. The hyphae on the right do not contain cross-walls, while cross-walls are present in the hyphae on the left.

Phloem sieve tube elements, shown in Figure 5, have a specialized function allowing transportation within a multicellular plant. These unique elements/cells have end walls with pores and minimal cellular components such as nuclei, ribosomes, cytoskeleton and cytoplasm. They are connected end to end, forming tube structures. These cells can only remain alive with the help of **companion cells**, which maintain a close connection with the sieve tube elements.



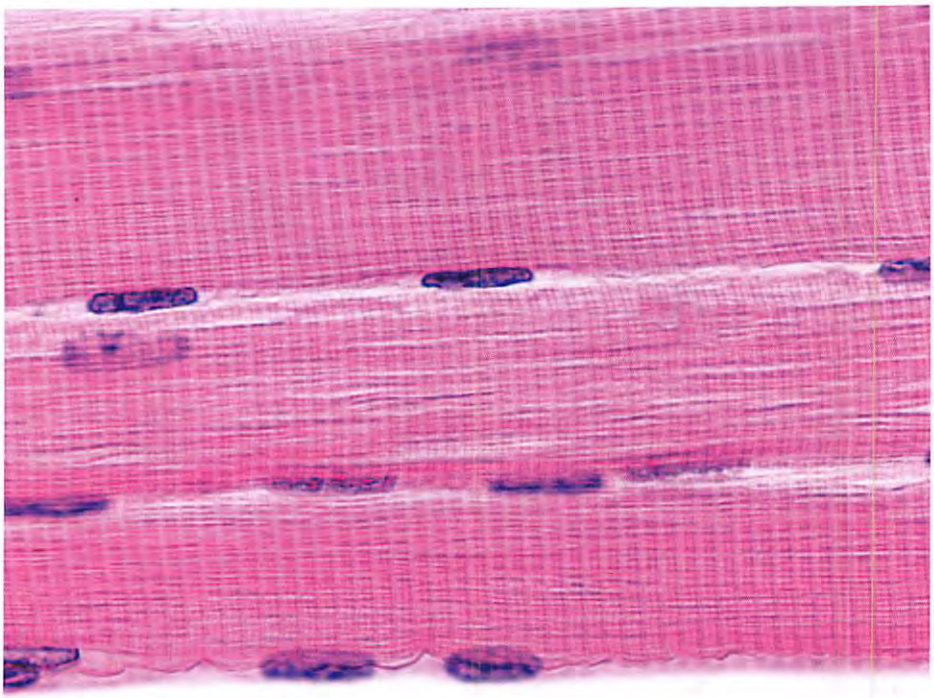
A2.2 Figure 5 A transmission electron micrograph (TEM) of a plant's sieve tube elements and associated companion cells. Notice the lack of substance in the sieve tube elements and the pores in the end wall.

Figure 6 shows a micrograph of human red blood cells. They have the specialized function of carrying oxygen throughout the body. They contain substantial amounts of a molecule called haemoglobin, which easily combines with oxygen. They are shaped to allow a large surface area for the absorption and release of oxygen. They do not have a nucleus, which allows them to carry even more oxygen.



A2.2 Figure 6 A micrograph of a human blood smear.

Figure 7 shows an electron micrograph of human skeletal muscle. This muscle type specializes in allowing body movement. It can carry out this function because of the presence of specialized proteins arranged in bands that contract and relax. The presence of cell membranes is limited, resulting in large, tubular cells with multiple nuclei, allowing more coordinating protein molecules.



A2.2 Figure 7 An electron micrograph (EM) of human skeletal muscle. Note the large, continuous cells.

Other cells with specialized structures to enable unique functions include:

- nerve cells, which are long and thin with branched connections at each end to transmit electrical impulses
- sperm cells, with many mitochondria and a tail allowing movement and a head with a tip capable of producing an enzyme that facilitates penetration of an egg cell
- cells found in the tubes associated with lungs, which have many tiny hairs called cilia on their exterior that work in unison to move mucus and other particles up and out of the airways.

Draw and annotate diagrams of organelles and other cell structures shown in electron micrographs. Full details of how to carry out this activity with a worksheet are available in the eBook.

SKILLS

A2.2.10 and A2.2.11 – Electron micrograph skills

A2.2.10 – Cell types and cell structures viewed in light and electron micrographs
Application of skills: Students should be able to identify cells in light and electron micrographs as prokaryote, plant or animal. In electron micrographs, students should be able to identify these structures: nucleoid region, prokaryotic cell wall, nucleus, mitochondrion, chloroplast, sap vacuole, Golgi apparatus, rough and smooth endoplasmic reticulum, chromosomes, ribosomes, cell wall, plasma membrane and microvilli.

A2.2.11 – Drawing and annotation based on electron micrographs
Application of skills: Students should be able to draw and annotate diagrams of organelles (nucleus, mitochondria, chloroplasts, sap vacuole, Golgi apparatus, rough and smooth endoplasmic reticulum and chromosomes) as well as other cell structures (cell wall, plasma membrane, secretory vesicles and microvilli) shown in electron micrographs. Students are required to include the functions in their annotations.

SKILLS

Utilizing the text, diagrams and pictures presented in this chapter, you should be able to differentiate between prokaryotic and eukaryotic cells when presented with light or electron micrographs. You must be able to identify the following cell structures: nucleoid region, prokaryotic cell wall, nucleus, mitochondrion, chloroplast, sap vacuole, Golgi apparatus, rough and smooth endoplasmic reticulum, chromosomes, ribosomes, cell wall, plasma membrane and microvilli. The internet has many sites that show cells of various types, which you can use to develop your skills in this identification process.

It is important that you practise the skills necessary to produce informative drawings throughout the course. Actual laboratory observation of cells using prepared slides and a microscope will help you develop your skills. Draw what you can see in the field of view, and compare your drawings, labels and explanations with those found on appropriate internet sites.

Guiding Question revisited

What are the features common to all cells and the features that differ?

In this chapter, we have discovered the following about cells:

- whether unicellular or multicellular, all organisms are composed of cells
- features common to all cells include DNA, cytoplasm and a plasma membrane forming an exterior boundary
- prokaryotic cells display a simple composition, lacking membrane-bounded organelles in their cytoplasm
- eukaryotic cells are compartmentalized, with isolated areas carrying out specialized tasks
- the cytoplasm of eukaryotic cells has many unique organelles working together, exhibiting all the life functions of the cell/organism
- variations of the cell structure result in some unique cellular compositions, such as cells with multiple nuclei and cells with no nuclei.

Guiding Question revisited

How is microscopy used to investigate cell structure?

In this chapter, we have discovered the following about microscopes:

- magnification and resolution are two properties of microscopes that are essential for the study of cells
- light microscopes have the advantage that living cells and tissue can be viewed
- EMs have increased the limits of magnification and resolution, allowing views of cells never thought possible even 50 years ago
- freeze fracture and fluorescent stains have furthered the study of cells via microscopy
- immunofluorescence using antibodies and specialized dyes has allowed visualization of the specific tissues viruses attack.

Exercises

Q1. Which pair of organelles is present in plant cells but not in animal cells?

A Chloroplasts and mitochondria.

B Centrioles and central vacuole.

C Chloroplasts and cell wall.

D Lysosomes and plasma membrane.

Q2. What carbon compound is most likely to be transported by rough endoplasmic reticulum?

Q3. Which of the following is not found in eukaryotic cells?

A Microtubules.

B Mitochondria.

C Nucleus.

D Chloroplasts.

Q4. Which cell type is the most likely to possess a capsule?

A Red blood cell.

B Prokaryotic cell.

C Sieve tube element.

D Eukaryotic cell.

Q5. What structure is directly related to prokaryotic cell reproduction?

A Cilia.

B Basal body.

C Centriole.

D Pili.

Q6. Which association is most accurate?

A Red blood cell: nucleus.

B Nucleus: mitochondrion.

C Basal body: ribosome.

D Golgi apparatus: vesicle.

Q7. Match the following features and organelles.

A	mitochondrion	**1**	food storage
B	cytoskeleton	**2**	cristae
C	ER	**3**	contains hydrolytic enzymes
D	lysosome	**4**	microtubules
E	vacuole	**5**	rough or smooth

A2 Practice questions

1. Describe two examples of a typical cell structure involving number of nuclei.

(Total 4 marks)

2. List three structures common to all cells.

(Total 3 marks)

3. Explain two advantages as well as two disadvantages concerning the use of electron microscopy.

(Total 4 marks)

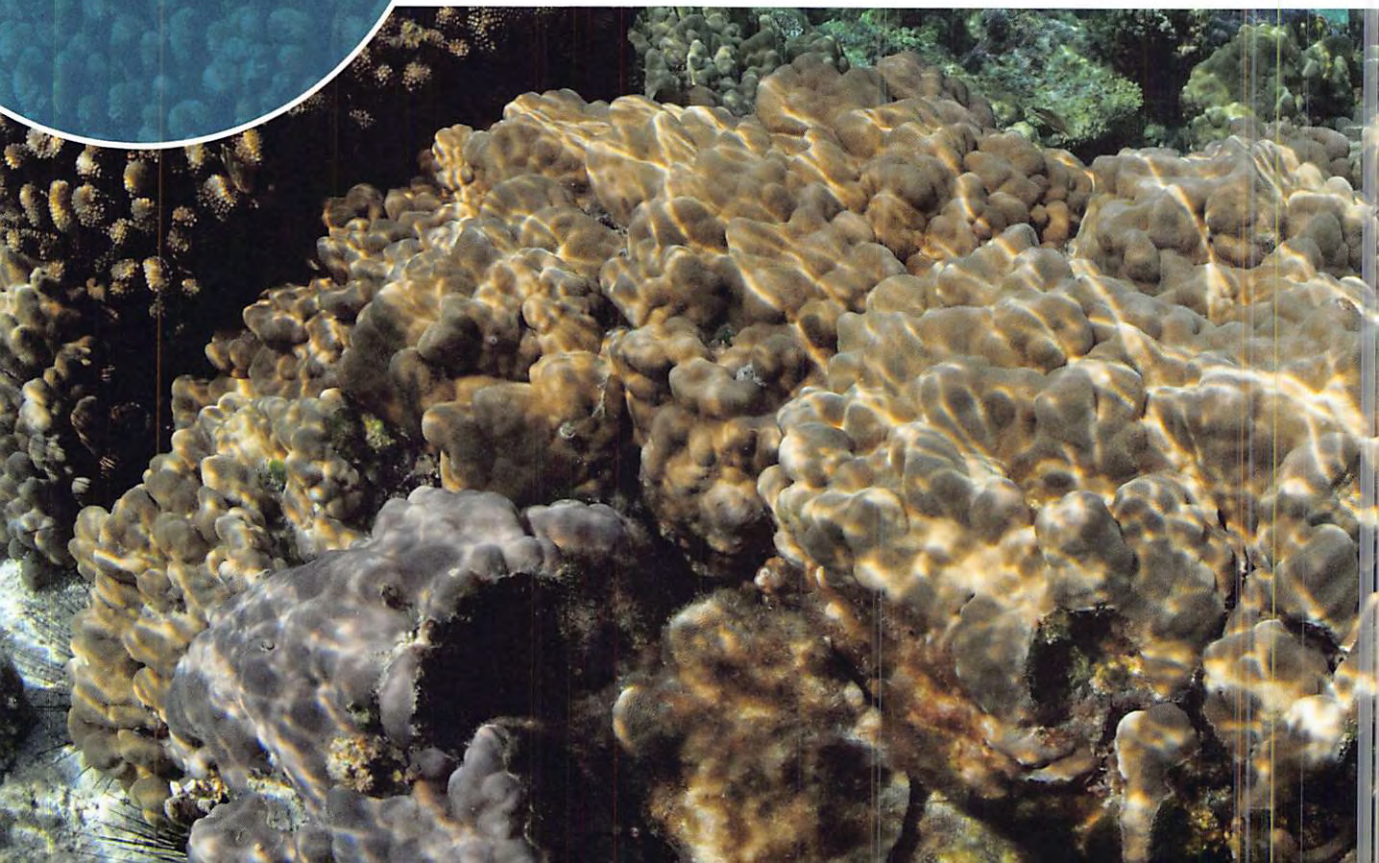
4. Compare and contrast the general features of prokaryotic and eukaryotic cells.

(Total 4 marks)

THEME

A Unity and diversity

3 Organisms



From single-celled organisms to coral reefs to trees, life on Earth shows a remarkable degree of variation. For centuries, physical characteristics have been used to name organisms and to put similar organisms into categories. More recently, thanks to DNA sequencing, we can use the genetic code of an organism (its genome) to help show how closely it is related to other species.

A3.1 Diversity of organisms

Guiding Questions

What is a species?

What patterns are seen in the diversity of genomes within and between species?

Although there are at least two dozen definitions for the concept of species in biology, we will examine two: the morphological definition that has been used for hundreds of years, and the biological species concept definition, which has only existed in the past few decades. The first looks at what physical features organisms have, while the second considers whether or not individuals can breed to produce fertile offspring. Each definition has its strengths and weaknesses. No single definition can encompass all living organisms as well as extinct species, because such an astoundingly large diversity exists among the various forms of life on Earth.

When DNA sequences of organisms are compared, it is possible to see that, between individuals of the same species, there are remarkably few differences compared to the differences between individuals belonging to two different species. A single-celled organism with no specialized tissue is likely to have a much smaller quantity of DNA than a multicellular organism with hundreds of different specialized tissues.

A3.1.1 – Variation between organisms

A3.1.1 – Variation between organisms as a defining feature of life
Students should understand that no two individuals are identical in all their traits. The patterns of variation are complex and are the basis for naming and classifying organisms.

If you have pigeons where you live, you might think that they all look the same. But ask pigeon experts and they will tell you that the level of diversity and variation among pigeons is equivalent to the level of diversity and variation in humans. Animal breeders such as pigeon fanciers recognize each individual in the population they are raising, just as you would recognize your dog in a group of similar dogs. No two individuals in a population share all the same traits. Even identical twins have slight differences.

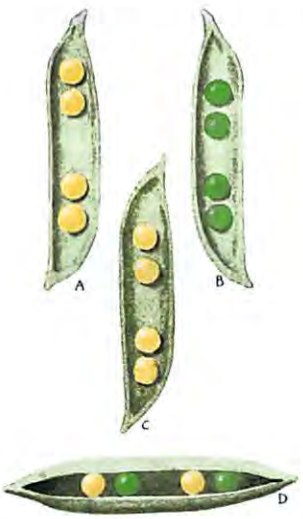
Observing the differences between individuals within one species and observing the differences between one species and another is a daunting task, especially when we consider that there are millions of species on Earth to observe, from invisible microbes to mighty redwood trees over 100 m tall.

How can we classify organisms? There are countless possible ways; a few examples are listed below.

- By feeding habits: it makes its own food/it is a carnivore or herbivore.
- By habitat: land-dwelling/aquatic.
- By movement: sessile (stuck in one place)/free moving.
- By daily activity: nocturnal/diurnal.
- By risk: harmless/venomous.
- By anatomy: plant/animal/vertebrate/invertebrate.

We generally start by categorizing organisms based on **morphology** (the physical appearance of an organism). Is the organism made of a single cell without a nucleus, or does it have a nucleus? If it has a nucleus, is it single-celled or multicellular? Think of these categories as boxes into which the organisms are placed. Each category is called a **taxon** (plural taxa). The biggest taxa are very broad and encompass many species, but as the defining features used become more and more detailed and specific, smaller and smaller boxes are used, containing fewer and fewer species per taxa, until we arrive at a single species. The largest taxon is a "domain" and it contains all the more specific taxa, from "kingdom" down to "species".

Table 1 illustrates the identification of two species from very different kingdoms: one species is an animal, humans, and the other is a plant, garden peas. The science and skill of categorizing life is called **taxonomy** and specialists who do it are called **taxonomists**.



The garden pea (*Pisum sativum*) is the plant Gregor Mendel studied.

Taxa	Human	Garden pea
Kingdom	Animalia	Plantae
Phylum	Chordata	Angiospermophyta
Class	Mammalia	Dicotyledoneae
Order	Primate	Rosales
Family	Hominidae	Papilionaceae
Genus	*Homo*	*Pisum*
Species	*sapiens*	*sativum*

A3.1 Table 1 The classification of two species

How do species exemplify both continuous and discontinuous patterns of variation?

To help remember the order of the taxa, a mnemonic (memory trick) is helpful. Make a sentence using the first letters of each level, such as "King Philip Came Over For Good Soup". The human brain is very poorly adapted for remembering lists of words but very highly adapted for remembering stories. Transforming lists into stories is a good example of a mnemonic.

The variations in characteristics for sorting species into their designated taxon might be obvious (plants have leaves and roots, whereas humans have limbs and a head), but can sometimes be very subtle. Two species of frog might look identical on the outside but can be distinguished by different mating calls. In such a case, the patterns of variation in morphology are not sufficient for classification.

When variation can be placed into distinct categories (type A blood versus type B, for example), we say it is **discontinuous**. When variation has a wide range of possibilities (how tall a tree can grow, for example), we say it is **continuous**. Sometimes we impose categories such as eye colour as if it is an example of discontinuous variation when, in fact, a hundred people who have blue eyes will show a certain amount of continuous variation, from deep blue to very light blue.

A3.1.2 – Species as groups of organisms

A3.1.2 – Species as groups of organisms with shared traits
This is the original morphological concept of the species as used by Linnaeus.

Carolus Linnaeus, an 18th century professor of medicine and botany in Sweden, had difficulty identifying the plants he found on his travels because different botanists used different systems for naming them. This made it difficult to categorize the organisms. Linnaeus then had a remarkable idea: what if we take all the known living organisms, put them into categories, and give them a name using a uniform system? Not just plants, but animals, too. By creating the names using Latin or Greek, no matter what anyone calls the organism in their native language (such as Swedish), it will always have a universally known name.

Linnaeus based the classification system, as well as the names, on the physical features of the organisms. This **morphological classification**, first published in his book *Systema Naturæ* in 1735, was used by generations of botanists and zoologists, and the naming system he created is still used today. Thousands of organisms still carry the scientific name that Linnaeus gave them over two-and-a-half centuries ago, such as the Asian elephant, which he named *Elephas maximus* in 1758.

A3.1.3 – The binomial naming system

A3.1.3 – Binomial system for naming organisms
Students should know that the first part of the name is the genus, the second part of the name is the species. Species in the same genus have similar traits. The genus name is given an initial capital letter but the species name is lowercase.

You have a scientific name based on your species: *Homo sapiens*. This system of naming organisms using two names is called **binomial nomenclature**. "Bi" means two, "nomial" means name and "nomenclature" refers to a system used to name things.

Myrmecophaga tridactyla is a name that literally means "eater of ants" plus "with three fingers". This name refers to the giant anteater of Central and South America. In fact, the animal really has five fingers, but they are hard to see because the animal walks on its front knuckles.

▲ The giant anteater (*Myrmecophaga tridactyla*)

i In the early days of classification, all known organisms were classified into only two kingdoms: plants and animals. With the invention of the microscope in the mid-1600s, many new creatures were discovered that were nothing like plants or animals. In effect, the microscope revealed that there is an entire world of invisible organisms living throughout the world's ecosystems.

The first name in the binomial nomenclature system is always capitalized and it refers to the **genus**; the second name always begins with a small letter and refers to the **species**. Both are always written in italics when typed, or underlined when written by hand. Organisms in the same genus will have a higher number of similar characteristics compared to organisms in a different genus.

There are three main objectives and associated rules to using binomial nomenclature:

1. each organism has a unique name that cannot be confused with another organism
2. the names can be universally understood, no matter what nationality or culture is using the name
3. there is some stability in the system, so that people cannot change the names of organisms without valid reasons.

Examples of binomial nomenclature

Sometimes scientific names for organisms are relatively easy to decipher because they contain their common names:

- *Amoeba amazonas*
- *Equus zebra*
- *Gekko gecko* (this lizard gets its name from the sounds it makes)
- *Gorilla gorilla*
- *Paramecium caudatum* (caudate means having a tail).

Sometimes, it is more difficult to guess their common name:

- *Apis mellifera* (honeybee, although you might have guessed this if you know that beekeeping is also called apiculture)
- *Aptenodytes patagonicus* (king penguin, although you can probably guess where it lives from its species name)
- *Loxodonta cyclotis* (African forest elephant)
- *Malus domestica* (apple tree).

Homo sapiens

Genus ***species***

The rules about writing binomial nomenclature names are that:

- the genus name is capitalized but the species name is not
- both are written in italics when typed, or underlined when handwritten.

SKILLS

In taxonomy, there are two opposing philosophies concerning what to do when an organism does not fit easily into existing categories: (1) broaden the definition of an existing category to include the new organism; or (2) invent a new category or subcategory. Specialists who take the first approach are referred to as **lumpers**, while those who take the second approach are referred to as **splitters**.

Scientists naming organisms sometimes have a sense of humour. Here are some examples.

- *Agra schwarzeneggeri* Erwin, 2002. This Costa Rican ground beetle was named after Arnold Schwarzenegger because of the insect's large biceps.
- *Dracula vampira* Luer, 1978. This orchid in Ecuador got its name from the fact that the petals on the flower look like a bat's wings.

Challenge yourself

1. Look up the following to find out what their scientific names are:
   - your favourite animal
   - your favourite fruit or vegetable
   - your favourite flower, tree or house plant.

A3.1.4 – Biological species

A3.1.4 – Biological species concept
According to the biological species concept, a species is a group of organisms that can breed and produce fertile offspring. Include possible challenges associated with this definition of a species and that competing species definitions exist.

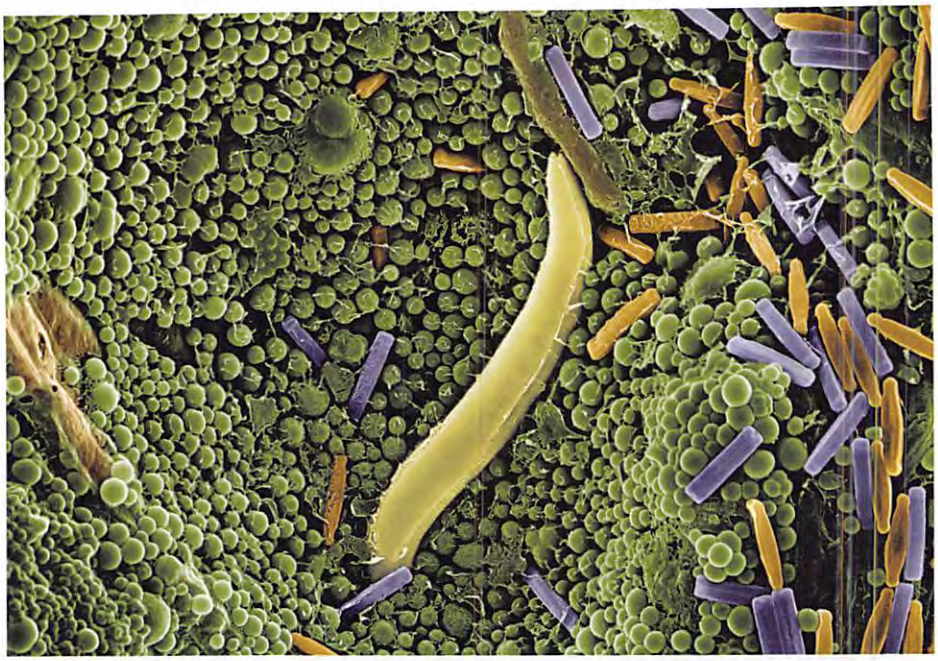
Another definition of a species that is now often preferred over Linnaeus' morphological definition is the **biological species concept**. This was proposed by Ernst Mayr in 1942. Using this definition, in order to be classified as the same species, individuals must be able to breed together and produce fertile offspring. All modern dogs, *Canis familiaris*, can interbreed to produce fertile offspring, so they are considered to be one species.

All domestic dogs are of the same species.

Not every biologist is happy with this definition, however. How can this definition apply to organisms that reproduce asexually and therefore do not breed? Hybrids produced from parents of closely related but separate species are usually infertile, but not always. Some species are made up of a mosaic of DNA from multiple species. How should they be classified? Should they receive multiple species names if they are composed of more than one? How can we apply the concept to extinct species such as velociraptors when we cannot know from skeletons whether members of a population could interbreed?

Depending on which expert you ask, there are dozens of definitions of the word "species". We have discussed two so far: the morphological definition used in the 18th century, and a more recent definition, the biological species concept, involving the ability to breed and produce fertile offspring. But other characteristics can also be taken into account when deciding on what counts as a species, such as the following.

- The ecological niche of an organism. Because microbes are single-celled, it is challenging to use just morphology to determine what species they belong to. Where they live and what they eat can help classify microbes into different species.
- Genetics. When a sequence of DNA found in a sample of soil from a forest does not match any known sample, it suggests that it is from a species that has not been catalogued yet.
- The types of molecules an organism can produce. This is also useful when classifying microscopic organisms that do not have easily observable features, unlike birds and primates, for example. It is common to find microbes that produce carbon dioxide, but some can make methane or hydrogen gas.
- For extinct species, their lineage. If we find a fossil of an extinct snail that has a shell similar to a modern species, we can use the similarities to assign it a species name based on its position on the same part of the evolutionary tree as the existing species.



Microscopic soil organisms can be challenging to identify because morphology is insufficient as a criterion to differentiate species.

Nature of Science

To some extent, the debate about what a species really is becomes just as philosophical as biological. "Is all we are doing simply naming things?" "Do the categories we use actually exist in reality or just in our minds?" "Is the difficulty of agreeing on a definition a fault of the limitations of language?" "Is it possible to use the same term (species) for organisms that exist today and to express how their populations evolved over time?" These questions are currently being debated by biologists and, because the variety of life is so diverse, it is difficult to find a consensus.

A3.1.5 – Distinguishing between populations and species

A3.1.5 – Difficulties distinguishing between populations and species due to divergence of non-interbreeding populations during speciation
Students should understand that speciation is the splitting of one species into two or more. It usually happens gradually rather than by a single act, with populations becoming more and more different in their traits. It can therefore be an arbitrary decision whether two populations are regarded as the same or different species.

Speciation, as explored in more detail in Chapter A4.1, is the process by which a population is separated into two groups that can no longer reproduce together. One part of the population evolves one way and the other, living with different selection pressures and producing different sets of mutations, evolves in a different way. The two populations become different enough over time that they can no longer interbreed to produce fertile offspring. As a result, a new species has branched off from the previous one, resulting in two species that have a common ancestor.

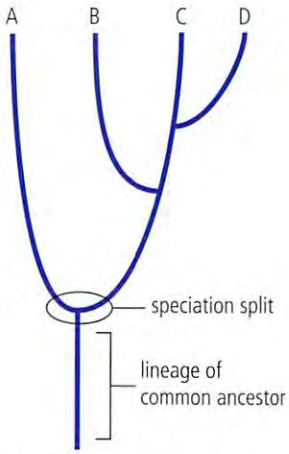
Lake Victoria in East Africa is, geologically speaking, a young lake, being only about 400,000 years old. Any fish species that live there have arrived since then. African cichlid fishes, of which there are over 200 species in the lake, all appear to have evolved from a single species introduced about 200,000 years ago. Each one has evolved in its own niche and as a result split off from the others. Some specialize in eating algae, some eat plankton and others eat snails. But each split would have taken many generations and, during those generations, the population that started to explore the new source of food would have continued to interbreed with some success with the original population. As the two populations became more different from each other, the success rates of interbreeding would have diminished until it was no longer possible. It is difficult for specialists to decide when the speciation occurred. When a cut-off point is chosen, it has an arbitrary and subjective aspect to it.

The last woolly mammoth became extinct thousands of years ago. It appeared to share many similar characteristics with today's Asian elephants (*Elephas maximus*), which is why it was originally classified in 1799 in the same genus, as *Elephas primigenius*. Because of the gap in time, it is difficult to apply the biological species concept to decide whether or not the two populations are one and the same species, because there are no living mammoths to test the hypothesis by breeding them with elephants. The mammoth's scientific name has since been changed to *Mammuthus primigenius*, without knowing for sure whether they could breed together or not, so it is a relatively arbitrary decision from the point of view of the biological species concept.

What might cause a species to persist or go extinct?

▲ The woolly mammoth went extinct thousands of years ago. We cannot test whether it was able to breed with modern elephants or not.

Figure 1 shows a common ancestor giving rise to four species. The first speciation event shown happened earlier in time, then the split that generated species B occurred, and, finally, D split from C. Although this type of diagram helps illustrate the sequence of events, it gives the impression that the splits occurred suddenly, which is not always the case.



▲ **A3.1 Figure 1** Species A, B, C and D evolved from a common ancestor. Three speciation splits led to the generation of these species, the first of which is circled.

A3.1.6 – Diversity in chromosome numbers

A3.1.6 – Diversity in chromosome numbers of plant and animal species
Students should know in general that diversity exists. As an example, students should know that humans have 46 chromosomes and chimpanzees have 48. Students are not required to know other specific chromosome numbers but should appreciate that diploid cells have an even number of chromosomes.

Diploid and haploid cells

The term **diploid** is used to describe a nucleus that has chromosomes organized into homologous pairs. Most cells in the human body are diploid cells, and in such cells the nucleus contains a set of 23 chromosomes from the mother and 23 from the father. There is a category of cells that only contain 23 chromosomes in total: the sex cells, also called **gametes**. Because the chromosomes in sperm and egg cells do not come in pairs, but rather only have a single chromosome from each pair, they are said to be **haploid**. The adult form of animal cells is rarely haploid, but there are exceptions, for example adult male bee, wasp and ant cells are haploid. Generally speaking, the vast majority of cells in sexually reproducing organisms are diploid, and only the gametes are haploid.

Note in Table 2 that diploid cells always have an even number of chromosomes. This is logical because one chromosome in each pair comes from one parent and the other from the other parent.

The variable n represents the **haploid number**, and it refers to the number of sets of chromosomes that a nucleus can have. For a human egg cell, $n = 23$. When an egg cell is fertilized by a sperm cell (a sperm is also haploid and therefore contains 23 chromosomes), a **zygote** is formed and the two haploid nuclei fuse together, matching up their chromosomes into pairs. Hence humans generally have a total of 23 + 23 = 46 chromosomes. This means that in humans, $2n = 46$, so diploid cells in humans have 23 pairs of chromosomes making a total of 46 chromosomes. Compare this number with some of the other species in Table 2.

A3.1 Table 2 A comparison of types of cells and chromosome numbers

	Types of cells and chromosome numbers	
Species	**Haploid = n**	**Diploid = $2n$**
Human (*Homo sapiens*)	23	46
Chimpanzee (*Pan troglodytes*)	24	48
Domestic dog (*Canis familiaris*)	39	78
Rice (*Oryza sativa*)	12	24
Roundworm (*Parascaris aquonum*)	1	2

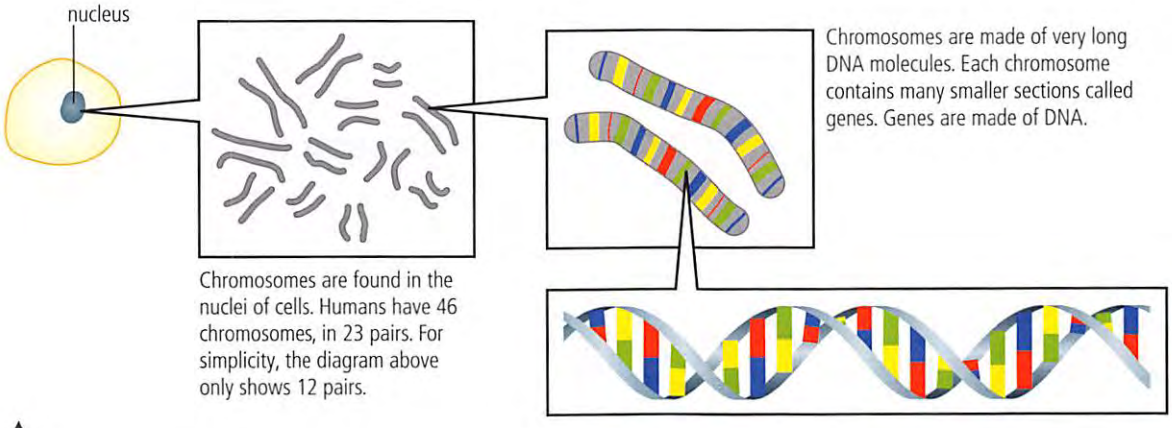
The number of chromosomes is a characteristic of a species

As you can see from Table 2, the number of chromosomes for humans (46) is very different to the number of chromosomes for the roundworm. One of the best-studied worms in genetics laboratories is *Caenorhabditis elegans*, whose genome was first sequenced in 1998. It has six chromosomes, meaning its diploid number, $2n$, is 6, and therefore its haploid number, n, is 3. It would be expected that all the cells in C. *elegans* would have six chromosomes, and, likewise, that all cells in humans would have 46. Although this is true for most cells, we have already seen the exception of haploid cells (n). Note as well that some cells do not contain a nucleus and have no chromosomes, such as red blood cells.

A3.1.7 – Karyotypes

A3.1.7 – Karyotyping and karyograms
Application of skills: Students should be able to classify chromosomes by banding patterns, length and centromere position. Students should evaluate the evidence for the hypothesis that chromosome 2 in humans arose from the fusion of chromosomes 12 and 13 with a shared primate ancestor.
NOS: Students should be able to distinguish between testable hypotheses such as the origin of chromosome 2 and non-testable statements.

A **karyogram** is a representation of the chromosomes found in a cell arranged according to a standard format, as in the example in Figure 2. The chromosomes are placed in order according to their size and shape. The shape depends mainly on the position of the **centromere**. A karyogram is used to show a person's **karyotype**, which is the specific number and appearance of the chromosomes in their cells.



▲ Zooming into a cell reveals where DNA is found.

A3.1 Figure 2 This is a karyogram showing all 23 pairs of chromosomes. What can we learn about the individual's karyotype from this figure? This karyogram was prepared using false-colour imagery.

SKILLS

You can use online tools to prepare your own karyogram by arranging chromosomes by size, banding patterns and the position of the centromere. The website Learn.Genetics from the University of Utah has an activity called "Make a karyotype", for example. Once you have made a karyogram, you can learn certain details about the person. Use the karyogram in Figure 2 to determine whether the individual is a male or a female. How do you know? Does the individual's karyotype include any anomalies? If so, describe what you see. For more about the consequences of extra or missing chromosomes, see Chapter D2.1.

How is a karyogram image obtained? Once the cells of an organism have been collected and grown in culture, a karyogram is made following the steps below.

1. The cells are stained and prepared on a glass slide, to see their chromosomes under a light microscope.
2. Photomicrograph images are obtained of the chromosomes during a specific phase of cell division called the mitotic metaphase (see Chapter D2.1).
3. The images are cut out and separated, a process that can be done using a print out and scissors or on a computer.
4. The images of each pair of chromosomes are placed in order by size and the position of their centromeres. Generally speaking, the chromosomes are arranged in order by decreasing length. The exception is in the 23rd pair of chromosomes, which can contain one or two X chromosomes, which are considerably larger than the chromosomes in the 22nd pair (see the chromosome pair marked X in Figure 2). In addition, the coloured bands that show up in the image can be used to identify which chromosome it is. For example, chromosomes 3 and 4 in the image show very different banding patterns.

The evolution of human chromosome 2

Modern humans have 46 chromosomes. Other human species that no longer exist but whose preserved fossil DNA we can study, such as Neanderthals and Denisovans, also had only 46 chromosomes. Gorillas and chimpanzees are the species most closely related to humans. Our last common ancestor with gorillas existed about 9 million years ago and the speciation split with chimpanzees occurred about 6 million years ago. However, when we prepare a karyogram of the contents of their nuclei, both gorillas and chimpanzees have 48 chromosomes instead of 46. If we shared a common ancestor with them, what happened to our chromosome number?

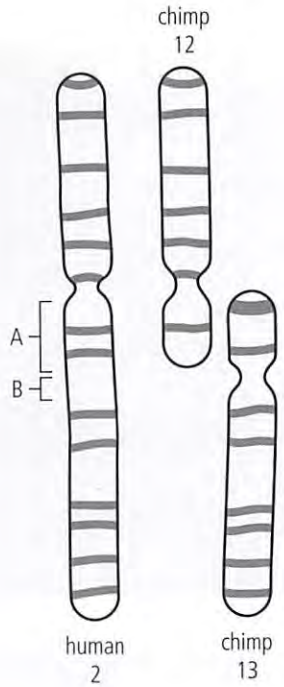
Two possible hypotheses can be formulated:

1. a complete chromosome disappeared
2. two chromosomes from an earlier common ancestor fused to become a single chromosome.

It is unlikely that an entire chromosome was deleted and disappeared, because removing hundreds of genes in that way would cause a major threat to the viability of the species. To test the second hypothesis, we can look for evidence, and can start by examining the two characteristics that help identify a chromosome: its shape (position of the centromere) and its banding patterns. One shape a chromosome can have is the "X" shape, with the centromere close to the centre. This is called a **metacentric** chromosome. Chromosomes can also have an **acrocentric** shape, meaning the centromere is at one end, making one arm of the chromosome much shorter and the other much longer. All primates have both types.

One hypothesis is that chromosome 2 in humans arose from the fusion of chromosomes 12 and 13 in a shared ancestor. In an article from *Molecular Cytogenetics* by Paweł Stankiewicz in 2016, human chromosome 2 was compared to chimpanzee

chromosomes 12 and 13. In terms of shape, these two acrocentric non-human chromosomes, when placed end to end, have a similar length to the human chromosome, although some parts overlap. The position of the centromere in human chromosome 2 lines up with the chimpanzee chromosome 12 but not with chromosome 13. This latter piece of evidence refutes the hypothesis. However, in the zone marked B on the human chromosome in Figure 3, we find the type of DNA we usually encounter in the centromere, known as **satellite DNA**, which consists of short repeating sequences of DNA. This zone corresponds to the position of the centromere in the non-human chromosome 13, giving credibility to the hypothesis. In terms of banding patterns, the long arm of chimpanzee chromosome 12 matches that of the short arm of human chromosome 2, and the long arm of chimpanzee chromosome 13 matches the banding patterns of the long arm of human chromosome 2.



A3.1 Figure 3 A comparison of human chromosome 2 with chimpanzee chromosomes 12 and 13.

Besides shape and banding patterns, other evidence to support the idea of fusion is the presence of telomeric DNA in the centre of human chromosome 2. The **telomeres** are caps at the tips of chromosomes that contain repeating sequences of DNA and provide protection, the same way that bumpers protect cars and aglets protect the ends of shoelaces. Such repeating telomeric DNA is not supposed to be in the centre of chromosomes, only at the tips. And yet, at position A in the human chromosome 2 shown in Figure 3, telomeric DNA is present at the position where the two chromosomes would have fused.

It is very important to understand that this evidence does not say we descended from chimpanzees. The fusion of the chromosomes would have happened after the speciation split of a common ancestor that led to the evolution of chimpanzees on one branch of the tree of life and the evolution of humans on another branch.

When asked to evaluate evidence for a claim, scientists and students need to express their opinion of whether or not the evidence is sufficient to convincingly confirm the claim. Some questions to consider asking are:

- Is the quantity of evidence sufficient to accept the claim?
- Has the method for collecting evidence been repeated and tested by other scientists, and have they found similar evidence?
- Is the method being used a reliable method?
- Are any counterclaims or refuting evidence enough to doubt the claim?
- Is there a mechanism to explain the cause, or is what we are seeing just a coincidence?

Nature of Science

Some claims are testable and others are not. The hominid fossil nicknamed Lucy, discovered in Ethiopia in 1974, is complete enough to test and confirm claims such as (1) she was a female, (2) she was not a modern human but rather an australopithecine, (3) she could walk on two legs and (4) she lived about 3.2 million years ago. There might be some debate about the details, but the challenges can also be tested. Can you think of any claims about her that would not be testable? For example: "Lucy had a great sense of humour." "Lucy had a recurring dream where she encountered a wildcat." "Lucy spoke three languages." Current tools in science have no way of testing these claims. Statements like these are speculation. What about these: "Lucy had very little meat in her diet." "Australopithecines such as Lucy had strong spiritual beliefs." Are they testable claims?

Some claims about the fossil called Lucy are testable and others are not.

A3.1.8 – Unity and diversity of genomes

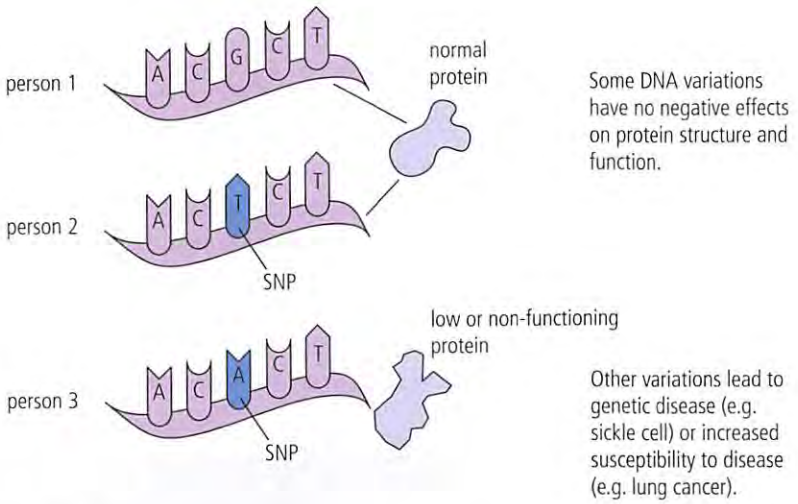
A3.1.8 – Unity and diversity of genomes within species
Students should understand that the genome is all the genetic information of an organism. Organisms in the same species share most of their genome but variations such as single-nucleotide polymorphisms give some diversity.

It seems counterintuitive, but it is possible to find lots of evidence to support the claim "we are all the same", and it is also possible to find lots of evidence to support the claim "we are all different". From a genetics point of view, humans share many more similarities than differences with each other, especially compared to another species.

If a chimpanzee was walking down your street, you would recognize right away that it was a non-human primate. And yet, the genetic difference between us and chimpanzees is only about 4%. That is a much bigger difference, however, than between you and other humans, which is estimated to be 0.1% to 0.6%. Why does *Homo sapiens* display so many similarities within its global population? Our unity arises

largely from the fact that all humans share the same genes. We do not all have the same versions of each of the genes (called **alleles**, see Chapter D3.2); some of us have type B blood and some have type O, for example. But we all possess the genes that determine the ABO blood type.

Where do we find these small but crucial differences between humans? The estimated 3 million to 20 million **base pairs** (e.g. A–T or G–C) of our DNA sequence that can reveal the differences are found scattered all over our chromosomes. Where most people have a T (thymine) nucleotide, for example, a small portion of humans might have a G (guanine) instead at that position. Such variations can start out as mutations (see Chapter D1.3) but are then passed down from generation to generation. Such a variation involving only one base is called a **single nucleotide polymorphism** or SNP (see Figure 4). It is estimated that about every 100 to 300 bases in a human's genetic code contains an SNP. Geneticists interested in the human genome have identified millions of SNPs, and they can be used to help determine ancestry or risk of genetic diseases.



A3.1 Figure 4 Person 1 has a gene that expresses a normal protein. Person 2 has a T (thymine) nucleotide instead of a G (guanine) in the SNP, but also expresses a normal protein. Person 3, however, has an SNP that causes the protein to not form correctly.

Only about 5% of SNPs are functional, meaning they actually produce a difference in a person's body. Most are neutral, meaning that they will not affect a person's **phenotype** (the physical expression of a gene, such as blood type or colour vision, see Chapter D3.2).

The Human Genome Project

In 1990, an international cooperative venture called the Human Genome Project set out to sequence the complete human **genome**. Because the genome of an organism is a catalogue of all the bases it possesses, the Human Genome Project hoped to determine the order of all the bases A, T, C and G in human DNA. As there were approximately 3,200,000,000 to find, it took over a decade. In 2003, the Project announced that it had succeeded in achieving its goal. Now, scientists are working on deciphering which sequences represent genes and which genes do what. The human genome can be thought of as a map that can be used to show the position of any gene on any one of the 23 pairs of chromosomes.

i In the 1997 science fiction film *GATTACA*, one of the main characters brings a sample of cells to a walk-up window at an establishment that provides anonymous genome services. Within seconds, she gets a full printout and analysis of the genome she is interested in. How far are we from being able to do this today? What ethical implications are there to such a service? Are there laws protecting your genome?

Thanks to modern communication technologies, it is possible for scientists working all over the world to collaborate and contribute to a scientific endeavour such as sequencing the genome of plants that help feed the world. Rice is one example: biologists from 10 countries contributed to sequencing the first rice genome.

The current estimate is that humans have approximately 22,000 genes, and, thanks to advances in technology, the sequencing of a person's genome can be done in hours instead of years.

TOK

Many companies offer genome sequencing for private citizens willing to pay the price. Some of the products reveal ancient family origins and risk factors for some health problems, such as the chances of developing certain types of cancer or heart disease. Would you want to know if there is a chance that your life could be suddenly shortened by the presence or absence of a certain gene? Would you tell your family and friends? Would you want your parents to have such a test? Should people tell their employer or each other about any health-related issues revealed by a genomic analysis? Or, in contrast, is this a private, personal thing that no one else needs to know about? How accurate and reliable are these analyses? Should we believe everything they say? Does all knowledge impose ethical obligations on those who know it?

A3.1.9 – Eukaryote genomes

A3.1.9 – Diversity of eukaryote genomes

Genomes vary in overall size, which is determined by the total amount of DNA. Genomes also vary in base sequence. Variation between species is much larger than variation within a species.

No humans have genes for characteristics such as bioluminescence (glowing in the dark), which many deep-sea organisms do. Although we see some diversity among humans, we do not see such huge ranges of diversity in the human population as wings for flight, gills to breathe underwater, echolocation organs for seeing without light, chloroplasts for photosynthesis, and so on. There is more unity within the human species (comparing any two humans) than diversity compared to other species (comparing humans to non-humans).

Humans are a diverse global population but there are remarkably few differences between any two humans compared to differences between humans and other species.

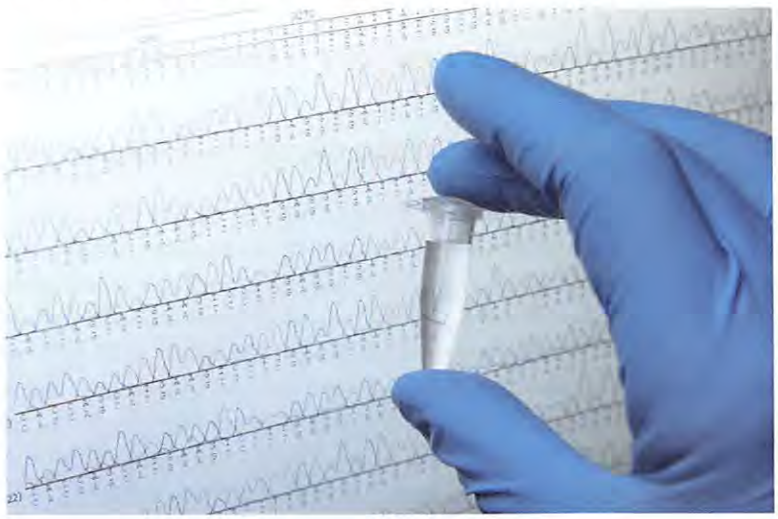
One major difference between genomes is their size: the quantity of DNA they have in their nuclei. As we will see in Section A3.1.10, some eukaryotic genomes only have a few thousand genes while others can have tens of thousands of genes. This means that one eukaryote will possess genes that another will not have at all. A fish does not

need to have genes to produce pollen, and a rose bush does not need genes for making fins to swim. Even with closely related species that have undergone a relatively recent speciation split, they have been evolving separately to the point where the genes are now different enough that they cannot interbreed anymore.

Such differences can be seen in the sequences of base pairs in each genome. Sequencing technology along with databases and computer programs for searching and comparing large data sets have allowed biologists to compare the genomes of organisms from all over the world.

Bioinformatics is a research field that uses both computer science and information technology to help us understand biological processes. Bioinformatics has grown exponentially in recent years. The most data-rich area of bioinformatics is genomics. Genome data is now available in public databases such as The National Center for Biotechnology Information (NCBI). Genetic information can also be explored using the following databases:

- Swiss-Prot, a database of protein sequences
- Ensembl, a database and browser of genomic information about humans and other vertebrates
- GenBank, a National Institutes of Health genetic sequence database that is an annotated collection of all publicly available DNA sequences.



A micropipette containing a DNA sample can be sequenced and added to a database and shared worldwide thanks to web-based information technology.

Instead of sifting through the entire genome of an organism, one way to compare genetic diversity in eukaryotes is to focus on their **mitochondrial DNA**. All eukaryotes have mitochondria, and the way mitochondrial DNA, present only in the egg, not in the sperm cell, is passed down from mother to offspring, means there is not the shuffling and mixing that we see in chromosomal DNA. It is estimated that, within a species, roughly 1 in 1,000 of the genetic code letters is different between individuals' mitochondrial DNA. These genetic differences are expressed in the amino acid sequence that is coded for by the organism's DNA sequence. To see differences between individuals within a species, or to see differences between species, it is possible to look up the amino acid sequences for a particular gene in a database and match them to see if there are amino acids missing, added or modified. Instead of the DNA bases A, T, C and G being displayed, the letters in the databases correspond to the 20 possible amino acids, such as S for serine, G for glycine, A for alanine and V

for valine. Some amino acids have a letter that is different from their first letter, such as E for glutamic acid, F for phenylalanine and K for lysine. You will not be asked to memorize the 20 amino acid names and their letters, but you do need to understand that, when comparing genetic differences, it is possible to either use the DNA code or the amino acid sequences.

Table 3 shows part of the sequence for a single gene selected from the online UniProt protein database. The chosen gene is one that all eukaryotes have in their DNA: *cyc1*, the gene for cytochrome c, which is a protein needed by mitochondria to perform their essential task of cellular respiration, to convert sugar into usable energy. Of the hundreds of species available in the database, four species of animal were selected and, rather than looking at all the amino acids that the gene codes for, a short sequence of 60 amino acids was selected for comparison. The differences between the first species and the three other species are highlighted in yellow.

A3.1 Table 3 Comparing a short sequence of 60 amino acids from the mitochondrial gene, *cyc1*, for cytochrome c, in four species

Database codes for specific species	Fragment of the sequence of amino acids coded for in the *cyc1* gene
golden-crowned babbler:	
TR|A0A7K9SBC6|A0A7K9SBC6_9PASS	SL--ALALSLGGGPLSAGELELHPPNFPWSHGGPLSALDHASVRRGFQVYRQVCSACHSM
brown-headed cowbird:	
TR|A0A7L3VSC4|A0A7L3VSC4_MOLAT	SLAVALSLSLGGGPVSAGELELHPPGLPWSHGGFLSALDHASVRRGFQVYRQVCSACHSM
green anole:	
TR|H9GCG1|H9GCG1_ANOCA	GLAVALH-----SAVSAGELELHPPSFPWSHSGPLSSLDHSSVRRGYQVYKQVCSACHSM
big-headed turtle:	
TR|A0A4D9DRJ9|A0A4D9DRJ9_9SAUR	GLALALH-----TAVSASDLELHPPSYAWSHNGLLASLDHSSIRRGYQVYKQVCAACHSM

The first organism in Table 3 is a bird, the golden-crowned babbler (*Sterrhoptilus dennistouni*), which lives in the Philippines. The next three organisms in Table 3 are a brown-headed cowbird (*Molothrus ater*), a lizard called a green anole (*Anolis carolinensis*), and a big-headed turtle that lives in Southeast Asia (*Platysternon megacephalum*). If we look at the first amino acid in the sequence for the first species, we see S, for serine. Moving down the second column in Table 3, we see that species 2 also has an S but species 3 and 4 have G for glycine instead. Species 1 does not have any amino acids at positions three and four, while the other three do. Of those three, they all have A for alanine in the third position but not all have V for valine in the fourth.

Not surprisingly, compared to the first bird's sequence, there are more differences in the lizard and in the turtle than there are in the other bird species, because the two bird species are more closely related to each other than they are to lizards and turtles. If we looked at the whole amino acid sequence and not just the fragment of 60 amino acids used for Table 3, we would see that the three species in Table 3 have the following percentage of matches with the golden-crowned babbler: 92.9%, 84% and 76.8%, respectively.

Between any two golden-crowned babblers, we would expect more than 99% of the amino acid sequence to be identical, with only one difference every few hundred amino acids. This illustrates that there is much more diversity between organisms in different species compared to organisms within the same species.

The Human Genome Project has shown that there are only a very small number of DNA bases that make one person different from any other person in the world. This creates a feeling of unity. All humans carry inside them a common genetic heritage.
On the other hand, the Human Genome Project has shown that the small differences that do exist make each person unique in terms of skin colour, facial features and resistance to disease, for example. These differences should be appreciated and celebrated as strengths. Unfortunately, they are often the basis of discrimination and misunderstanding.
Can one group of people be considered genetically superior to another? History has shown that many people think so, yet genetics shows that this is not the case. All human populations, whatever slight differences their genomes may have, deserve equal esteem as human beings.

A3.1.10 – Genome sizes

A3.1.10 – Comparison of genome sizes
Application of skills: Students should extract information about genome size for different taxonomic groups from a database to compare genome size to organism complexity.

Using online tools, it is possible to compare the genome of an organism, such as a fruit fly, with other eukaryotes. Table 4 shows data extracted from the NCBI database at the time of writing; because the database is being continually updated, the numbers you find might be different.

Species	Genome size in millions of base pairs, Mb
Saccharomyces cerevisiae, baker's yeast	12.1
Drosophila melanogaster, fruit fly	143.7
Mus musculus, house mouse	2,500
Escherichia coli, bacterium	5.12
Homo sapiens, modern human	3,200
Neoceratodus forsteri, Australian lungfish	34,557.6
Plasmodium falciparum, a parasite that causes malaria	22.9
Oryza sativa, rice	420
Caenorhabditis elegans, a nematode worm	100

A3.1 Table 4 A comparison of genome sizes of various organisms

Escherichia coli, a bacterium that lives in your large intestine, has about 5 million letters (base pairs) in its DNA code.

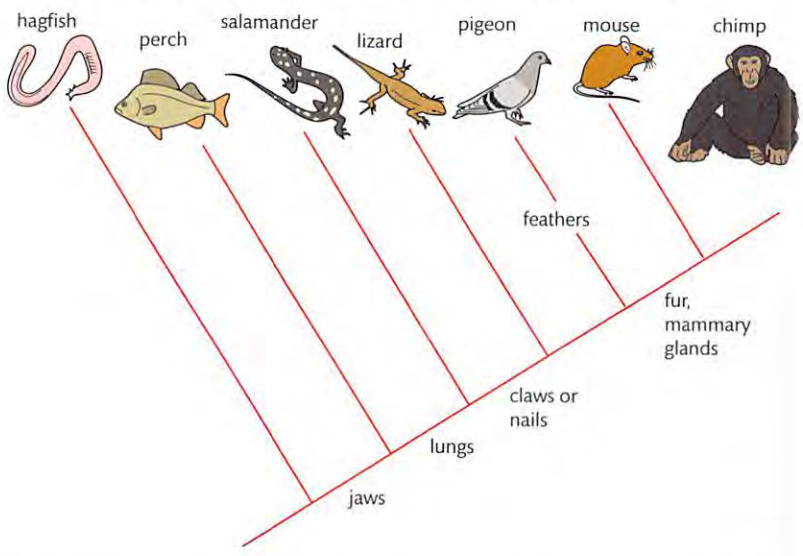
Do you get the impression that the more complex an organism is, the bigger its genome is? For example, we think of humans as being extremely complex and advanced, so when we compare ourselves to the fungus in Table 4, the baker's yeast, we see that our genome size is hundreds of times bigger. But rice has only three times more DNA than the fruit fly. And when we compare our human genome size to the Australian lungfish, it is ten times smaller. Does that mean lungfish are more complex than we are or that we are more complex than yeast? It depends on our definition of complex. Although they may not be capable of doing creative and complex tasks such as sending a spaceship to Mars, both lungfish and yeast can survive in conditions in which humans would die. The examples given and the ones you can find on your own will often give the impression that genome size can indicate complexity, but there are enough exceptions to conclude that it is not a reliable indicator.

A3.1.11 – Whole genome sequencing

A3.1.11 – Current and potential future uses of whole genome sequencing
Include the increasing speed and decreasing costs. For current uses, include research into evolutionary relationships and for potential future uses, include personalized medicine.

Researchers are very excited about genome sequencing because it allows them to identify species and compare them to see evolutionary relationships. They can compare whole genome sequences to see how organisms are related to each other. Such a technique is known as **phylogenetics**. In general, organisms that share similar genomes tend to be more closely related than those that do not.

In Figure 5, the mouse is shown to be much more closely related to the chimpanzee than to the salamander. The DNA sequences (or corresponding amino acid sequences) of the mouse and the chimpanzee would show fewer differences between each other than if one of their DNA sequences was compared to the salamander's genome. In humans, it can tell us about our ancestry, and about possible health risks related to the genes we have inherited.

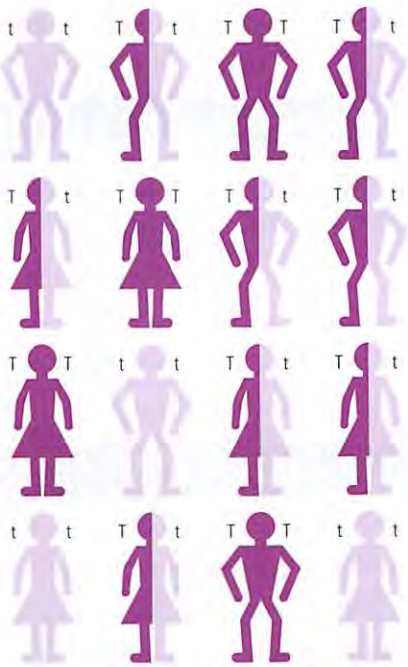


A3.1 Figure 5 A phylogenic tree of vertebrate chordates

Thanks to **next-generation sequencing techniques**, which use a mix of laboratory hardware, chemical markers and powerful software to increase the speed and decrease the cost of sequencing people's genomes, it is possible for private citizens in some countries to get their genomes sequenced. Other countries have made it illegal to

request genome sequencing: laws have been put in place to protect people's privacy. A parent who has put up a child for adoption and does not wish to be identified, for example, might have their identity revealed by this technology even if they do not have their own genome scanned, because a close relative's genome might be sufficient to find the match. In other countries, such services are fully legal and gaining popularity. Several companies in the United States offer genomic testing and provide detailed reports about ancestry and possible health issues related to DNA.

One potential such sequencing holds is the concept of **personalized medicine**, sometimes called precision medicine: information about a person's genetic makeup can be applied to an individual when prescribing treatments. The premise is that, if doctors know a patient's DNA profile, the best adapted treatment can be prescribed. When a doctor prescribes a drug today, the choice of molecule and the dose is based on studies involving people who might not be representative of everyone's genetic makeup. By sequencing the genomes of the participants in drug trials, patterns can be identified that suggest one drug might work better with people who possess a particular genetic sequence, but that for others, another molecule, combination of drugs or different dose would provide better results or perhaps fewer side effects.



A3.1 Figure 6 Knowing that a particular medication produces severe side effects only in people who receive the t version of an identified gene from both parents (*tt*) would allow doctors to know that four people in this group of patients should not be prescribed that medication. All the other patients have received a T from at least one parent (they are either *TT* or *Tt*) and can benefit from the medication without severe side effects.

Personalized medicine is better adapted for diseases that are dynamic, such as cancer, type 2 diabetes or cardiovascular disease, and require different treatments at different stages of the illness. Knowing more about how a patient's genome might cause new proteins to be produced in their cells or trigger certain genes to be turned on or off could lead to breakthroughs in medical treatments. By creating databases of biomarker profiles within a population (such as ***TT***, ***Tt*** or ***tt*** in the example in Figure 6), researchers of personalized medicine hope to provide better diagnoses and more effective treatments with fewer undesirable side effects.

Another advantageous use of the human genome is the production of new medications. This process involves several steps:

- find beneficial molecules that are produced naturally in healthy people
- find out which gene controls the synthesis of a desirable molecule

- copy that gene and use it to instruct synthesis of the molecule in a laboratory
- distribute the beneficial therapeutic protein as a new medical treatment.

This is not science fiction: genetic engineering firms are finding such genes regularly. One current line of research is dealing with genes that control ageing. How much money do you think people would be willing to pay for a molecule that could reverse the effects of ageing and prolong life by several decades?

Guiding Question revisited

What is a species?

In this chapter we have learned that:

- there is no single definition of the term "species" because the sheer variety of currently living species and extinct species is so enormous and complex
- using morphology works up to a point, but this methodology is poorly adapted for microbes or for species that are visually very similar
- the biological species concept works most of the time but is does not work for single-celled organisms that do not breed, or for organisms that are only found in the fossil record.

Guiding Question revisited

What patterns are seen in the diversity of genomes within and between species?

In this chapter we have discussed how:

- there is some diversity in genomes of individuals of the same species
- there is much more diversity when two different species are compared, especially if they were separated in a speciation event that occurred long ago.

Exercises

Q1. The system of giving a scientific or Latin name to organisms such as *Canis familiaris* is used worldwide. State the name of this system and identify the person who perfected and popularized it.

Q2. Distinguish between the morphological definition of species and the biological species concept.

Q3. Explain the features of chromosomes that are taken into consideration when making a karyogram.

Q4. Distinguish between haploid and diploid cells.

Q5. A karyogram can be used to determine if an unborn baby will be a girl or a boy. Explain how a karyogram is analysed to do this.

Q6. Outline the evidence for a fusion of ancestral chromosomes to become human chromosome 2.

Q7. Outline the advantages of personalized medicine using genomes.

A3 Practice questions

1. In a pollen grain of a species of flower, there are 20 chromosomes.

Which of the following is true of the species?

A $2n = 10$

B $2n = 20$

C $n = 10$

D $n = 20$ *(Total 1 mark)*

2. What determines the genomic size of a species?

A The total amount of DNA

B The total number of genes

C The total number of alleles

D The total number of chromosomes *(Total 1 mark)*

3. The table gives common names and binomial names for some mammals.

Common name	Binomial name
Golden bamboo lemur	*Hapalemur aureus*
Golden jackal	*Canis aureus*
Grey wolf	*Canis lupus*
Red fox	*Vulpes vulpes*

(a) Identify the **two** species most closely related. (1)

(b) Identify **two** species from the list that are classified in different genera. (1)

(Total 2 marks)

THEME

A Unity and diversity

4 Ecosystems

The hand on this marine iguana from the Galápagos Islands has five digits. It shares an ancestor with other species that have limbs with five digits. Species adapt to their environment, and when a population finds itself in a unique habitat such as the volcanic beaches of the Galápagos Islands, it can develop adaptations that might transform the genetic makeup of the population enough to make it impossible to breed with other members of the original population. When this occurs, a speciation has happened: where there was once only one species, there are now two.

This process has taken place ever since life first appeared on Earth. As a result the planet is rich in species that fill every available niche. Biodiversity is the variety of life in all its forms. However, humans impact their environment in a variety of ways and many of their actions result in a loss of biodiversity. Scientists fear that we are currently in the middle of the sixth mass extinction. Conservation programmes exist to try to halt the loss of species around the globe. For example, the Galápagos Islands are recognized as an area of particular species richness and the whole area is now a national park. National park status means that the area is carefully managed to preserve the species that live there.

A4.1 Evolution and speciation

Guiding Questions

What is the evidence for evolution?

How do analogous and homologous structures exemplify commonality and diversity?

There is abundant evidence for evolution, and we will examine three types: molecular evidence from genetic data and amino acid sequences; experimental evidence from selective breeding of animals and plants; and morphological evidence from homologous structures, which are features of organisms that reveal they come from a common ancestor. Appendages with five bony digits can be found in animals as diverse as lizards, whales and bats, illustrating the diverse ways in which a limb can be used, such as for walking, swimming and flying. But the uniformity in bone structure and positions within the limbs also reveals that all these organisms had a common ancestor. In addition to homologous structures, there are analogous structures, which evolved on different branches of the tree of life but which serve the same purpose, for example wings in birds and insects. Wings allow flight in both these groups of organisms, but they have not evolved from the same body parts.

A4.1.1 – Evolution

A4.1.1 – Evolution as change in the heritable characteristics of a population
This definition helps to distinguish Darwinian evolution from Lamarckism. Acquired changes that are not genetic in origin are not regarded as evolution.
NOS: The theory of evolution by natural selection predicts and explains a broad range of observations and is unlikely ever to be falsified. However, the nature of science makes it impossible to formally prove that it is true by correspondence. It is a pragmatic truth and is therefore referred to as a theory, despite all the supporting evidence.

TOK

Darwin was very reluctant to publish his ideas, in part because he knew how controversial they were at the time. He knew that other scientists would be highly sceptical of his work and would challenge it strongly. It is only when he read Wallace's ideas outlining a very similar theory that he decided to publish: he was afraid Wallace would get all the credit. Using this example, do you think competition between scientists helps or hinders the production of knowledge?

Darwin and Wallace

At the age of 22, Charles Darwin had the opportunity to travel on board the *HMS Beagle* for a scientific exploration mission that started in 1831 and lasted for 5 years. Little did he know that it would allow him to see nature in a new way and come up with what would become one of the most important, controversial and misinterpreted ideas in biology: **the theory of evolution by natural selection.**

Darwin was not the only person to develop a theory to explain evolution. He was surprised to discover in 1858 that Alfred Russel Wallace had independently developed an almost identical theory. The two men presented their ideas jointly to the Linnaean Society in 1858.

What is evolution?

Evolution is defined as the process of cumulative change in the heritable characteristics of a population. The word heritable means that the changes must be passed on genetically from one generation to the next, which implies that evolution does not happen overnight. The word cumulative is in the definition to stress the fact that one change is not usually enough to have a major impact on a species. Finally, the word population is in the definition because the changes do not affect just one individual.

Evolution is defined as the process of cumulative change in the heritable characteristics of a population.

Over time, if enough changes occur in a population, a new species can arise in a speciation split (explored in Chapter A3.1). The members of the new population will be different enough from the pre-existing population that they originated from that they will no longer be able to interbreed.

Once evolution by natural selection is understood, many of the mysteries of nature are revealed. When the role of DNA in inheritance (genetics) became known, decades after Darwin's theory had been published, there was a chance that it might have contradicted evolution by natural selection; contradictions often arise with new developments in science, making us rethink and revise our theories. In fact, the opposite happened. DNA evidence provided new support for natural selection beyond anything Darwin could have dreamt of, and led to the **modern synthesis** theory, or neo-Darwinism, a combination of Darwin's ideas with the newer ideas of genetics (based on work by Gregor Mendel, also in the 19th century), which was only confirmed long after Darwin and Wallace had died. One of the fundamental insights of the modern synthesis is the concept of common ancestry (which is explored in Chapter A3.1).

Lamarckism

Darwin and Wallace's theory replaced a previous idea formulated by French naturalist Jean-Baptiste Lamarck. His theory was that organisms acquired characteristics through their lifetime and then passed them on to their offspring. For example, Lamarck explained how kangaroos developed more powerful hind limbs and tails during their lifetimes by using them a lot while letting their forelimbs atrophy through underuse. These characteristics were then passed on to their offspring. That sounds plausible, but experiments designed to illustrate the passing on of acquired traits do not produce the results Lamarck expected.

One remarkable feature of kangaroos is the large discrepancy between the size of their forelimbs and hindlimbs.

Nature of Science

The theory of evolution by natural selection predicts and explains a broad range of observations and is unlikely ever to be completely falsified. Some parts of the theory have been falsified, however, such as the pace at which natural selection can work. Darwin thought it was always slow, but we have observed it happening in just a few generations. Darwin also incorrectly predicted that the fossil record would not contribute evidence to support his theory. Scientists do not throw out an entire theory just because there is some evidence against certain aspects of it. When new evidence is presented that contradicts a theory, the theory can be updated rather than being totally invalidated. The role of a theory is to explain the mechanism of how something works in nature, and the theory of natural selection explains evolution very convincingly. No theory has been developed since that has had any success replacing it. Equally, given the nature of science, it is not possible to formally prove that the theory of evolution is true, which means that it is referred to as a theory, in spite of all the evidence supporting it.

A4.1.2 – Biochemical evidence for evolution

A4.1.2 – Evidence for evolution from base sequences in DNA or RNA and amino acid sequences in proteins
Sequence data gives powerful evidence of common ancestry.

Your DNA includes genes that go back not just to your parents, grandparents and great-grandparents, but back to when we had a common ancestor with fish (roughly 400 million years ago) and beyond. Some, but not all, of those sequences are still inside you now. This explains how, during the development of human embryos, we have, for a period of time, slits in our neck that are similar to the parts of fish embryos that develop into gills.

Using modern bioinformatic tools, we can compare nucleic acid (DNA or RNA) and protein data from many organisms, including humans, to examine their evolutionary relationships. Computer software can process millions of codes in seconds, and compile the differences and similarities to show how species are related to each other.

Access the link on this page of your eBook for instructions on how to find DNA sequences in the NCBI database.

In other words, to show which species are more closely related (e.g. chimpanzees and humans) and which are more distantly related (e.g. humans and fish).

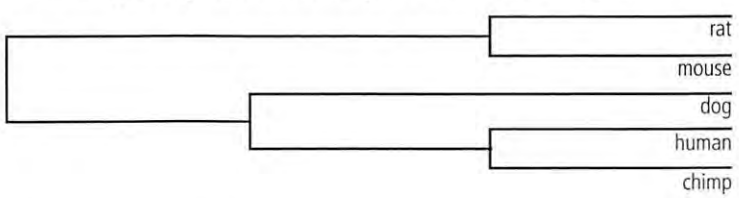
As an example, we can use a protein present in many organisms, haemoglobin, which is the oxygen-carrying molecule found in red blood. It contains four protein chains, two alpha and two beta. Using software that is easily available online, it is possible to compare the protein chains in different organisms. The results of a DNA sequence analysis are shown in Table 1.

Species	DNA nucleotide sequence	Number of base pairs
Rat	ATAATTGGCTTTCAGGCTAAGATGATA-G----GGAAATATATATTTTGCATATAAATTT	960
Mouse	ATAATTGGCTTTTATGCCAGGGTGACAGG----GGAAGAATATATTTTACATATAAATTC	1,003
Dog	ATTGTTGGAGTCA----------TATGGATTG	971
Human	AATTTCTGGGTTAAGGCAATAGCAATATCTCTGCATATAAATATTTCTGCATATAAATTG	1,192
Chimp	AATTTCTGGGTTAAGGCAATAGCAATATTTCTGCATATAAATATTTCTGCATATAAATTG * * * * *** ***	1,312

A4.1 Table 1 An excerpt showing 60 DNA nucleotides of compared sequences

Notice that in any position marked with an asterisk (*) under it, all the letters match in that column. In the other positions, there is at least one nucleotide that does not match with the others. Where there is a dash (–), a sequence does not exist there in that species. Only humans and chimpanzees have the middle four letters in this part of the sequence, for example. This implies that humans and chimpanzees are more closely related to each other than they are to the other organisms, and that they have a more recent common ancestor than the others. In fact, in this 60-letter sequence, between the human and chimpanzee there is only one nucleotide that does not match.

Although this line-by-line and base-by-base comparison is helpful, it is not easy to see which organisms are more closely related and which are more distantly related. Instead, we can use **phylogenetic trees**. Figure 1 shows an example.



A4.1 Figure 1 An example of a phylogenetic tree.

In addition to comparing A, T, C and G in DNA sequences, it is possible to compare RNA nucleotides or amino acid sequences to reveal evolutionary changes over time.

The phylogenetic tree in Figure 1 indicates the similarities and differences between the sequences of the haemoglobin beta gene, *HBB*, in different species. It suggests that there was a speciation split between rodents and other mammals early on, then a split between dogs and primates. But we must be careful: this is only what *one* gene reveals about our past. Humans have over 20,000 genes, so just looking at evidence from one is unlikely to tell the whole story of how organisms are related.

A4.1.3 – Selective breeding

A4.1.3 – Evidence for evolution from selective breeding of domesticated animals and crop plants
Variation between different domesticated animal breeds and varieties of crop plant, and between them and the original wild species, shows how rapidly evolutionary changes can occur.

Artificial selection and evolution

The breeding of domesticated animals such as cattle, horses, dogs, sheep and pigeons, provides a good opportunity to study changes in heritable characteristics.

By controlling which males mate with which females, animal breeders can make predictions about the characteristics the offspring will have. Over the years, breeders have learned to choose the males and females with the most agriculturally desirable genetic characteristics, and breed them together. This is called **selective breeding**.

This cow has been bred to have a straight back for easier birthing and long legs for easier milking using automated mechanical pumps. She is a product of artificial selection by humans and she never existed in this form before human intervention.

After practising selective breeding for dozens and sometimes hundreds of generations, farmers and breeders realized that certain varieties of animals now had unique combinations of characteristics that did not exist before. Today, the meat or milk available to us is very different from that which was produced thousands of years ago or even only a hundred years ago. This is thanks to the accumulation of small changes in the genetic characteristics of livestock chosen by breeders.

Although selective breeding is evidence that evolution is happening as a result of an accumulation of small changes over time, the driving force is, of course, human choice. The farmers and breeders choose which animals will reproduce together and which will not. This is called **artificial selection** and it should be obvious that it is certainly not the driving force of evolution in natural ecosystems.

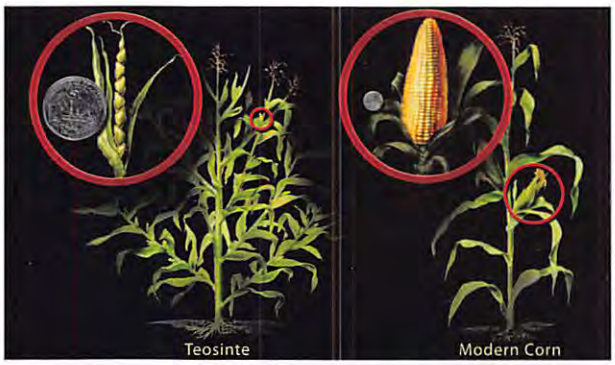
Plant breeding

Teosinte is a plant that you may never have heard of, but you probably consume its descendant every day. It is an ancient wild grass, from what is now Mexico, central America and the Andes region, that has small hard edible kernels. About 10,000 years ago, farmers in these regions started saving seeds from the plants that had the most desirable characteristics, and only planted those seeds the following season.

TOK

Animal breeding raises ethical questions. From an animal rights activist's point of view, breeding animals involves needless suffering and cruelty, including broiler chickens that grow too quickly for their bones to support their weight, and lifelong respiratory problems in certain dog breeds. From a breeder's point of view, they are providing safe, nutritious and affordable food for billions of people, or providing adorable pets to keep us company. Whose perspective is more convincing? What counts as a good justification for a claim?

The farmers selected plants that grew successfully in varied habitats, had larger ears with more kernels on them, and ears that were better protected by the outer leaves. Over countless generations, this artificial selection led to what today we call maize or corn (*Zea mays*) one of the most successful and widely planted crops on Earth. Hundreds of millions of tons of corn are grown every year.



Thanks to Neolithic farming techniques of artificial selection, teosinte was transformed into modern corn.

Maize is an ingredient in more foods than you might think. For example, high fructose corn syrup, HFCS, is a food additive found in everything from candy to fast food, to fruit-flavoured drinks and sweet carbonated drinks, all sold worldwide. If you are eating or drinking something that has corn syrup added, you are consuming a product from *Zea mays*.

Selecting seeds with specific desirable traits generation after generation leads to small changes that accumulate over time, and results in a very different plant. The remarkable transformation from teosinte to maize is an example of evolution by artificial selection, and the changes can happen in a geologically short time. Thousands of years or even a hundred years might sound like a long time to you, but compared to the time scale of species (i.e. millions of years), these time scales are extremely short.

A4.1.4 – Homologous and analogous structures

A4.1.4 – Evidence for evolution from homologous structures
Include the example of pentadactyl limbs.

Homologous structures

Homologous structures are structures derived from the same body part of a common ancestor. One of the most striking examples of a homologous structure is the five-fingered limb found in animals as diverse as humans, whales and bats. Such limbs are called **pentadactyl limbs** because "penta" means five and "dactyl" refers to fingers. Although the shape and number of the bones may vary, the general format is the same. However, the specific functions of the limbs may be very different. Darwin explained that homologous structures were not just a coincidence but evidence that the organisms in question have a common ancestor and have therefore evolved from that common ancestor.

The front right fin of a Southern right whale (*Eubalaena australis*), showing five articulated digits.

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Randy McGonegal's 43 years of teaching included 32 years of teaching IB Biology. He enjoyed leading over 100 workshops for new and experienced IB Biology teachers. He is now retired and enjoys travel, photography, golf and adventures with his six grandchildren.

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ISBN 978-1-292-42773-7

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