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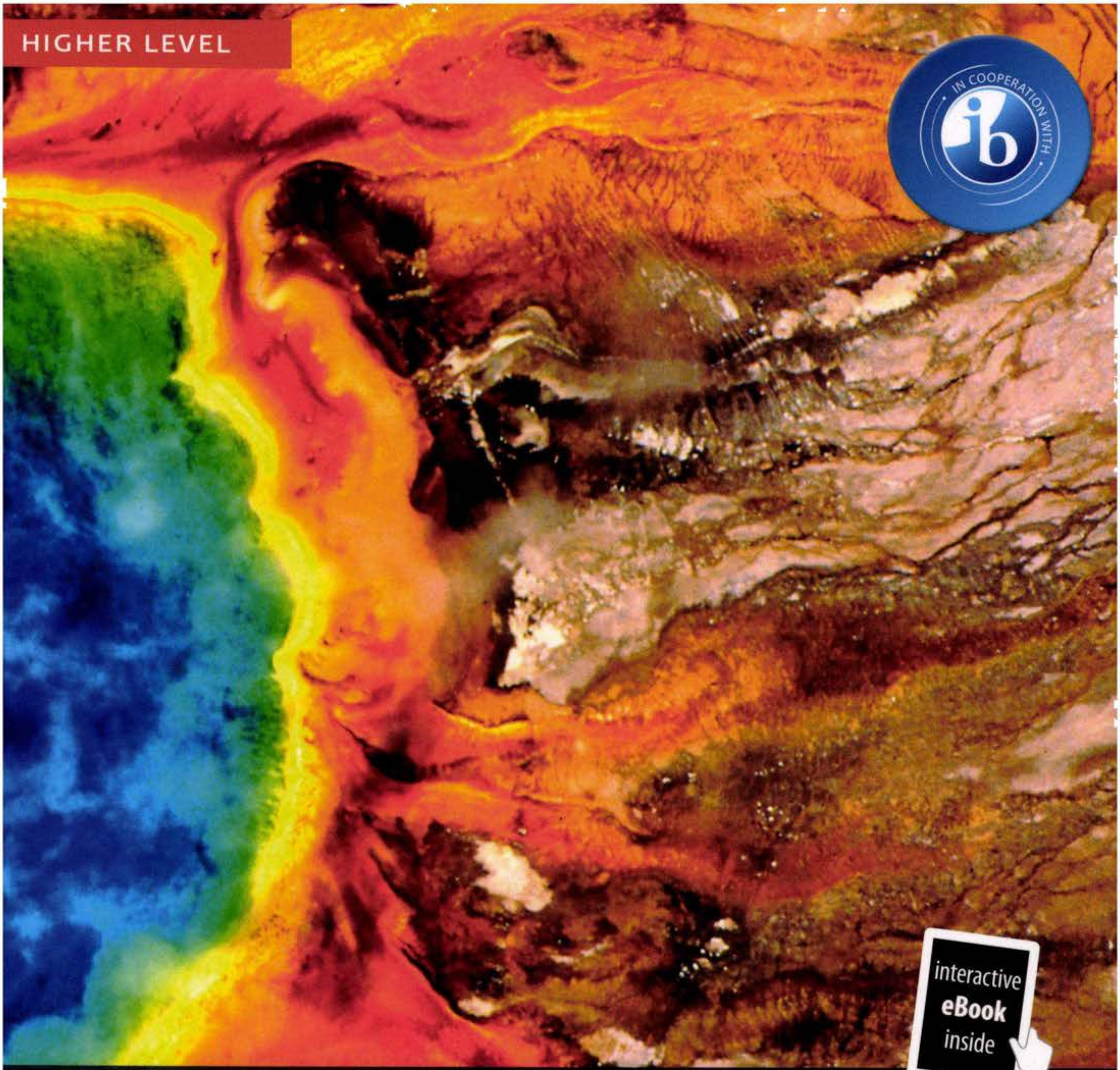

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HIGHER LEVEL

Biology

for the IB Diploma Programme

3rd Edition

Pearson

ALAN DAMON
RANDY McGONEGAL
WILLIAM WARD

HIGHER LEVEL

Biology
for the IB Diploma Programme

Alan Damon, Randy McGonegal, William Ward

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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	**A2.1** Origins of cells *[HL only]* **A2.2** Cell structure **A2.3** Viruses *[HL only]*	**A3.1** Diversity of organisms **A3.2** Classification and cladistics *[HL only]*	**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 compartmental-ization **B2.3** Cell specialization	**B3.1** Gas exchange **B3.2** Transport **B3.3** Muscle and motility *[HL only]*	**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	**C2.1** Chemical signalling *[HL only]* **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 **D2.2** Gene expression *[HL only]* **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 Higher Level (HL) 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

The Understandings are presented in the same sequence as in the subject guide, so that common Standard Level (SL) and HL content is covered first, followed by HL only material. The transition from SL to HL content is shown by icons as follows.

HL

Individual icons to identify HL material such as exercises and practice questions can also be found throughout the book.

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.

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).

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

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.

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

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.

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

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.

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.

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.	

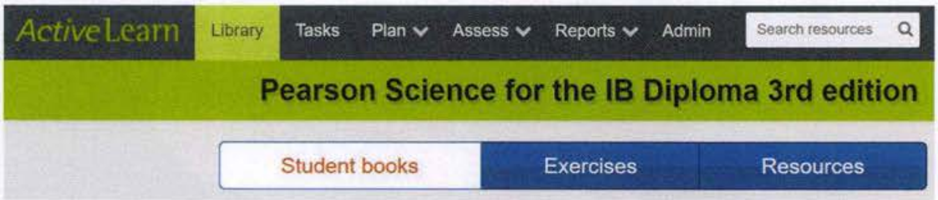
(4)

(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)

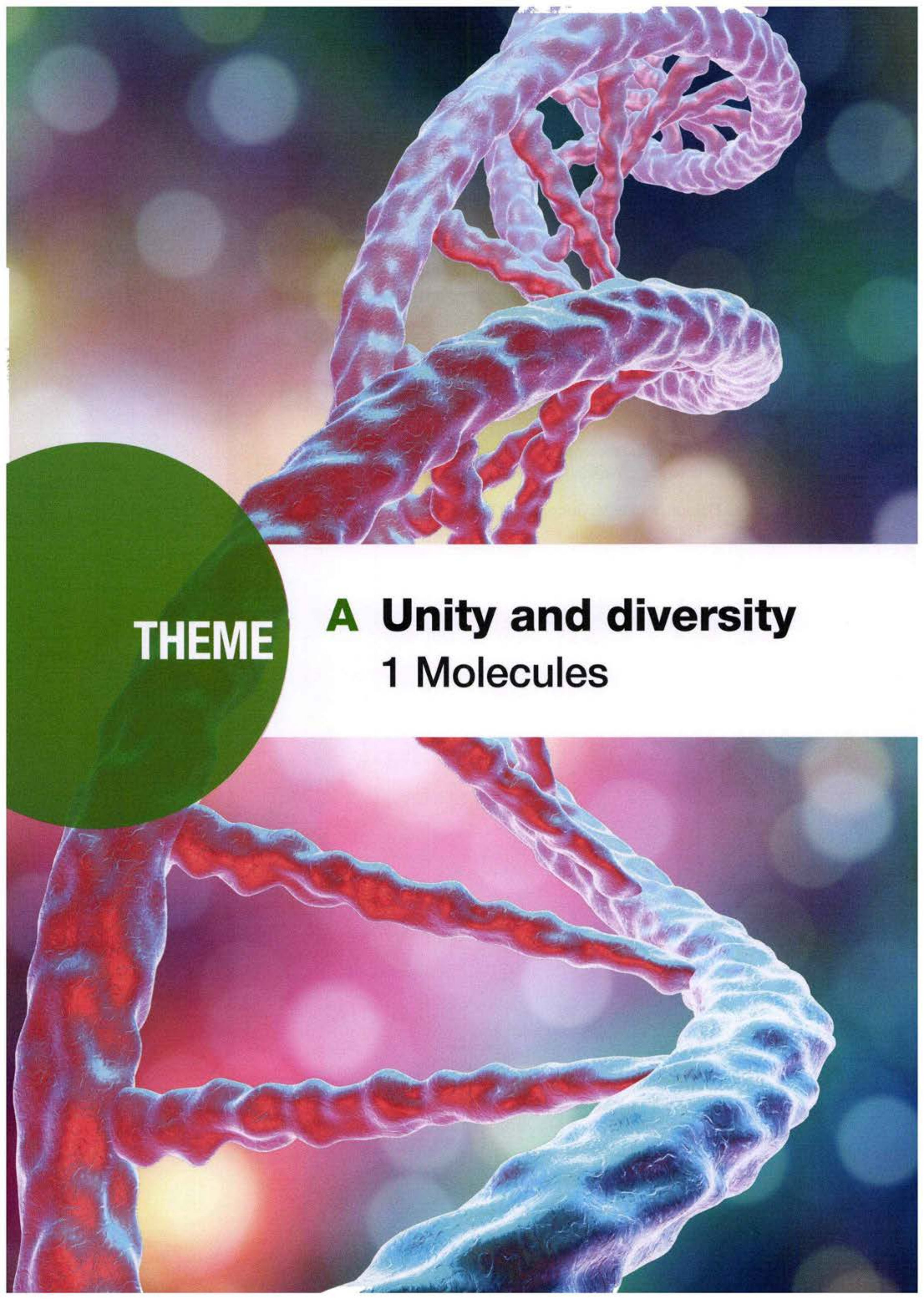
eBook

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.

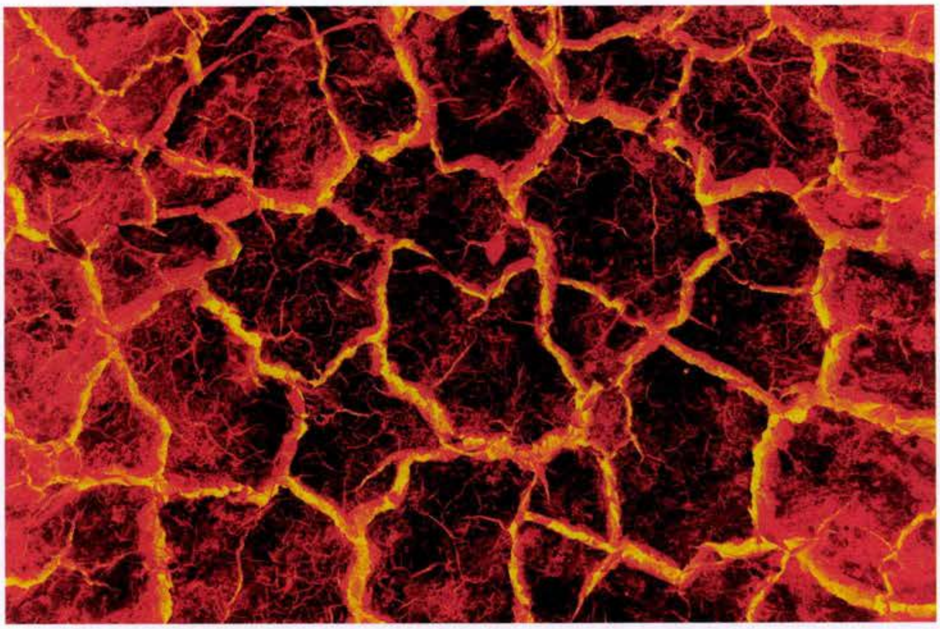
Water has both advantages and disadvantages for the aquatic and marine organisms that use it as a habitat. Advantages include the fact that water provides buoyancy and stable thermal properties for these organisms. Disadvantages include its relatively high viscosity compared to air. This means that many 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.



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.

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.

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

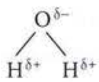
Measurements in science often change over time. If you research the world's deepest and tallest points you may find slightly different numbers (metres below and above sea level). There are various possible reasons including: how recently the data point was taken; what method was used to obtain the data; 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

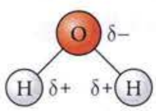
A1.1.2 – Hydrogen bonds as a consequence of the polar covalent bonds within water molecules

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.



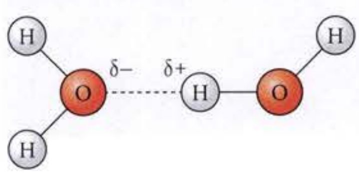
A1.1 Figure 1 This image shows the covalent bonds in a water molecule. Each of two hydrogen atoms is bonded at an angle to a single oxygen atom. Remember that each of the two covalent bonds is a pair of shared electrons.

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.

i 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.

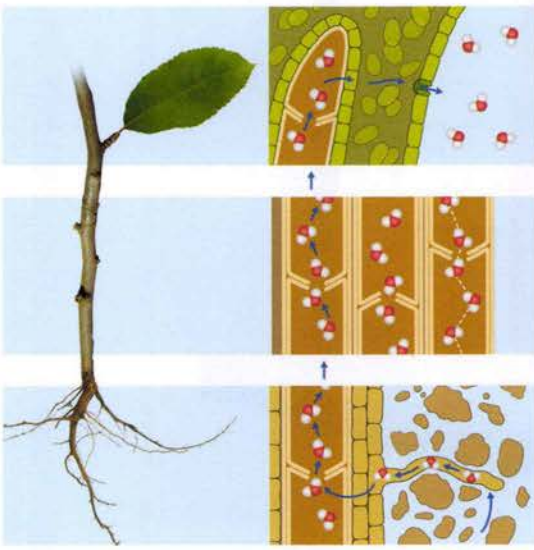
You can float a paperclip on water because of the surface tension of the water. Make sure you maximize the surface area of the paperclip on the water if you try this.

- 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.

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.

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 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.



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.

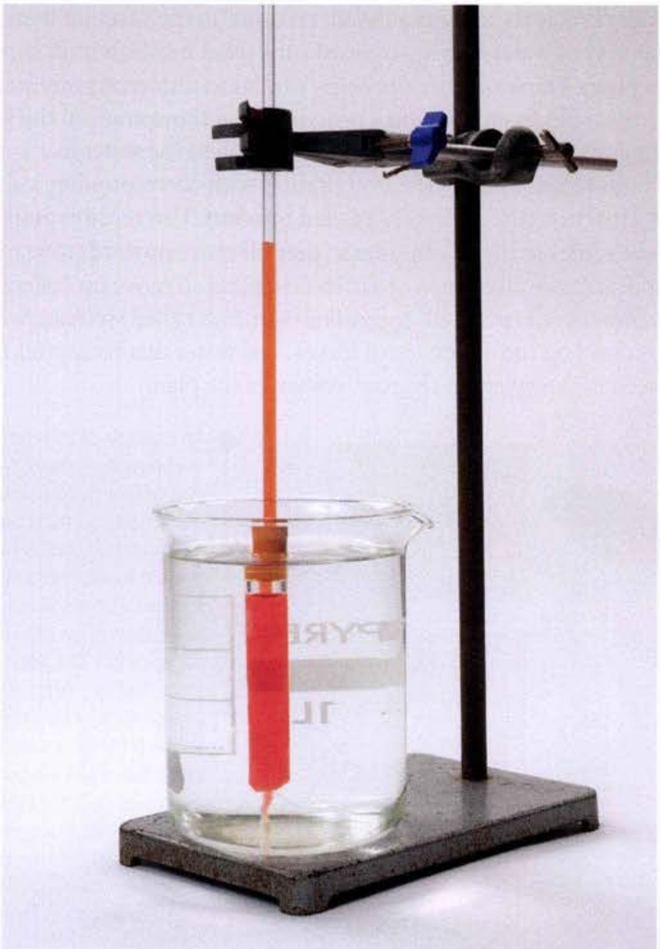
A1.1.4 – Adhesion between water and other polar substances

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).

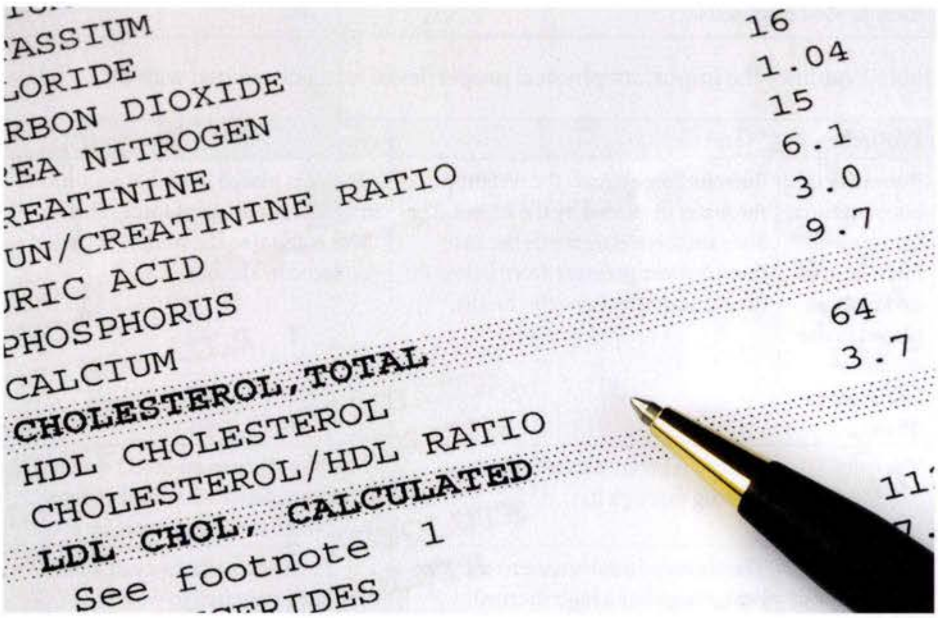
Hydrophilic molecules

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.

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.

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.

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*).

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

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.

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*).

HL

A1.1.7 – The origin of water on Earth

A1.1.7 – Extraplanetary origin of water on Earth and reasons for its retention

The abundance of water over billions of years of Earth's history has allowed life to evolve. Limit hypotheses for the origin of water on Earth to asteroids and reasons for retention to gravity and temperatures low enough to condense water.

Earth has excellent conditions for retaining its large volume of water. As stated previously, approximately 70% of the surface of Earth is covered by water and some of that water is very deep. Earth's temperatures allow water to change phases readily, but most remains as liquid water. In addition, our planet is large enough to have a gravitational pull to retain water on or near its surface. Some of the water that helps form our planet is almost permanently trapped deep in the crust. Temperatures deep in the Earth are tremendously high but there are a few opportunities for this water to escape.

Castle Geyser in Yellowstone National Park erupts once every 14–18 hours. The discharge of water is due to underground magma superheating water partially trapped in the crust. There are only a few areas on Earth where water deep in the crust can escape this way.

Water molecules exist in two forms. The difference between the two forms is the number of neutrons in the nucleus of the hydrogen atoms of the molecule. Typically, water contains "ordinary" hydrogen atoms without any neutrons. "Heavy water" contains hydrogen atoms that have a neutron. This hydrogen is called **deuterium**. All bodies of water contain a mix of these two forms, with typical water (no neutrons) being much more common. When researchers calculate the ratio of hydrogen to deuterium in the water of the oceans they get a ratio that is very similar to the ratio found in many asteroids.

Nature of Science

Several countries currently have space craft that are tracking near-Earth asteroids, some of which are known to contain a great deal of water. In addition, several land-based telescopes are also tracking other near-Earth asteroids attempting to pick up signals showing the presence of water. From this and other work it has been estimated that near-Earth asteroids may contain as much as 400 billion to 1,200 billion litres of water.

The water contained within asteroids is not liquid water. The water is in the form of hydrated minerals. These are solid mineral substances molecularly bonded to water molecules or its components.

A common theory is that Earth had an early stage where the surface was nothing other than magma, incredibly hot, molten rock that could not have retained or formed water. Over very long periods of geological time as the Earth cooled, numerous asteroids struck the Earth bringing hydrated minerals that released water, becoming part of the Earth's crust. Our planet's early history had many more asteroid collisions because of the unsettled time period of our early solar system and there were many millions of years in which the collisions could have occurred.

Artist's rendition of a large asteroid striking Earth.

NASA is pairing with some private companies to send an exploratory craft to an asteroid named 16 Psyche. This asteroid is about the size of the state of Massachusetts and is found in an asteroid belt between Mars and Jupiter. 16 Psyche is primarily a metallic asteroid and is projected to contain as much as 10,000 quadrillion US dollars-worth of valuable minerals. The first unmanned mission will be exploratory only, but it is expected that later missions could focus on mining operations for gold and other valuable substances.

Nature of Science

The asteroid theory for the existence of water on Earth is not the only scientific explanation. Some researchers believe that comets were a more important origin. Others believe that hydrogen was trapped in the original cloud of materials that formed the planet. The data is not conclusive for any one theory. Researchers will continue to add data and it is likely that a firm explanation will emerge over time. That is the way science approaches complex questions.

A1.1.8 – The search for extraterrestrial life

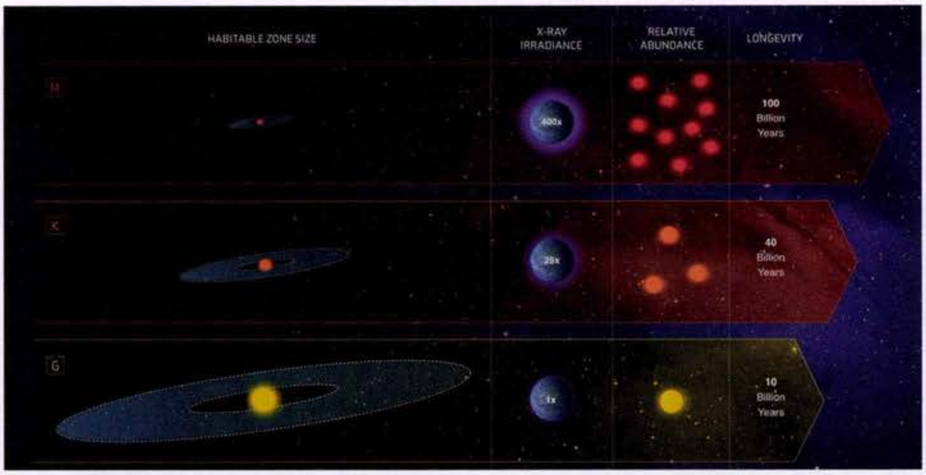
A1.1.8 – Relationship between the search for extraterrestrial life and the presence of water
Include the idea of the "Goldilocks zone".

Any planet that could possibly support life must have water. Like Earth, that planet must exist in an area of its solar system that would allow water to exist in its liquid form. This position of Earth in relation to the Sun is called the habitable zone or **Goldilocks zone**.

Earth is in an orbit that is nearly perfect for water retention to occur. There are suitable temperatures for water to exist as a liquid and sufficient gravity for retaining this water. In addition, Earth is of a size that allows a suitable gravitational pull to enable water to remain on and just under the surface. Earth has also developed an atmosphere and magnetic field that protects it from most harmful ionizing radiation being emitted from the Sun.

Collectively, these are rare but necessary conditions for a planetary body to be classified as being in a Goldilocks zone. Our galaxy, the Milky Way, is huge. It has approximately 100,000 million stars possibly acting as the centres of solar systems. The Hubble Space Telescope has shown that our galaxy is only one of 125 billion galaxies in the known portions of the universe. Considering these prodigious numbers of stars, it is reasonable to conclude that Earth is not the only planet in our galaxy or universe that has the conditions necessary to support water and thus life.

This illustration compares three types of star: yellow G stars (like the Sun), orange K dwarf stars and red M dwarf stars. It shows the relative sizes of habitable zones for each type of star as well as the relative X-ray radiation, their relative abundance and expected star longevity.



The possible existence of water is not the only factor that influences the possibility of life evolving on a planetary body. Our Sun is one of the rarer star types that exist. It is classified as a G type star based on its size and the radiation given off. Two more abundant star types are types K and M. Each of these give off much more radiation than a G star and that radiation would be harmful to life. Notice that K and M stars have a Goldilocks (habitable) zone that is much smaller than a G star like our Sun.

HL end

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

HL

- how water is necessary for life and very few planetary bodies possess conditions necessary to retain water
  - surface temperatures must allow water to exist in liquid form
  - sufficient gravity must exist to prevent water from escaping.

HL end

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.

Q6. HL State three of the conditions necessary for a planetary body to be classified in the Goldilocks zone.

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.

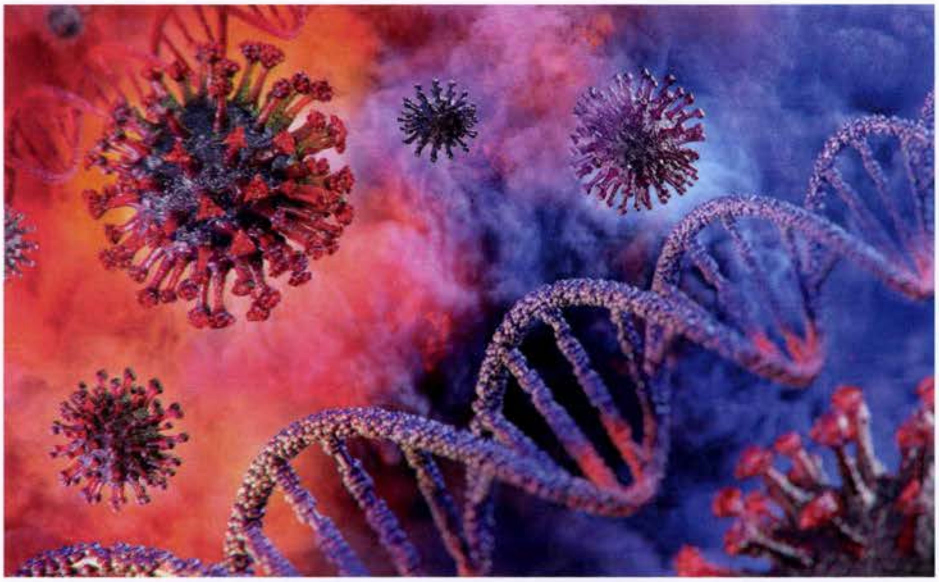
This chapter will introduce you to DNA and other molecules termed nucleic acids. Nucleic acids include DNA and three types of RNA that are all involved in the synthesis of proteins in cells.

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.



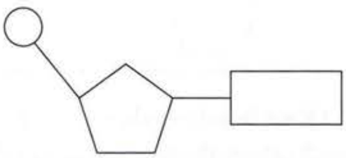
An artist's rendering of the interior of a cell showing viral particles and a DNA molecule. The spikes on the viral particles are modified proteins that attach to the cells of an organism they infect. Inside each of the viruses is a nucleic acid, either DNA or RNA (ribonucleic acid), that may undergo 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

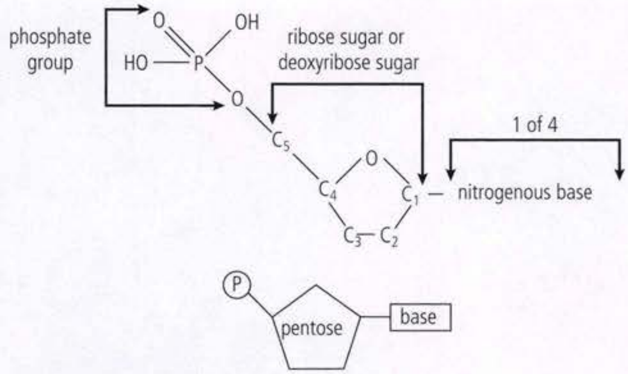
A1.2.2 – Components of a nucleotide

In diagrams of nucleotides use circles, pentagons and rectangles to represent relative positions of phosphates, pentose sugars and bases.

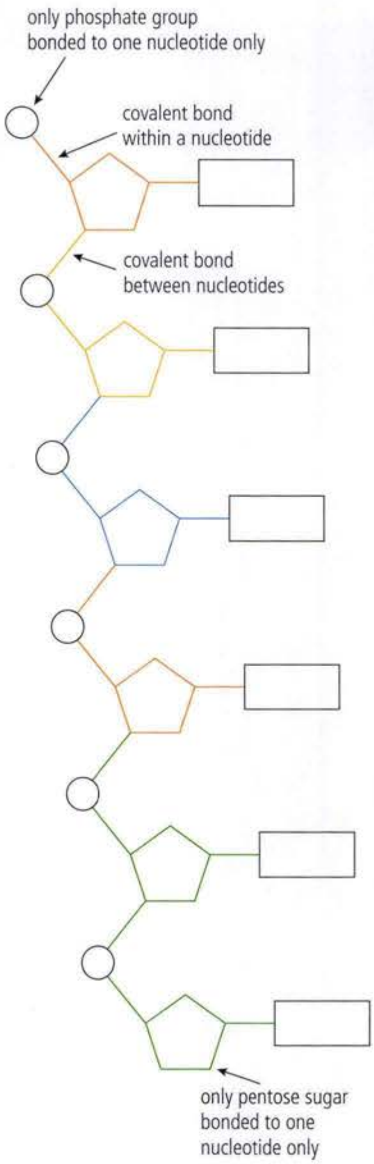


Both DNA and RNA are **polymers** of **nucleotides.** This means that both DNA and RNA have repeating units called nucleotides within the much larger molecule. So, in order to understand the structure of these two molecules important to life, we must first start with the structure of the nucleotides. 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.

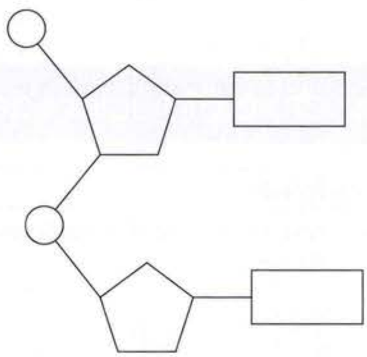


A1.2 Figure 1 Two representations of a single nucleotide are shown in the diagram. The upper drawing shows more detail, although not every atom and bond are shown of the pentose sugar and only a bonding location is shown for a nitrogenous base. The lower drawing shows the level of detail the IB requires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

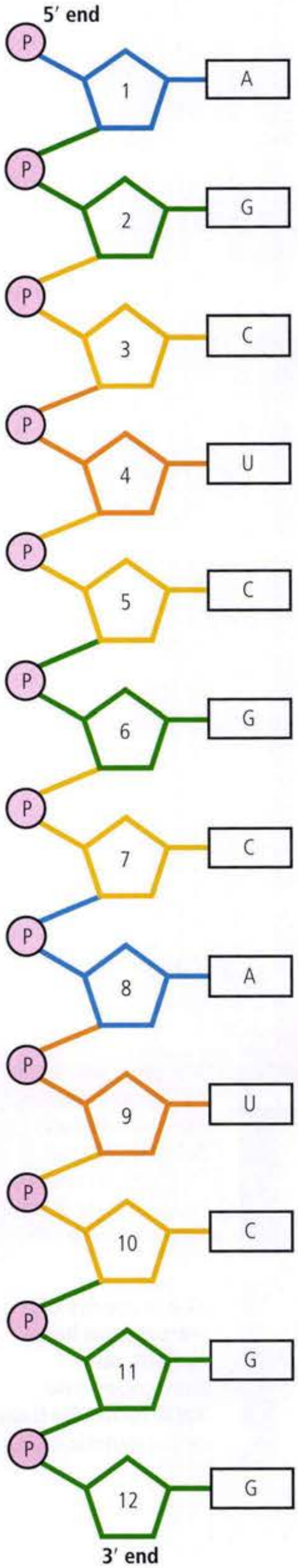
RNA nitrogenous bases	DNA nitrogenous bases
Adenine (A)	Adenine (A)
Uracil (U)	Thymine (T)
Cytosine (C)	Cytosine (C)
Guanine (G)	Guanine (G)

▲
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?

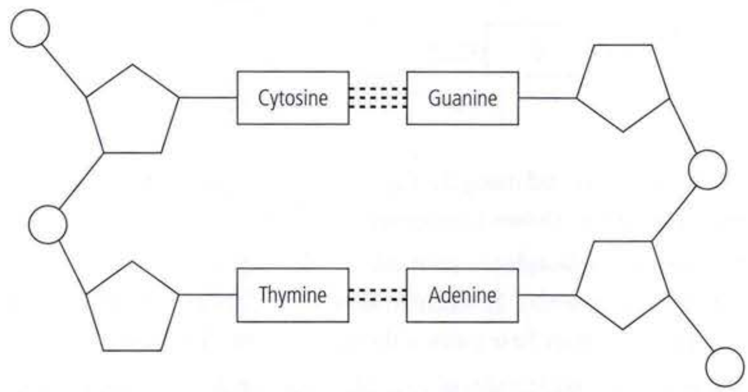
i Even though the RNA depiction in Figure 3 has only 12 nucleotides shown, the actual RNA may have as many as a few thousand nucleotides.

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

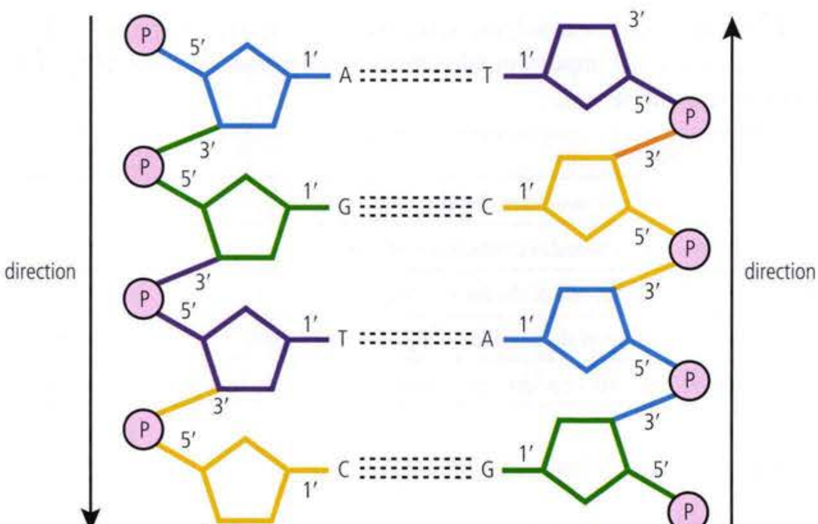
A1.2.6 – DNA as a double helix made of two antiparallel strands of nucleotides with two strands linked by hydrogen bonding between complementary base pairs

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.

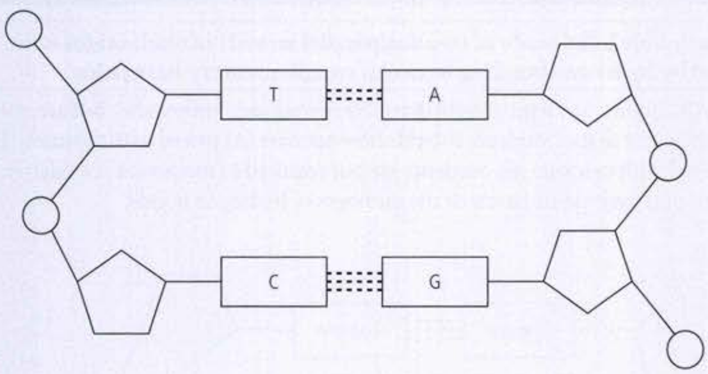


Two antiparallel strands of DNA

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.

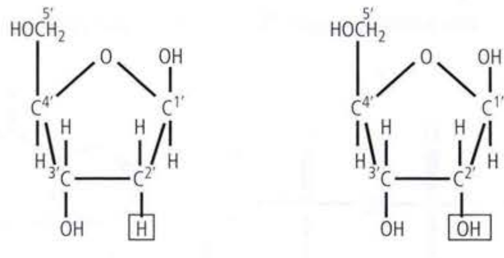
DNA and RNA are both linear polymers, consisting of sugars, phosphates and bases, but there are some important differences between the two molecules. Table 2 summarizes these differences.

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.

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.

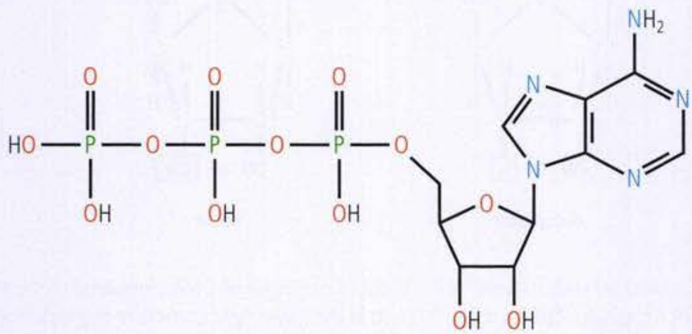
Challenge yourself

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?

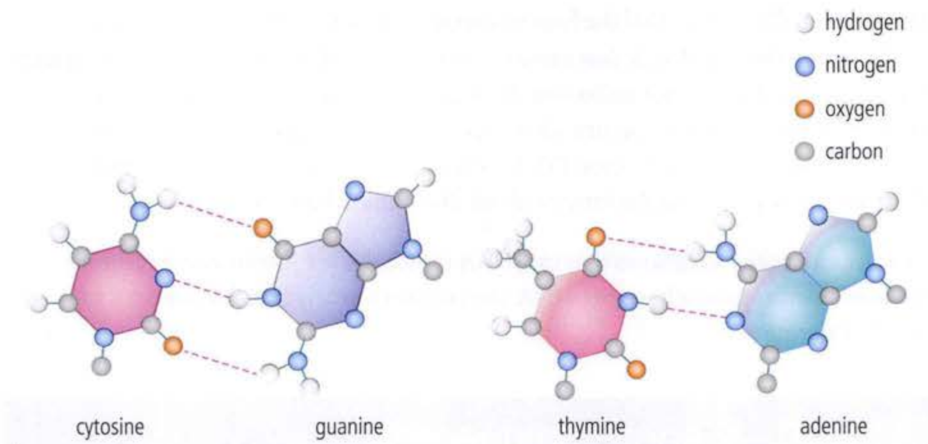
11. The "adenosine" portion of the molecule's name comes from the nitrogenous base bonded to the pentose sugar. What is that nitrogenous base?



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.

How can polymerization result in emergent properties?

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.

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.

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

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

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**.

HL

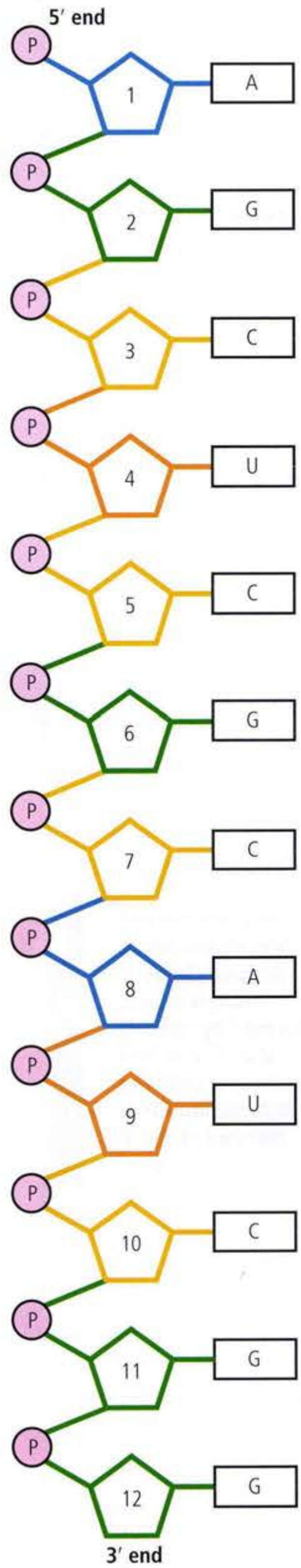
A1.2.11 – Directionality of RNA and DNA strands

A1.2.11 – Directionality of RNA and DNA
Include 5′ to 3′ linkages in the sugar–phosphate backbone and their significance for replication, transcription and translation.

The 5′ and 3′ designations refer to the fifth and third carbon atoms in the ribose and deoxyribose sugars (see Figures 5 and 6).

In a DNA molecule there are two strands that run antiparallel to each other. This means that if you compare the sides of DNA, one strand will run 5′ to 3′ and the other will run 3′ to 5′. This does not mean the direction in which they were synthesized is different. Both strands of DNA are synthesized starting with the 5′ nucleotide and working towards the 3′ end.

DNA does not have a single 5′ end or 3′ end. DNA is composed of two strands and each strand has a 5′ and 3′ end.



A1.2 Figure 6 This is the same very small section of RNA you studied in Figure 3. Because each nucleotide has one phosphate, one sugar and one nitrogenous base, there are 12 of each of these subunits. Any single strand of DNA or RNA will have an unbound phosphate group at one end (the upper left corner). This end is identified as the 5′ (5 prime) end of the strand. All the other phosphate groups are bonded to two sugars, linking adjacent nucleotides. The opposite end of the strand terminates with deoxyribose sugar with no additional phosphate groups. This end is called the 3′ (3 prime) end of the strand.

Challenge yourself

12. Since the two strands of DNA are antiparallel to each other, you only need to know one end of one strand in order to extrapolate the other three ends.

3′ ____ X

Y ____ Z

Each horizontal line shown above represents a strand of DNA of a double-stranded molecule. Notice that only the 3′ end of one strand has been labelled. Using 5′ and 3′, label each of the ends currently labelled X, Y and Z.

The importance of directionality

When RNA or DNA is formed, one nucleotide at a time is added to the molecule. The nucleotide is not added at a random spot: it is added as the next nucleotide in a growing chain. As all nucleotides have a phosphate group, pentose sugar and nitrogenous base, you can trace this formation by looking for the first nucleotide in the sequence. That first nucleotide will always be the 5′ end of the strand.

This is important when a new nucleic acid strand is formed. When DNA replicates, the two strands separate from each other in a particular area, and each separated strand acts as a template for a new strand to be formed. A *new* strand will always begin with the 5′-end nucleotide first.

DNA and RNA molecules are both integral to the process of protein synthesis. The first stage of protein synthesis is called **transcription**. This occurs when a gene of DNA (one of the two DNA strands) is opened and an RNA molecule is synthesized using complementary base pairing. The transcription process synthesizes the 5′ end of the RNA first. The resulting RNA is called mRNA, and represents the genetic information of one gene. The mRNA then pairs with an organelle in the cell called a **ribosome**. Another RNA called tRNA, bonded to a specific amino acid, now pairs (by complementary base pairing) to triplets of the mRNA. This process is called **translation**. Translation is accomplished in a sequence starting nearest to the 5′ end of the mRNA molecule. These molecular processes will be difficult to understand completely and visualize until you study Chapter D1.1 on DNA replication and Chapter D1.2 on protein synthesis. For now, visualize nucleic acids as having a directionality (5′ and 3′ ends), and remember that the directionality is important to their structure and function in DNA replication and RNA synthesis.

Any *new* nucleic acid strand being formed (DNA or RNA) is always formed by starting at its 5′ end and continuing until the final nucleotide is bonded at the 3′ end.

A1.2.12 – Purine-to-pyrimidine bonding

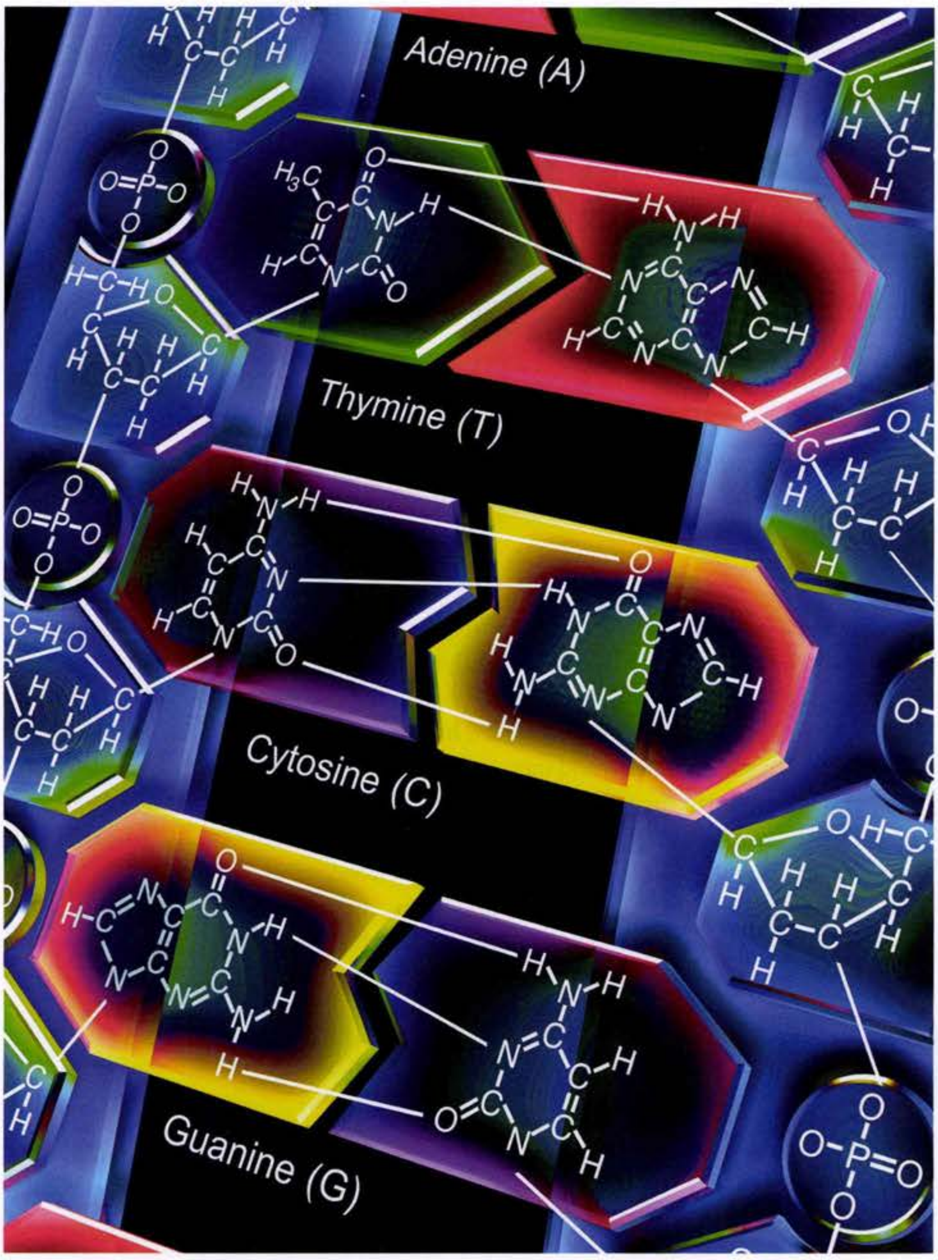
A1.2.12 – Purine-to-pyrimidine bonding as a component of DNA helix stability
Adenine–thymine (A–T) and cytosine–guanine (C–G) pairs have equal length, so the DNA helix has the same three-dimensional structure, regardless of the base sequence.

The nitrogenous bases of DNA are grouped into pyrimidines and purines, as shown in Table 3. Pyrimidines are smaller as they contain a single-ringed structure, whereas purines are larger as they contain a double-ring structure.

Purines (double ring size)	**Pyrimidines** (single ring size)
Adenine (A)	Thymine (T)
Guanine (G)	Cytosine (C)

▲
A1.2 Table 3 Types of nucleotides found in DNA

When bonding the two strands of DNA together to make the double helix, a purine is always bonded to a pyrimidine. This results in the two strands of DNA being a consistent distance from each other (with three rings in total), leading to an amazing and stable double helix shape as the two strands wind around each other in three dimensions.



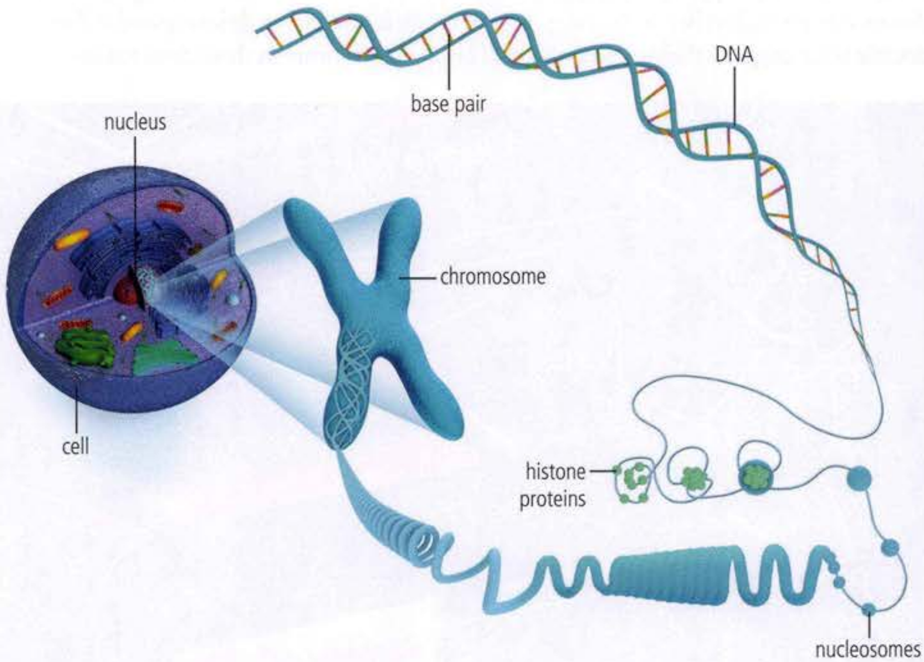
◀ This figure shows complementary base pairing and nitrogenous base structures within a small portion of DNA. You do not have to memorize the nitrogenous base structures for the IB. Notice the double-ring structures of adenine and guanine (purines) and the single-ring structures of thymine and cytosine (pyrimidines).

i You learned that complementary base pairing requires A–T and C–G. As you can see, in each case one is a purine and the other a pyrimidine. But, why not G–T and A–C ? Even though that pairing would bond a purine to a pyrimidine, hydrogen bonding between the pairings cannot occur and thus it does not occur in nature.

A1.2.13 – Efficient packaging of DNA molecules

A1.2.13 – Structure of a nucleosome
Limit to a DNA molecule wrapped around a core of eight histone proteins held together by an additional histone protein attached to linker DNA.
Application of skills: Students are required to use molecular visualization software to study the association between the proteins and DNA within a nucleosome.

A1.2 Figure 7 One chromosome from a cell's nucleus expanded to show the coiling and structure of nucleosomes.

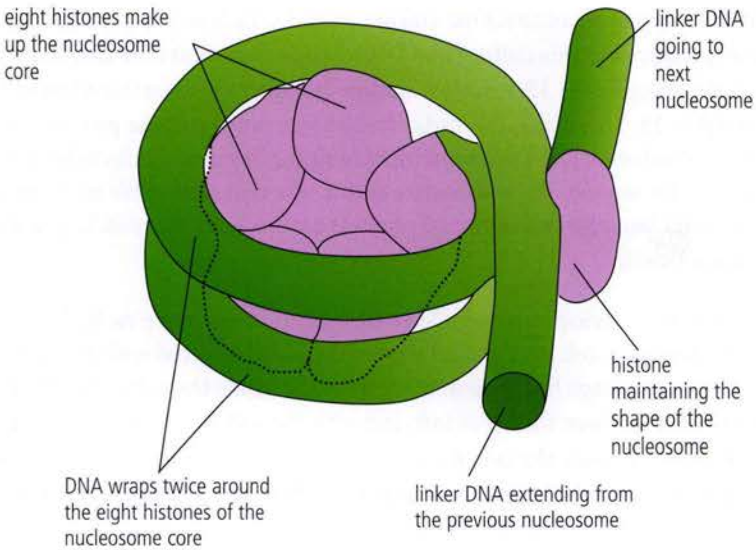


Biologists often describe DNA organized into nucleosomes as "beads on a string". In this analogy, the DNA (the string) is wrapped around the histones (the beads), rather than running through them as in an actual beads.

DNA is a very, very long molecule. Some DNA molecules in human cells are approximately 2 m in length. In order to fit the very long molecules of DNA inside the nucleus of a cell, a very efficient "packaging" solution has evolved (see Figure 7). Within the nucleus there are proteins called **histones**. First, DNA wraps itself around eight of these histone proteins, and then an additional histone helps hold the structure together. This occurs in many adjoining areas of DNA. Each resulting structure is called a **nucleosome** (see Figure 8). The DNA that extends from one nucleosome to the next is called linker DNA. The multitude of nucleosomes then stack up in an organized pattern and begin coiling around other proteins in a very condensed shape. The overall "packaged" shape is a chromosome. A human cell contains 46 chromosomes.

SKILLS

You can find videos and other molecular visualization aids online to view the use of histone proteins to form nucleosomes and the formation of chromosomes.



A1.2 Figure 8 A nucleosome showing the DNA wrapped around eight histone proteins with one additional histone helping to keep the structure intact. Linker DNA is found between adjoining nucleosomes. Look back at Figure 7 to see how nucleosomes organize into a chromosome.

A1.2.14 – The Hershey–Chase experiment

A1.2.14 – Evidence from the Hershey–Chase experiment for DNA as the genetic material

Students should understand how the results of the experiment support the conclusion that DNA is the genetic material.

NOS: Students should appreciate that technological developments can open up new possibilities for experiments. When radioisotopes were made available to scientists as research tools, the Hershey–Chase experiment became possible.

Before the middle decades of the 20th century, biologists were unsure of the genetic material of living organisms. Primarily, they debated whether genetics was based on nucleic acids or proteins. Because DNA was composed of only four types of nucleotides, and proteins were composed of 20 types of amino acids, it made sense to many that proteins could better provide the complex genetic variety found in living organisms.

TOK Sometimes it is difficult for scientists to let go of long-held beliefs. The beliefs become ingrained as part of their core knowledge, and few even think to challenge that knowledge. How do our expectations and assumptions have an impact on how we perceive things?

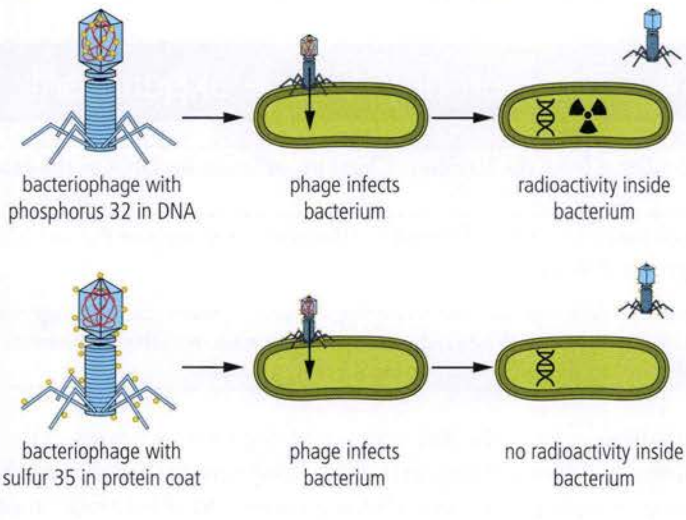
In 1951 and 1952, two researchers, Alfred Hershey and Martha Chase, working at Cold Spring Harbor, NY, carried out experiments that helped confirm DNA as the genetic material. The experiment used a bacteriophage and the bacterium *Escherichia coli*. A bacteriophage is a virus that infects bacteria, and is composed of a protein outer coat and an inner core of DNA. When a bacteriophage infects a cell, the virus takes over the metabolism of the cell, resulting in multiple viruses of that type being formed using molecules such as nucleotides in their synthesis.

Hershey and Chase made use of radioisotopes in their experiment in a process called radioactive isotope labelling. Radioisotopes are radioactive forms of elements that can be detected within molecules. The particles released during their decay allow the specific radioisotope used to be detected. The researchers grew bacteriophage viruses in two different types of culture. One culture included radioactive phosphorus 32. The viruses produced in this culture had DNA inside their viral core labelled with the detectable phosphorus 32. Another culture included a radioactive form of sulfur known as sulfur 35. This detectable radioisotope was present in the protein outer coat of the viruses produced. DNA does not include sulfur (because nucleotides do not contain any sulfur atoms). The radioactive sulfur was only detectable in the protein shell of the virus, because two of the 20 possible amino acids that can be present in protein contain sulfur.

The two types of bacteriophages labelled with radioisotopes were each allowed to infect the bacterium *E. coli*. As Figure 9 shows, the *E. coli* infected with the phosphorus 32-labelled bacteriophage had radioactivity detected inside the cells, a location indicating DNA. However, the *E. coli* infected with the sulfur 35-labelled bacteriophage had no radioactivity inside the cell. Because DNA contains phosphorus and not sulfur, this allowed Hershey and Chase to conclude that DNA, not protein, was the genetic material.

It is important for researchers to publish the details and findings of their experimental work. This allows other scientists all over the world to learn and build upon previous work in future research projects.

Once the results of the Hershey–Chase experiment were published, further research involving genetics centred primarily on DNA was possible, and collectively that body of work provides conclusive evidence that DNA is the genetic material.



A1.2 Figure 9 A summary of the Hershey–Chase experiment. Radioactivity was detectable inside cells after radioactive isotopes of phosphorus had been used when growing *E. coli* cultures. These radioactive isotopes were used within the nucleotides when *E. coli* cell division occurred and DNA was replicated. Recall that phosphorus is a component of nucleotides within phosphate groups.

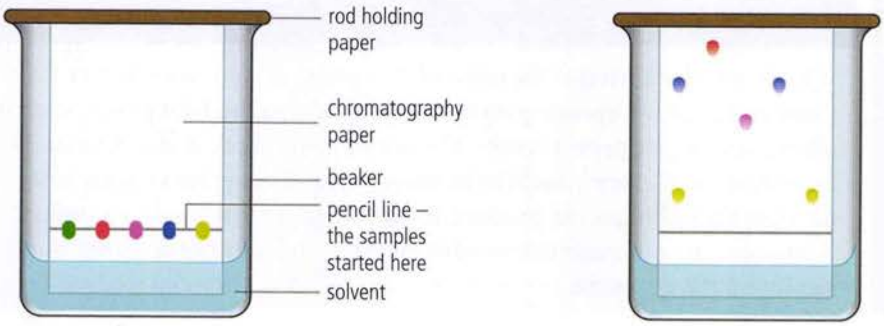
The Hershey–Chase experiment is sometimes referred to as the "blender experiment" because the experimental process involved using a kitchen-type blender. The blender sheared the viral coatings containing the sulfur radioisotope away from the living bacterial cells containing the phosphorus radioisotope.

Nature of Science

It is not very often that "eureka" moments occur in science. More often scientific advances move along slowly, with one discovery providing information that leads to another. Such was the case with the Hershey–Chase experiments. Their work was made possible by earlier research using radioactive isotopes to trace the pathway of different types of molecules. The Hershey–Chase work showing DNA is the genetic material was not the result of a single experiment but a series of experiments, during which techniques were refined as they worked through the problem one step at a time.

A1.2.15 – Chargaff's rule

A1.2.15 – Chargaff's data on the relative amounts of pyrimidine and purine bases across diverse life forms
NOS: Students should understand how the "problem of induction" is addressed by the "certainty of falsification". In this case, Chargaff's data falsified the tetranucleotide hypothesis that there was a repeating sequence of the four bases in DNA.



▲
Erwin Chargaff's experimental work determining the nitrogenous base ratios within DNA involved the technique shown in this figure: paper chromatography. A mixture of substances is embedded into chromatography paper. The bottom of the paper, below the embedded substances, is placed into a solvent. The solvent wicks up the paper, carrying components of the mixture with it. Each component travels a different distance based on its molecular size and charge.

As mentioned earlier, scientists in the early part of the 1900s worked under the assumption that protein was responsible for genetic traits. Research showed that there were both DNA and proteins in the nucleus of a cell. The hypothesis was that DNA existed as a tetranucleotide molecule, in other words, in repeating set units of the four nucleotides, and was there to help give structure to chromosomes.

In the late 1940s a researcher named Erwin Chargaff developed a research technique designed to show the proportions of nitrogenous base types found in various sources of DNA. His separation and identification technique involved paper chromatography. Some of the results of his studies are shown in Table 4.

DNA source	Adenine	Thymine	Guanine	Cytosine
Calf thymus	1.7	1.6	1.2	1.0
Beef spleen	1.6	1.5	1.3	1.0
Yeast	1.8	1.9	1.0	1.0
Tubercle bacillus	1.1	1.0	2.6	2.4

▲
A1.2 Table 4 A summary of some of the data from Chargaff's research. Look for approximate 1:1 proportions, reading across the table for each of the four sources of DNA

Start by looking at the results for the DNA Chargaff extracted from the thymus gland of a calf. As you can see, there is almost the same ratio of adenine to thymine, and also the same ratio of guanine to cytosine. Very similar ratios exist for the other three biological sources of DNA shown.

Over time, this and similar data became known as Chargaff's rule: DNA contains the same number of adenine as thymine nucleotides, as well as the same number of guanine and cytosine nucleotides.

James Watson and Francis Crick made use of information provided by several other research teams when they proposed and built the first accurate model of DNA in 1953. X-ray crystallography work by Rosalind Franklin showed DNA to be a double helix. Erwin Chargaff's work showed the complementary pairing of the nitrogenous bases.

Nature of Science

Why do you think it is that the ratios of A–T and C–G were not a perfect 1:1 in Chargaff's results? Depending on the experimental methodology used, science often does not give perfect results. This is frequently because of experimental error. Some of that error could be human error, and sometimes it is the best data that the technique can produce. It does not mean that the data is useless. A large data set can minimize some of the error, and statistics can show how significant the errors are.

The importance of Chargaff's rule

The data from Chargaff's work not only showed that the proportion of adenine to thymine, and guanine to cytosine, is equal, it also showed that the tetranucleotide theory is false. The tetranucleotide theory, if correct, would have resulted in the proportion of all of the nitrogenous bases being equal. In other words, the same quantities of A, T, C and G. The data did not show equal proportions of all four bases, and thus the tetranucleotide idea was falsified.

This led to a whole new set of ideas as to what the genetic code could be. Researchers began to consider the sequence of nucleotides in DNA as highly variable and the possibilities of DNA containing the genetic code. We now know the proteins in the nucleus of the cell were primarily histone proteins helping to form nucleosomes.

Nature of Science

The process of science always struggles with the conclusions that can be reached from various data sets. The "problem of induction" is evidenced by assuming something is always true because one or more data sets seems to lead to that conclusion. In actuality, the process of science is often better served by asking questions that lead to falsifications. This is what Erwin Chargaff did when he falsified the idea that DNA was organized into tetranucleotides.

HL end

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"
- HL nitrogenous base sizes (a purine with a pyrimidine) and hydrogen bonding ensure accuracy when new base pairs are formed.

Exercises

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

Q2. State the structural similarity of the two nitrogenous bases (adenine and guanine) used to classify them as purines.

Q3. 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.

Q4. You are visualizing a single sequence of nitrogenous bases and you see multiple uracil bases. What does that tell you about the molecule?

Q5. Which of these is not a nucleic acid?

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

Q6. 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.

HL

Q7. Even though cytosine is a pyrimidine and adenine is a purine, they are not complementary to each other. State what prevents these two bases from being complementary to each other within DNA.

Q8. In the experimental work by Hershey and Chase, why was the presence of radioactive phosphorus correlated with DNA and not protein?

Q9. Which statement best describes a single chromosome?

A A length of DNA coiled around eight histone proteins with an additional histone.

B A length of DNA coiled around many groupings of eight histones each having one additional histone.

C Protein structures found within the nucleus of a cell.

D DNA structures found within the nucleus of a cell.

HL end

A1 Practice questions

1. Describe the importance of water to living organisms.

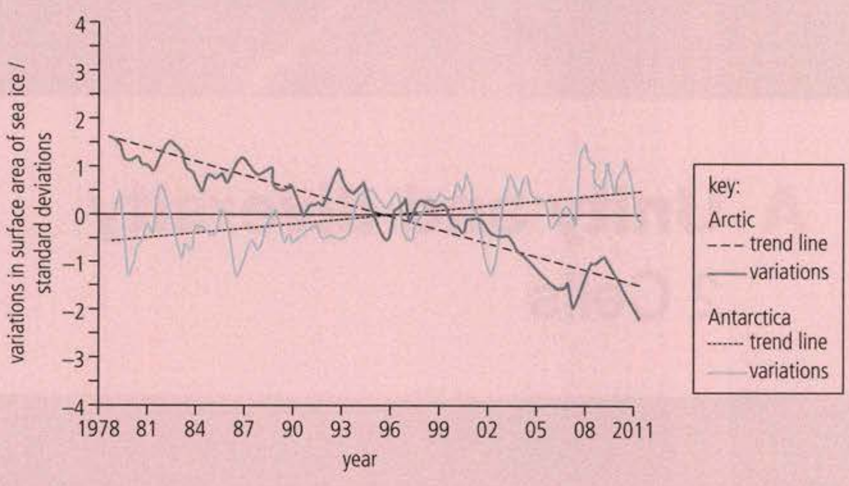
(Total 5 marks)

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

(Total 4 marks)

3. Global warming has changed both the thickness and surface area of sea ice of the Arctic Ocean as well as the Southern Ocean that surrounds Antarctica. Sea ice is highly sensitive to changes in temperature.

Scientists have calculated a long-term mean for the surface area of sea ice in the Arctic and in the Southern Ocean around Antarctica. This mean value is used as a reference to examine changes in ice extent. The graph shows the variations from this mean (zero line) over a period of time.



(a) State the trend in the surface area of sea ice in the Southern Ocean around Antarctica. (1)

(b) Distinguish between changes in the surface area of sea ice in the Arctic and Antarctica. (2)

(c) Discuss the data as evidence of global warming. (3)

(Total 6 marks)

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

(Total 5 marks)

5. HL Outline the structure and functions of nucleosomes.

(Total 4 marks)

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.

HL

A2.1 Origins of cells

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?

How exactly did life begin on our planet? How can life come from non-life? How did all the different forms of life present on Earth today come from the first life form? Many, many more questions can be asked. For most of them, we will never have an answer. However, science is about attempting to answer difficult, seemingly impossible questions. We develop hypotheses, we try to imagine and recreate early environmental conditions, we build models, we constantly look for clues in every possible situation, and we gaze at the stars and wonder.

As scientists, we do not stop asking questions and seeking answers. We want to know how we came to be a life form on this third planet from our Sun.

A2.1.1 – The formation of carbon compounds

A2.1.1 – Conditions on early Earth and the pre-biotic formation of carbon compounds
Include the lack of free oxygen and therefore ozone, higher concentrations of carbon dioxide and methane, resulting in higher temperatures and ultraviolet light penetration. The conditions may have caused a variety of carbon compounds to form spontaneously by chemical processes that do not now occur.

Early Earth was quite different from the planet we know now. Our planet is believed to be approximately 4.5 billion years old, and to have been formed from a swirling mass of smaller particles that collided with one another and formed larger masses. Larger masses have more gravity than smaller ones, and so attract other masses; in this way Earth eventually took form. There was no atmosphere on early Earth, allowing various objects from space to impact the surface, causing the planet to grow and the temperature of the surface to rise.

Physicists have provided evidence that the universe was once a single mass. Sometime between 12 and 14 billion years ago, this single mass exploded in a "big bang". Expansion in all directions from this central explosion has been occurring ever since.

SKILLS

Coacervate lab. Full details on how to carry out this activity with a worksheet are available in the eBook.

About 4 billion years ago the number of impacts on the Earth's surface began to decrease. It is thought that the Earth's developing atmosphere at this time was thick with water vapour and other compounds being released by volcanic eruptions. Lightning was most probably a regular occurrence. Early gaseous compounds may have included methane, ammonia, carbon dioxide and hydrogen sulfide, along with many others. These gases, especially carbon dioxide and methane, which were present in higher concentrations than today, allowed ultraviolet light to penetrate the early atmosphere and retained heat, resulting in high surface temperatures. Free oxygen was not present. Had it been, it would have formed a layer of ozone in the upper regions of the atmosphere, thus blocking ultraviolet light penetration and preventing the development of higher temperatures.

Component	Chemical formula
Methane	CH_4
Ammonia	NH_3
Water vapour	H_2O
Carbon dioxide	CO_2
Hydrogen sulfide	H_2S
Hydrogen	H_2
Nitrogen	N_2

▲ Possible components of Earth's early atmosphere

It is thought that the Earth's early atmospheric components coupled with high surface temperatures and lightning, followed by a gradual cooling, resulted in the spontaneous formation of many carbon compounds. This spontaneous formation occurred during the unique conditions early in the geological history of our planet, and is not evident today.

A2.1.2 – Functions of life

A2.1.2 – Cells as the smallest units of self-sustaining life
Discuss the differences between something that is living and something that is non-living. Include reasons that viruses are considered to be non-living.

Today, all organisms exist in either a unicellular or a multicellular form. Interestingly, all organisms, whether unicellular or multicellular, carry out all the functions of life. These functions include:

- metabolism
- growth
- reproduction
- response
- homeostasis
- nutrition
- excretion.

These functions act together to produce a viable living unit. **Metabolism** includes all the chemical reactions that occur within the organism. As a result of metabolism, cells can convert energy from one form into another. **Growth** may be limited but is always present. **Reproduction** involves hereditary molecules that can be passed to offspring. **Responding** to stimuli in the environment is essential for an organism to survive. These responses allow an organism to adapt to its environment. **Homeostasis** refers to the maintenance of a constant internal environment. For example, an organism may have to control fluctuating temperature and acid–base levels to create a constant internal environment. Using a source of compounds with many chemical bonds that can be broken down to provide an organism with the energy necessary to maintain life is the basis of **nutrition**. **Excretion** is essential to life because it enables those chemical compounds that an organism cannot use or that may be toxic or harmful to be released from the organism's system.

The functions of life manifest in different ways in different types of organisms. Because of this variety, you may come across different terms for the same function when you read different sources. However, all organisms maintain the same general functions that allow them to live.

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

Viruses are not considered to be living organisms. They cannot carry out the functions of life on their own. However, they can use cells to perpetuate themselves.

Cell theory

Many scientists, over several hundred years, have contributed to the three main principles of today's **cell theory**:

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

Cell theory has a solid foundation, largely because of the use of the microscope. Robert Hooke first described cells in 1665, after looking at cork through a self-built microscope. A few years later Antonie van Leeuwenhoek observed the first living cells and referred to them as "animalcules", meaning little animals. In 1838, botanist Matthias Schleiden stated that plants are made of "independent, separate beings" called cells. One year later, Matthias Schleiden made a similar statement about animals.

The second principle continues to gain support today, because no one has been able to find any living entity that is not made of at least one cell.

Many famous scientists, such as Louis Pasteur in the 1880s, have performed experiments to support the third principle. After sterilizing chicken broth (soup) by boiling it, Pasteur showed that living organisms would not "spontaneously" reappear. Only after exposure to pre-existing cells was life able to re-establish itself in the sterilized chicken broth.

Nature of Science

Theories are developed after the accumulation of data via observation and/or experimentation. As with most theories, the current cell theory is not without problems. A key characteristic of a scientist is a sceptical attitude towards theoretical claims. To overcome or validate this scepticism, more evidence obtained by observation or experimentation is essential. Whenever possible, controlled experiments are needed to verify or refute theories. Controlled experiments include a control group and a variable group(s); the groups are kept under similar conditions, apart from the factor that is being tested. The factor being tested is referred to as the independent variable. The other factors, the dependent variable, are measured or described using quantitative or qualitative data. Relatively recent findings that have raised questions about the cell theory include observations of striated muscle, giant algae and aseptate fungal hyphae. Sometimes theories will be abandoned completely because of conflicting evidence. When this happens a **paradigm shift** is said to have occurred.

A2.1.3 – Evolution of the cell

A2.1.3 – Challenge of explaining the spontaneous origin of cells
Cells are highly complex structures that can currently only be produced by division of pre-existing cells. Students should be aware that catalysis, self-replication of molecules, self-assembly and the emergence of compartmentalization were necessary requirements for the evolution of the first cells. **NOS:** Students should appreciate that claims in science, including hypotheses and theories, must be testable. In some cases, scientists have to struggle with hypotheses that are difficult to test. In this case the exact conditions on pre-biotic Earth cannot be replicated and the first protocells did not fossilize.

Cells are complex structures that carry out the functions of life. The third principle of cell theory states that cells may only come from other pre-existing cells. We have not found an exception to this principle on present-day Earth. Protocells or simple cells had to appear in a pre-biotic (non-life) environment so that the more complex cells we see today could form. Scientists hypothesize that a series of chemical and physical processes have to occur for a cell to evolve. These processes or stages are:

1. The synthesis of small carbon compounds from abiotic (non-living) molecules, such as demonstrated in the Miller–Urey experiment.
2. Small organic molecules joining to form large-chain molecules called **polymers**.
3. Polymers becoming contained by membranes, creating a protective homeostatic environment around the polymers, separate from their surroundings.
4. The development of self-replicating molecules so that inheritance and control can occur.

Nature of Science

Hypotheses about the origin of the first cells are frustrating for scientists, because they are not testable. We do not know the exact conditions of early Earth, so we cannot replicate them for experimentation. Nor have the first protocells been preserved in the fossil record.

The evolution of early cells required the emergence of compartmentalization and self-replication of molecules, and the process would have been helped by the presence of enzyme-like components.

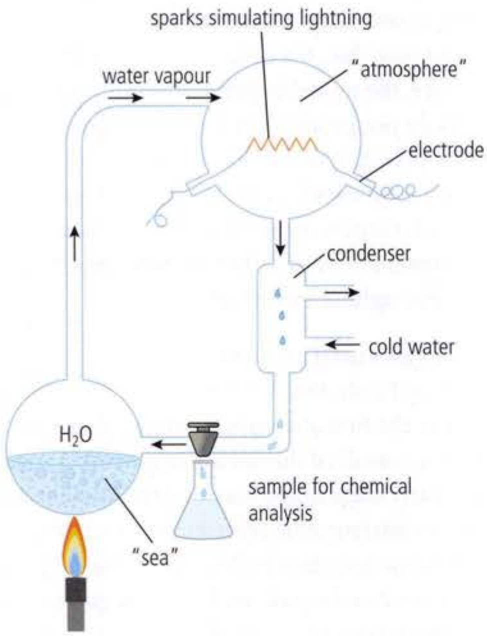
Based on the observation of present-day chemical reactions, small organic molecules can join to form larger chain molecules more rapidly if a compound called an **enzyme** is present. Enzymes are proteins that act as biological catalysts and accelerate chemical reactions. Enzymes are carbon compounds, which means they always contain the elements carbon and hydrogen, usually along with other elements. It is doubtful that enzymes existed when protocells first formed. Scientists have been able to produce polymers from simple compounds by exposing them to hot sand, clay or rock. This vapourizes water from the simple compounds, and molecule chains are formed, suggesting that polymers could have formed on early Earth even if no enzymes were present.

A2.1.4 – Inorganic to carbon compounds

A2.1.4 – Evidence for the origin of carbon compounds
Evaluate the Miller–Urey experiment.

Early biologists and biochemists were puzzled about how simple atmospheric components could be converted or evolve into the more complex compounds necessary for the origin of life. **Inorganic compounds** do not usually contain carbon (an exception is carbon dioxide, which is considered to be an inorganic compound). **Carbon compounds** (often called organic compounds) contain carbon and can be quite complex. It is these more complex compounds or molecules that make life possible, thus the element carbon can be said to be the keystone element for life on Earth.

In 1953, Stanley Miller and Harold Urey conducted an experiment to simulate the conditions thought to be present on early Earth, and to determine if these gases could interact to produce the first stage in the evolution of life. Most scientists believe this first stage will result in simple, non-living organic molecules. The apparatus designed for this experiment is shown in Figure 1.



A2.1 Figure 1 The Miller–Urey apparatus used to simulate the conditions on early Earth.

The important features of Figure 1 are:

- the apparatus is initially charged with the simple inorganic compounds CH_4, NH_3 and H_2, representing Earth's early atmosphere
- heat is used to produce water vapour, which rises to the chamber containing the simple inorganic compounds
- two electrodes in this chamber produce 7,500 volts at 30 amps of electricity, representing the lightning that existed on early Earth
- cold water flows into the condenser to allow condensation of gaseous compounds from the chamber
- a sample is collected in the collecting device for chemical analysis.

An organism is an individual living thing consisting of one or more cells. Organisms demonstrate the characteristics of life.

During the experiment, Miller identified several simple organic molecules in the collecting device that are known to exist in **organisms.** These molecules included long chains of hydrogen and carbon, called **hydrocarbons.** He also found some of the building blocks of proteins called **amino acids.** Proteins are major biochemicals essential to all organisms, and are explained in detail in Chapter B1.2. The fluid collected during the experiment suggested to many scientists that life originated in a **primordial soup**, a water-based sea of simple organic molecules.

Nature of Science

The Miller–Urey experiment uses a model to demonstrate how more complex molecules could evolve from simple compounds. Models are much simpler than the complex environments in which actual natural phenomena occur. However, they allow observation of possible reactions that may have occurred on, for example, early Earth. It is important to understand that models have limitations, and these limitations must be considered when making any conclusions or statements.

TOK

In some instances, natural sciences rely on or make assumptions that are not actually provable. The Miller-Urey experiment includes some such assumptions. This would be a wonderful time to discuss with your classmates the value and the limitations of the assumptions made in this experiment. Some concerns to address in this discussion include:

1. What role do models play in the acquisition of knowledge?
2. Do the natural sciences rely on any assumptions that are themselves unprovable by science?
3. What knowledge, if any, is likely to always remain beyond the capabilities of science to investigate or verify?

Many laboratories around the world have reproduced the Miller–Urey experiment with comparable results. Similar experiments with many new variables have also been conducted, resulting in several types and amounts of larger carbon compounds. However, it is important to note that, because we have no definite knowledge of the early Earth's atmosphere, the model/experiment produced by Miller–Urey and other similar experiments do not produce reliable evidence of the first steps in the development of life on our planet. As a result of the unprovable assumptions of this experiment, several other hypotheses have been suggested to explain how more complex carbon compounds came to exist on our planet. One of these alternative hypotheses involves the introduction of carbon compounds by comets and meteorites, as they have struck Earth throughout its history.

Some scientists believe the gases used in the Miller–Urey experiment were not likely to have been present on early Earth. For these scientists, the Miller–Urey results are invalid. Instead, they believe the first atmosphere of our planet formed slowly over extended periods of time as a result of the release of gases from volcanoes. If this is accurate, the gases at this early stage in the Earth's development would have originated from the planet's mantle, an intermediate layer surrounded by the exterior crust and resting on the core. These same scientists believe the chemical properties of the mantle are the same today as they were in the past, and volcanic gases today do not contain methane or ammonia. If this is true, this hypothesis results in an early atmosphere that had the following composition:

- water vapour
- carbon dioxide
- sulfur dioxide
- small amounts of carbon monoxide and hydrogen sulfide.

A hypothesis is an explanation based on reasoning that can be tested by gathering more data. Often, this data is gathered by experimentation.

These atmospheric gases would produce a **non-reducing environment** that, because of the lack of adequate hydrogen for bonding, would not result in simple carbon compounds. The compounds used in the Miller–Urey experiment produce a **reducing environment** favourable for the development of carbon compounds.

Another concern with the Miller–Urey experiment and the primordial soup theory is that, when water is present with proteins, the proteins break down into individual amino acids. In a water environment, amino acids are not observed joining into more complex structures resulting in proteins. This is in conflict with the belief that complex molecules could form in a primordial soup environment, thus allowing the eventual development of life.

Because of these and other concerns, many scientists have questioned the credibility of the Miller–Urey experiment in proposing a means for the first life first to form on Earth. Scientists are now pursuing hydrothermal vents as a possible environment for the origin of cells and life. These hypotheses are discussed Section A2.1.9.

A reducing environment or atmosphere is one in which no free oxygen is present. However, hydrogen is present. If the early Earth's atmosphere was non-reducing, there would have been no hydrogen to allow the production of the first carbon compounds, composed largely of carbon and hydrogen.

A2.1.5 – The formation of vesicles

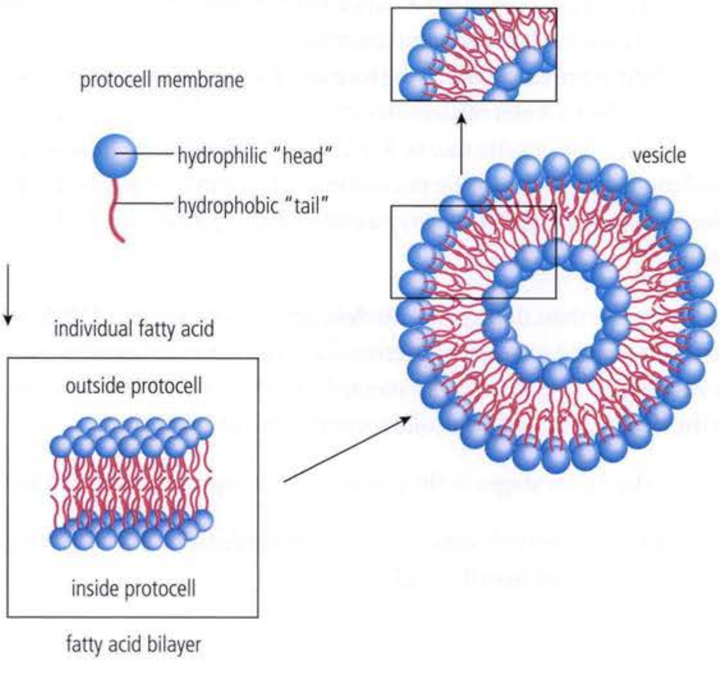
A2.1.5 – Spontaneous formation of vesicles by coalescence of fatty acids into spherical bilayers
Formation of a membrane-bound compartment is needed to allow internal chemistry to become different from that outside the compartment.

Membrane formation is thought to have been essential to the origin of the first cells on Earth. A membrane provides a barrier or boundary between the inside of the cell and the surrounding environment. This barrier allows the regulation and maintenance of activities within the cell.

Present-day cell membranes are complex in structure and include many different components to allow regulation and maintenance within the cell. This is quite different from the membranes of protocells, which are thought to have been composed of only a single group of compounds.

One of the carbon compounds thought to have been present on early Earth was a simple group known as fatty acids. These fatty acids, when present in water, display a polarity, with one end having water-attracting, **hydrophilic**, properties, and the other end having water-repelling, **hydrophobic**, properties. When large numbers of fatty acids are placed in water, they tend to organize themselves into small, cell-sized double-layer bubbles often referred to as **vesicles**.

These vesicles are often referred to as liposomes, which means "fat bodies". They are highly likely to have been the first protocells.



Fatty acids and the development of a protocell bilayer membrane.

Vesicles produced in the laboratory can conduct several key processes, including the ability to engulf other types of organic molecules, grow, and even replicate themselves.

The development of a boundary around a vesicle is called **compartmentalization** and was necessary for the formation of the first cells. As cells continued to progress in complexity, compartmentalization became evident within this outer boundary, allowing specialization of functions in different regions inside the outer protective fatty acid bilayer.

A2.1.6 – RNA as the first genetic material

A2.1.6 – RNA as a presumed first genetic material
RNA can be replicated and has some catalytic activity so it may have acted initially as both the genetic material and the enzymes of the earliest cells. Ribozymes in the ribosome are still used to catalyse peptide bond formation during protein synthesis.

The final process in the formation of the cell is the development of molecules that can allow inheritance and control the cell's functions of life. One hypothesis is that this molecule was **ribonucleic acid**, often referred to as **RNA**.

Short RNA molecules display some interesting properties.

- RNA can assemble spontaneously from simpler organic molecules called nucleotides.
- RNA can form copies of itself, thus acting as a type of genetic material.
- RNA demonstrates the ability to control chemical reactions, thus acting in an enzymatic role.

These properties of RNA would have allowed all the functions necessary for the formation of early cells. A type of RNA called **ribozymes** is highly active today in catalysing activities, such as allowing faster development of peptide bonds. These types of bonds are essential for the formation of proteins. The fact that RNA can spontaneously form when nucleotides are present enables its appearance in early cell formation. The genetic role of RNA is possible because of the varying types of nucleotides present capable of combining to form a larger molecule. This larger molecule of RNA could then carry a code allowing inheritance of specific characteristics.

RNA is a single-chain molecule, while DNA is a double-chain molecule. Both compounds are polymers of nucleotides. However, there are differences in the nucleotides that these two genetic compounds are composed from.

RNA is much simpler than **deoxyribonucleic acid**, also known as **DNA**, which is the predominant genetic material of present-day organisms. Because of its relative simplicity and its ability to form spontaneously, RNA, not DNA, is hypothesized to have been the first genetic and controlling compound of a living cell.

An overview of the major stages in the origin of life is represented by the following:

early Earth → abiotic chemical compounds → small organic molecules → polymers of organic molecules → protocell → cell

A2.1.7 – Evidence for a last universal common ancestor

A2.1.7 – Evidence for a last universal common ancestor
Include the universal genetic code and shared genes across all organisms. Include the likelihood of other forms of life having evolved but becoming extinct due to competition from the last universal common ancestor (LUCA) and descendants of LUCA.

Evidence for the existence of a **last universal common ancestor (LUCA)** for all life on Earth includes:

- a universal genetic code carried by DNA and shared by all cells
- over 300 genes or sections of DNA common to all cells
- the same building blocks for both DNA and RNA in all cells
- common molecular processes within all cells, including the replication of DNA molecules and the production of proteins
- similar transport mechanisms for cellular materials in and out of cells, as well as within cells.

It is hypothesized that other forms of life, demonstrating distinctive characteristics other than these, have evolved over the past 3.5 billion years. However, they are not present today as a result of unsuccessful competition with the LUCA and its descendants.

A2.1.8 – Dating the first living cells and LUCA

A2.1.8 – Approaches used to estimate dates of the first living cells and the last universal common ancestor
Students should develop an appreciation of the immense length of time over which life has been evolving on Earth.

Charles Darwin in his theory of evolution by natural selection utilized the concept of common ancestry. He believed all life on Earth that has existed and does exist can be traced back to a single ancestor, the LUCA.

As mentioned previously, the Earth is thought to be approximately 4.5 billion years old. The earliest evidence of life on Earth comes from **fossils**. Fossils are the remains and/or traces of past life. Most fossils originate from the hard parts of past organisms, such as shells, bones and teeth. However, some fossils can represent the remains of trails and footprints, or even the impressions of soft body parts. Using various dating techniques, it is estimated that the earliest life occurred on Earth about 3.5 billion years ago.

One of the most accurate means of dating fossils involves radiometric techniques, which are based on the **half-life**, the length of time it takes for half of a radioactive isotope to change into another stable element. An isotope is an unstable form of an element. Fossils contain isotopes of elements that accumulated when the organisms were alive. Radioactive isotopes are taken up by organisms at constant rates. Therefore, by measuring the amount of an isotope in a fossil and comparing it with the amount taken up when the organism was alive, we can determine an age for the fossil. This is known as **absolute dating** of a fossil's age, because the half-life of each isotope is not known to vary. Some radioactive isotopes used in this procedure and their half-lives are shown in Table 1.

Palaeontologists study the fossil record to learn about the history of life on our planet as well as the past climate and environment. Other means of dating previous life have also been developed. One recently developed technique involves genomic or genetic analysis. Genomic dating compares the amount of genetic difference between living organisms and computes an age based on rates of genetic mutation over time. However, it is quite difficult to find DNA in fossils, making this technique unfavourable for dating older life forms.

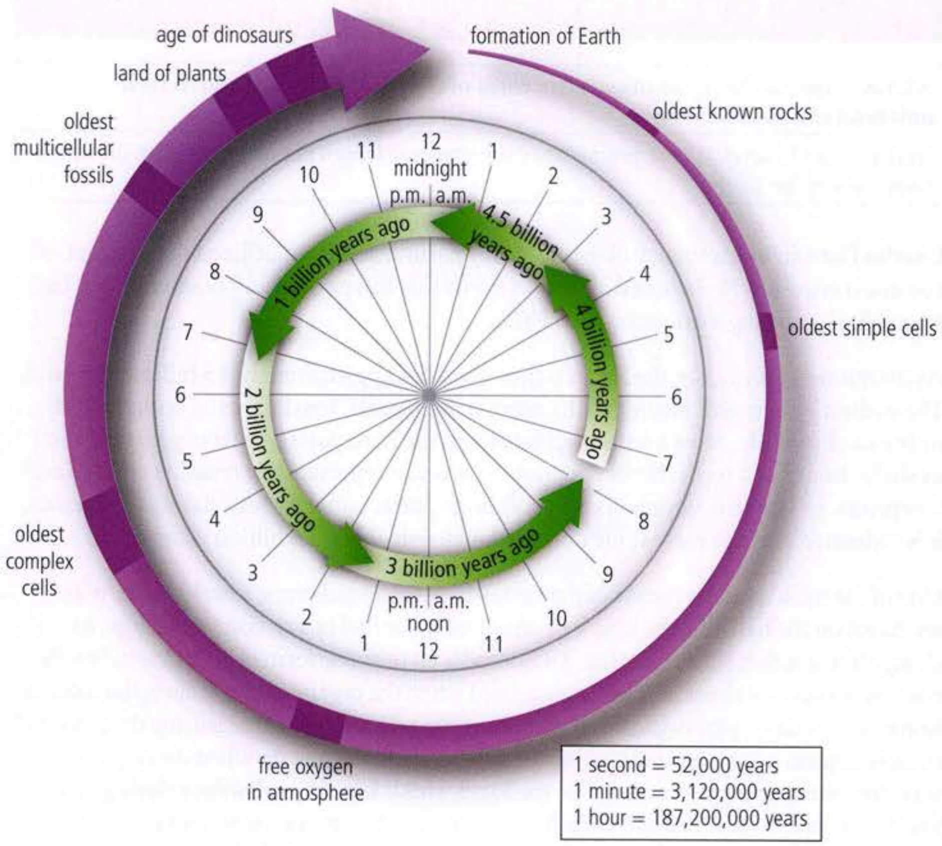
Isotope	Half-life
Uranium-238	4.5 billion years
Uranium-235	700 million years
Carbon-14	5,730 years
Radium-226	1,600 years

▲

A2.1 Table 1 The half-life of various radioactive isotopes

Relative dating of fossils is not as exact as absolute dating. It utilizes the sediment layers of the Earth and **index fossils.** Sediments are particles of eroded and weathered rock and soil that may form layers or strata. These sediment layers occur in sequence, with the oldest layers at the bottom. This layering sequence allows a relative means of working out the age of a fossil. It is important to note, however, when using this method of dating, that geological processes may disturb the original sequence of layers, thus potentially providing inaccurate fossil ages. Index fossils are fossils of the same age that are found in strata in different parts of the world. Therefore, all strata around the world that contain the same fossil(s) must be of the same age.

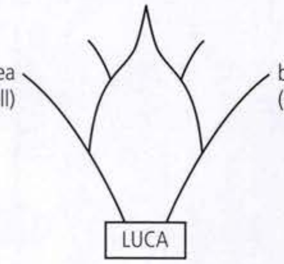
One way to get an impression of the length of time life has been on our planet is to use a 24-hour time span to represent the 4.5-billion-year existence of Earth, as shown in Figure 2.



A2.1 Figure 2 Earth's past represented in a 24-hour time span.

Note in Figure 2 the time it took for the first simple cells to evolve or change into the first complex cells. That modern humans do not appear in this 24-hour representation of the Earth's history until 1 second before midnight indicates the immense period of time life has been evolving on our planet, and the relatively short period of time humans have been part of it. Many scientists believe the LUCA existed about 3.5 billion years ago, but it is important to remember that the LUCA is not thought to have been the first life on Earth, but rather the latest that is ancestral to all current existing life (see Figure 3).

What is needed for structures to be able to evolve by natural selection?



A2.1 Figure 3 Bacteria and archaea are both examples of quite simple cells, compared to the more complex plant and animal cells. Archaea differ from bacteria in the composition of their cell boundary and certain life processes.

A2.1.9 – Hydrothermal vents and the evolution of the LUCA

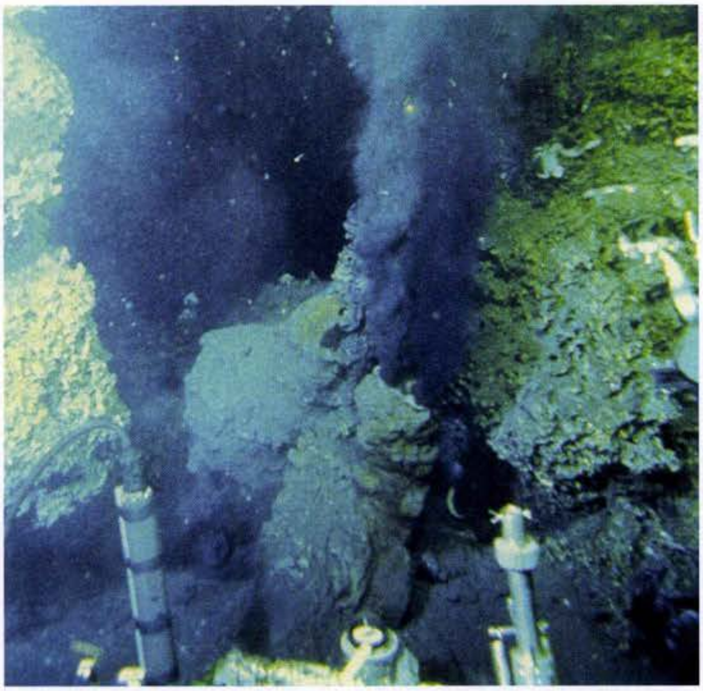
A2.1.9 – Evidence for the evolution of the last universal common ancestor in the vicinity of hydrothermal vents
Include fossilized evidence of life from ancient seafloor hydrothermal vent precipitates and evidence of conserved sequences from genomic analysis.

One hypothesis suggests that the location for the origin of life on Earth is around **hydrothermal vents**, places where hot water emanates from beneath the ocean floor. The first deep-sea hydrothermal vent was observed in 1977. Such a structure forms when cracks in the crust of the seabed expose seawater to rocks below, which are heated by magma. The hot water rises and picks up countless minerals along the way.

Today, we know about entire communities living around these vents, including creatures never seen before 1977, such as metre-long white-and-red tube worms that absorb the minerals from the water and transfer them to symbiotic bacteria. The bacteria then make food from the minerals, and this food nourishes the tube worms. The discovery of these communities disproves the idea that the bottom of the ocean must be lifeless because there is no sunlight. It also gives credibility to the hypothesis that the earliest forms of life could have formed deep in the ocean around hydrothermal vents.

Hydrothermal vents are sometimes referred to as "black smokers" because the water coming out of them contains so many dark minerals that it looks like smoke.

Hydrothermal vents such as this one are major sites of study. They provide a warm, nutrient-rich environment with the necessary gases, energy and chemical compounds for life to evolve.



Evidence to support the possible appearance of the LUCA at hydrothermal vents include:

- some of the world's oldest fossilized traces or precipitates have originated at these vents
- the commonality of genetic sequences in the organisms near these vents, indicating a likely single ancestor
- the presence of a mineral-rich environment with both the acidic and basic fluids that are necessary for chemical reactions
- the presence of both hydrogen and carbon dioxide at these locations, resulting in the reducing environment essential for carbon compound formation.

A reducing environment has been observed to support an increasing number of bonds between carbon and hydrogen.

Many questions still remain about the how and where of the origin of life on our planet. Various hypotheses offering explanations will continue to be presented in future research. It is important to approach each with an open mind, and rely on experimentation to verify supporting evidence.

Guiding Question revisited

What plausible hypothesis could account for the origin of life?

In this chapter we have presented various hypotheses concerning the origin of life on Earth, some of which may be more plausible than others. Key ideas include:

- it is extremely difficult to explain the spontaneous origin of life because of our lack of knowledge of what the early Earth conditions actually were
- the Miller–Urey experiment resulted in the primordial soup theory for the first protocells
- there is evidence to support a theory that life originated near hydrothermal vents on the ocean floor.

Guiding Question revisited

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

In this chapter we have looked at various requirements for the development of life. Key ideas include:

- high concentrations of carbon dioxide and methane were present without free oxygen on early Earth
- the processes that formed the first life on Earth no longer occur today because the present-day environment is so different
- all organisms are composed of a cell or of multiple cells and have common functions
- the formation of a membrane was essential for the formation of the protocell and the more complex cells that followed
- RNA has characteristics that could mean it had the genetic material and control of chemical reactions essential for the first cells
- life has been evolving on Earth for an extremely long period of time
- the last universal common ancestor (LUCA) out-competed other forms of life with different life characteristics, resulting in all the forms of life observed on our planet today.

Exercises

Q1. Define what a radioisotope's half-life is.

Q2. State three conditions of early Earth that Miller and Urey tested in their model, leading to the primordial soup hypothesis.

Q3. Describe the importance of membranes in allowing survival and further development of the first cells.

Q4. Describe how RNA could have been essential to early cells.

Q5. Explain the position of the last universal common ancestor on the modern tree of life.

HL end

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.

HL Chapter A2.1 discusses the cell theory and the functions exhibited by all forms of life.

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)

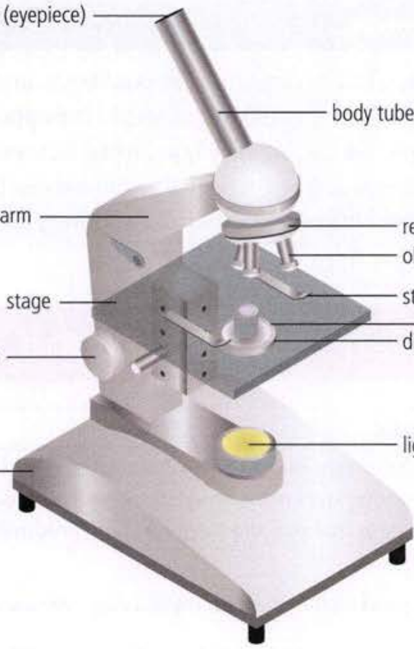
▲ Commonly used microscope metric equivalents

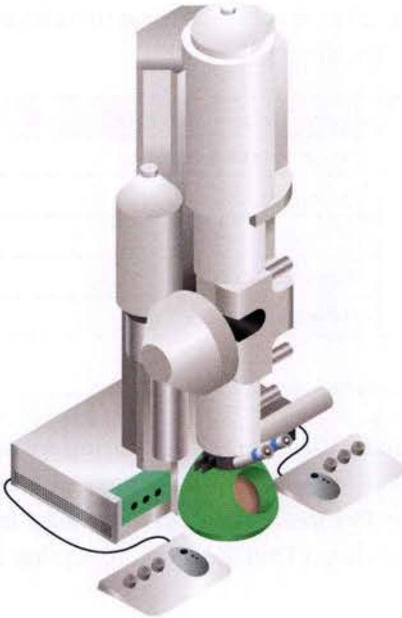
Microscopes with a high **magnification** and **resolution** are needed to observe cells and especially their subunits. Magnification is the increase in an object's image size compared to its actual size. Pictures or drawings of an image from a microscope include the number of times larger than the actual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

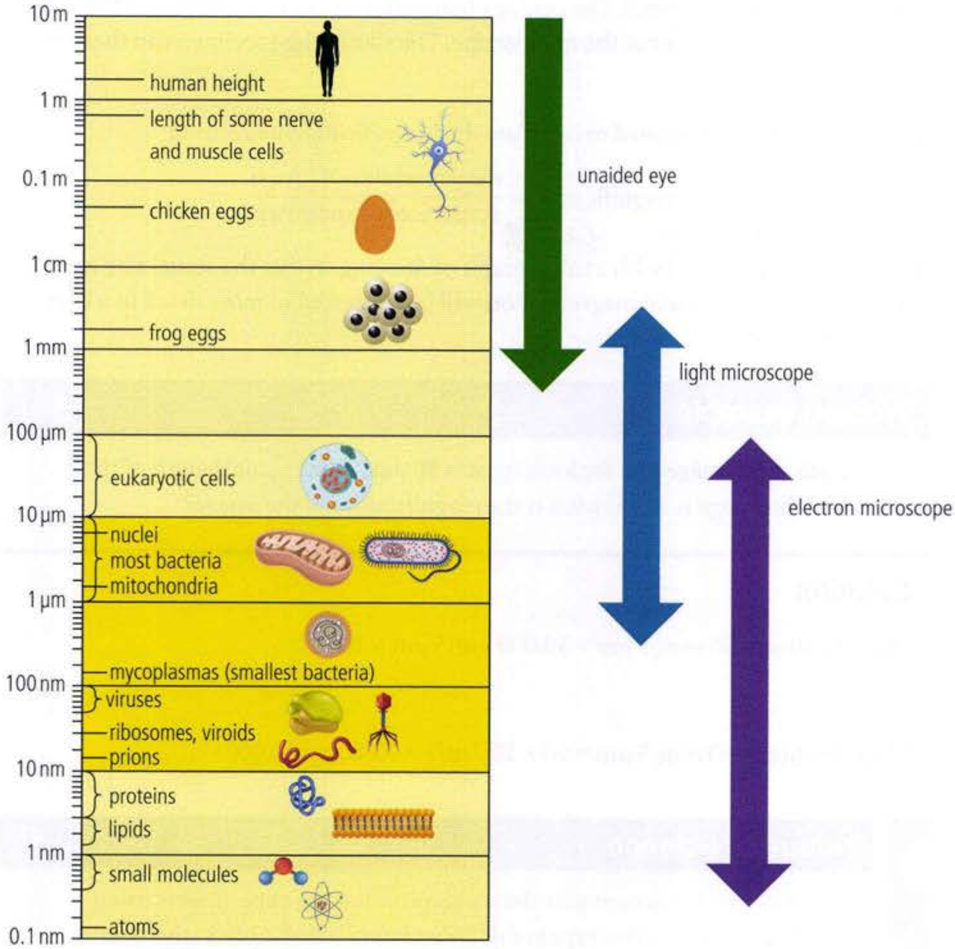




Most cells can be up to 100 micrometres (100 μm) in size. Organelles are up to 10 μm in size. Bacteria are between 1 and 10 μm in size. Viruses are up to 100 nanometres (nm) in size. Cell membranes are 10 nm thick, while molecules are about 1 nm in size. All these structures are three-dimensional.

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



▲ 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.

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 **artefacts** are seen in the pictures produced by an EM. These artefacts do not actually exist in the cell but are produced during the preparation of the samples for an EM.

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 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).

i

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.

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

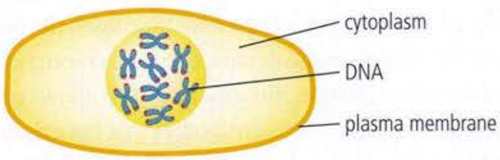
Each advance of the microscope, whether light or electron, leads to a corresponding increase in our understanding of the cell's structures and functions.

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.

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.

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 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?

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.

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.

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.

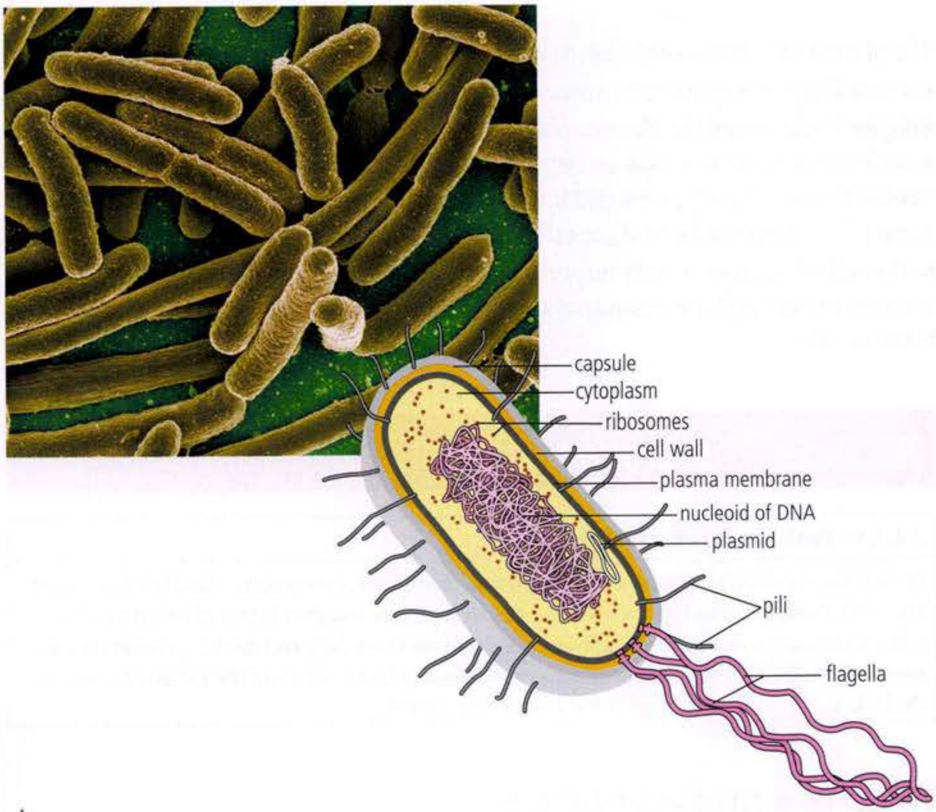
Prokaryotic organisms include bacteria and archaea. Bacteria and archaea appear to have followed different branches to eukaryotes (in the domain Eukarya) in the evolution of life. Prokaryotes are mostly small and unicellular. There are thousands of distinct types differentiated by many factors, including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

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.

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.

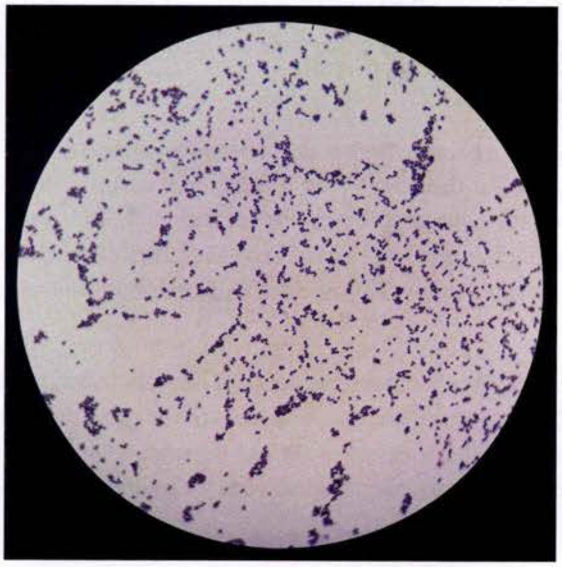
Cell wall and plasma membrane

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.

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.

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.



▲ 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.

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.

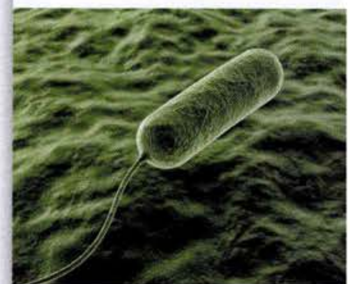
SKILLS

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

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.

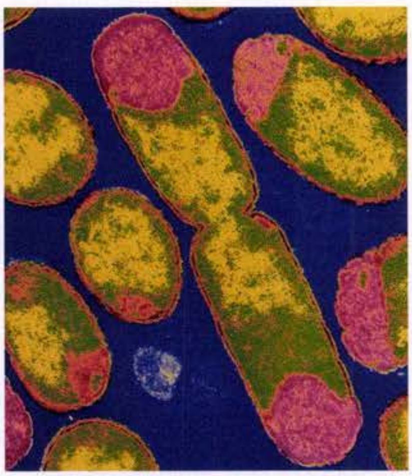
In addition to the bacterial chromosome, bacteria may also contain **plasmids**. These small, circular, DNA molecules are not connected to the main bacterial chromosome. The plasmids replicate independently of the chromosomal DNA. Plasmid DNA is not required by the cell under normal conditions, but it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

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.

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.

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.



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.

A2.2.6 – The eukaryote cell

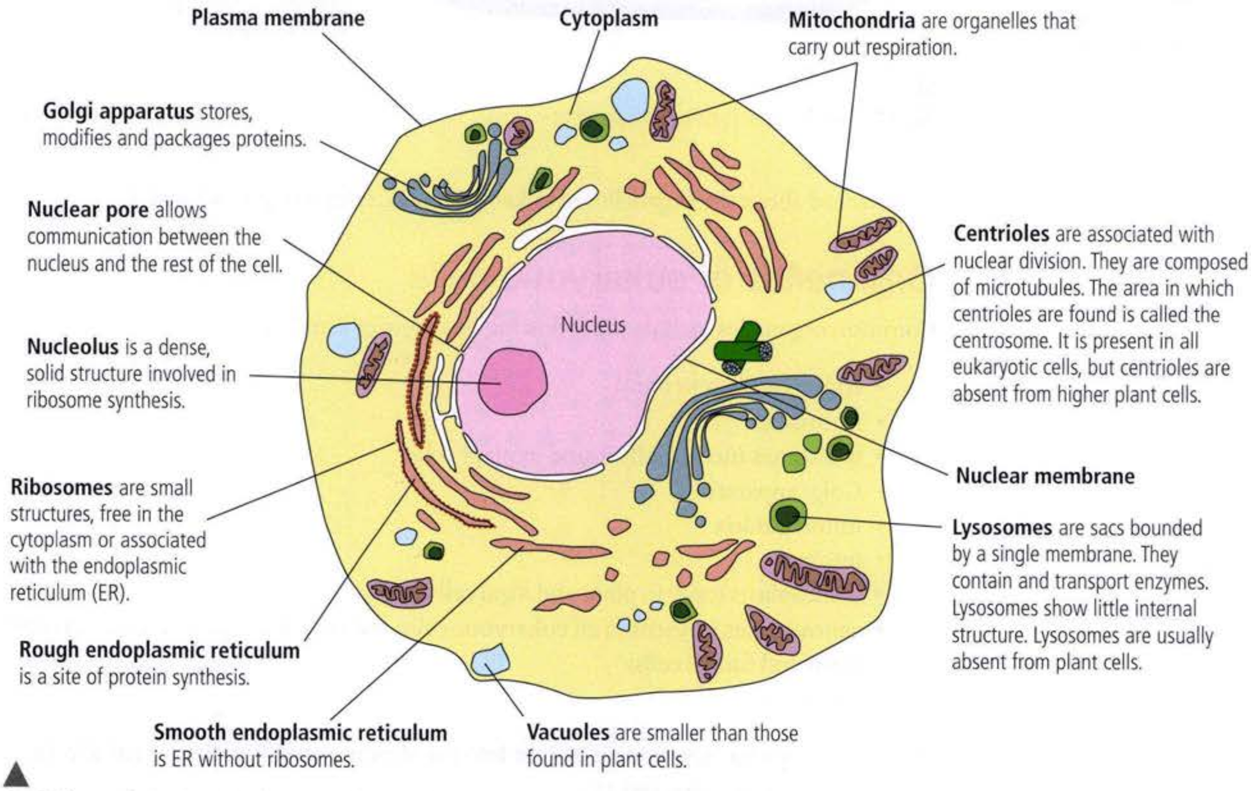
A2.2.6 – Eukaryote cell structure
Students should be familiar with features common to eukaryote cells: a plasma membrane enclosing a compartmentalized cytoplasm with 80S ribosomes; a nucleus with chromosomes made of DNA bound to histones, contained in a double membrane with pores; membrane-bound cytoplasmic 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?

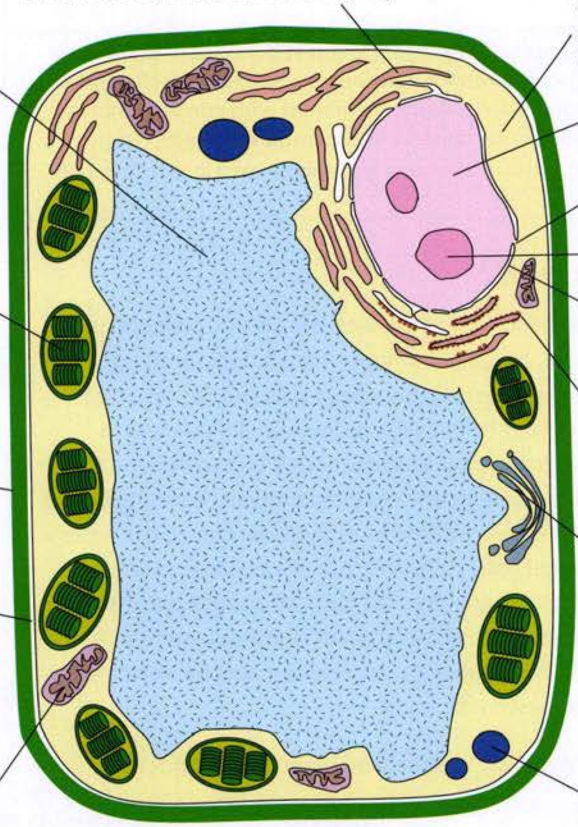
Whereas prokaryotic cells occur in bacteria and archaea, eukaryotic cells occur in organisms such as algae, protozoa, fungi, plants and animals. Eukaryotic cells range in diameter from 5 to 100 μm. A "kernel" or nucleus is usually noticeable in the cytoplasm. Other **organelles** may be visible within 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.

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

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.

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

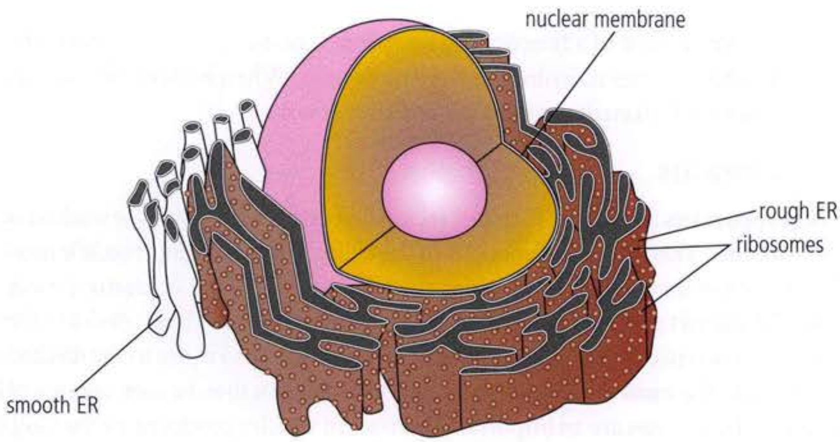
The eukaryotic cell cytoplasm contains a network of fibres collectively called the **cytoskeleton**. These fibres are composed of protein and provide the following functions within the cell:

- 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).

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.

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.

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.

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.

Lysosomes

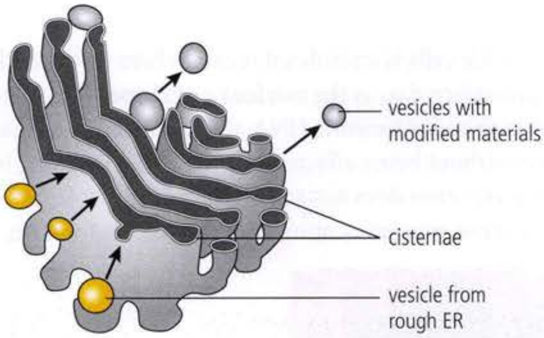
Lysosomes are intracellular digestive centres that arise from the Golgi apparatus. A lysosome does not have any internal structures. Lysosomes are **vesicles** (sacs) bounded by a single membrane that contains as many as 40 different enzymes. The enzymes are all **hydrolytic** and catalyse the breakdown 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.

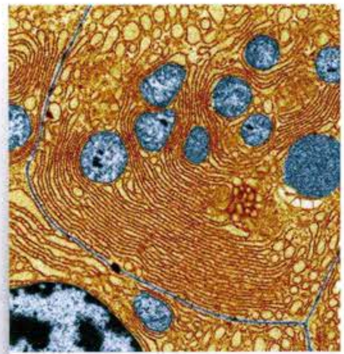
The interior environment of a functioning lysosome is acidic; acidic conditions are necessary for the enzymes to hydrolyse large molecules. When **hydrolysis** occurs, large molecules are broken down with the addition of water.

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.



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?

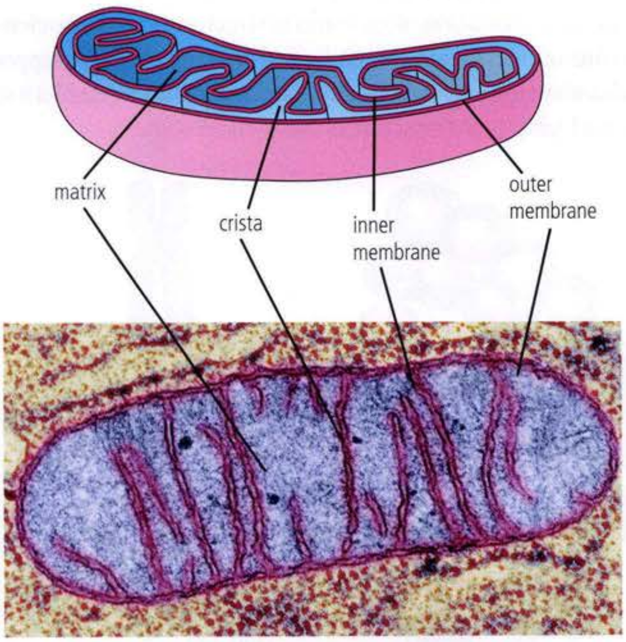


A transmission electron micrograph (TEM) of a pancreatic exocrine cell. Can you tell that this is an animal cell? Locate as many of the structures of an animal cell as you can. How do the structures of this cell reflect the overall functions of the pancreas?

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.



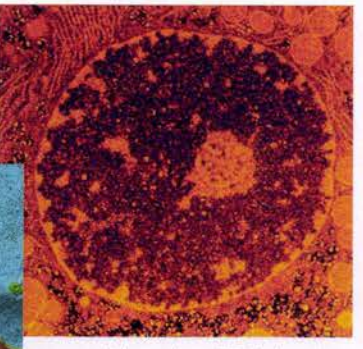
Compare this drawing of a mitochondrion with the corresponding false-colour transmission electron micrograph (TEM) below it.

Nucleus

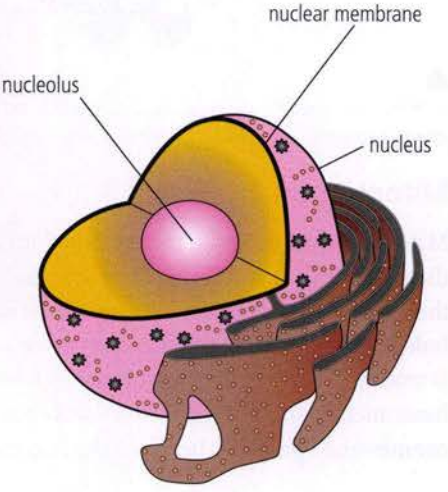
The **nucleus** in eukaryotic cells is an isolated region where DNA resides. It is bordered by a double membrane referred to as the **nuclear envelope**. This membrane allows compartmentalization of the eukaryotic DNA, thus providing an area where DNA can conduct its functions without being affected 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.

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

False-colour TEM showing pores in the nuclear membrane.

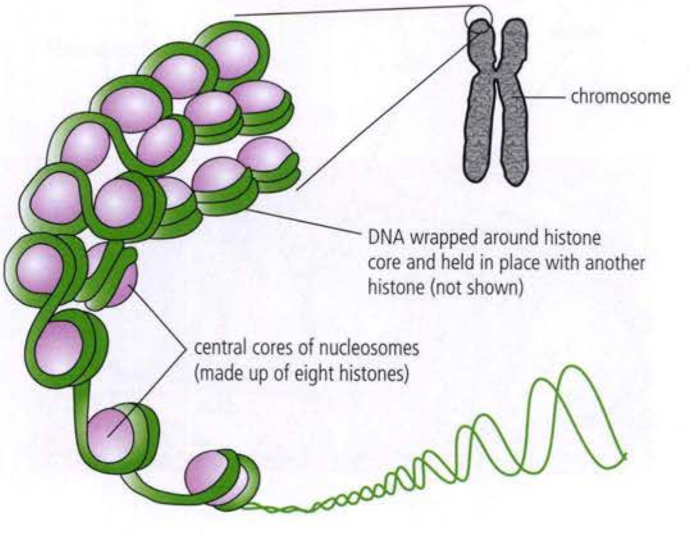


False-colour TEM showing nucleus and nucleolus.



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.



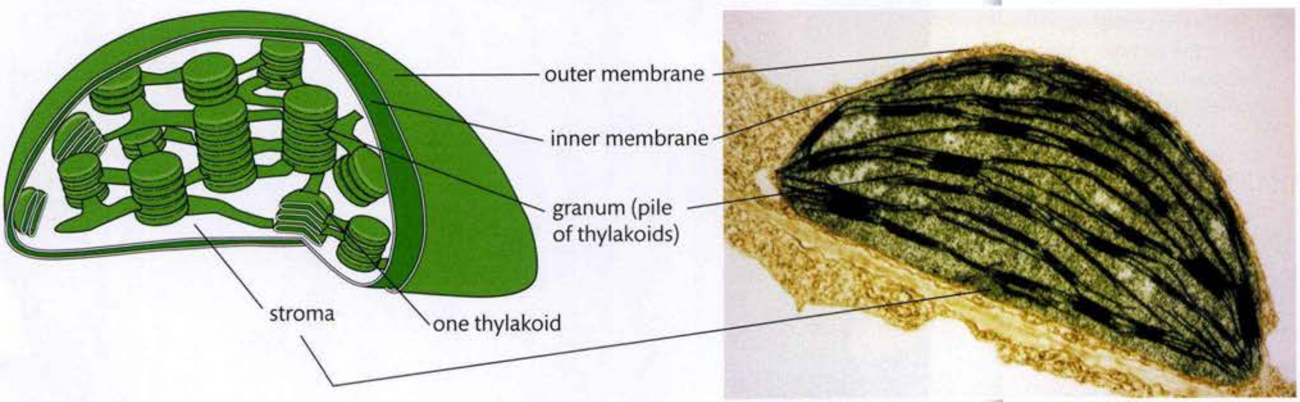
The nucleus is often located centrally within the cell's cytoplasm, although in some cell types it is pushed to one side or the other. The side position is characteristic of plant cells, because these cells often have a large central vacuole. Most eukaryotic cells possess a single nucleus, but some do 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

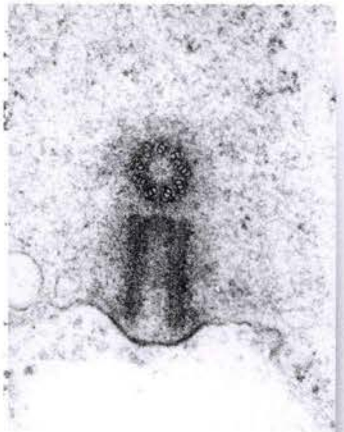
Chloroplasts occur only in algae and plant cells. The chloroplast contains a double membrane and is about the same size as a bacterial cell. Like the mitochondrion, a chloroplast contains its own DNA and 70S ribosomes. The DNA of the chloroplast takes the form of a ring.

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.



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.

Centrosome

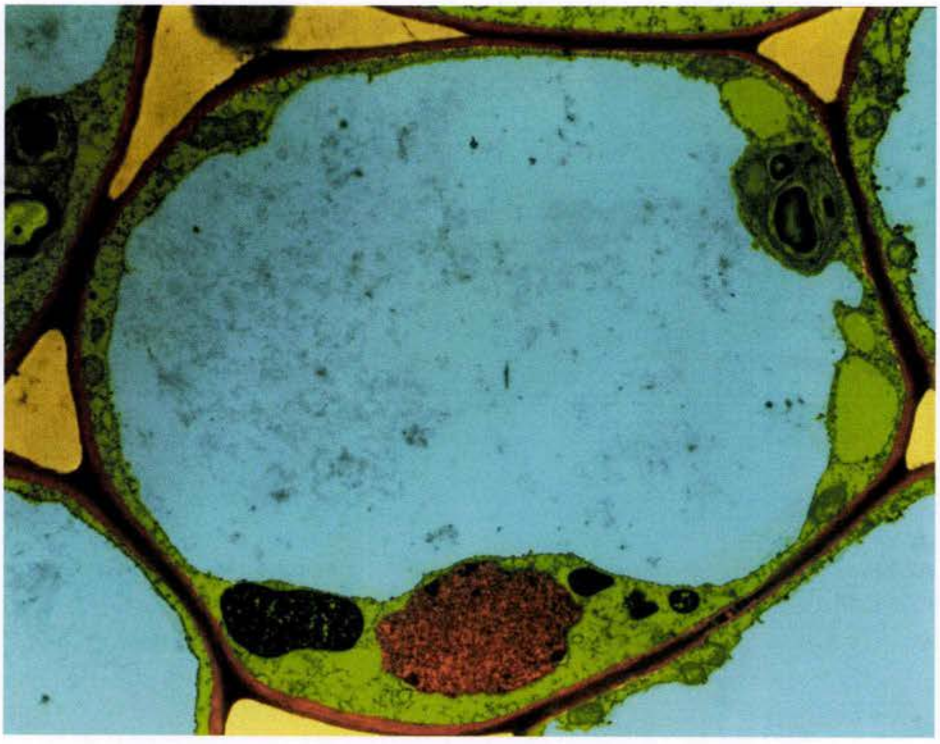
The **centrosome** occurs in all eukaryotic cells. In animal cells it consists of a pair of **centrioles** that are often at right angles to one another. The centrioles are involved with the assembly of **microtubules**, which are important to a cell because they provide structure and allow movement. 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.

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.



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

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

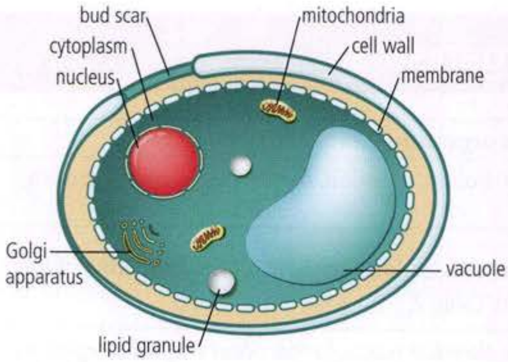
- The cell membrane controls the movement of materials in and out of the cell, to help maintain homeostasis.
- Vacuoles isolate and store waste so that it does not harm the organism.
- Cells often possess cilia or flagella that allow movement in response to changes in the environment.
- Vacuoles carry 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.

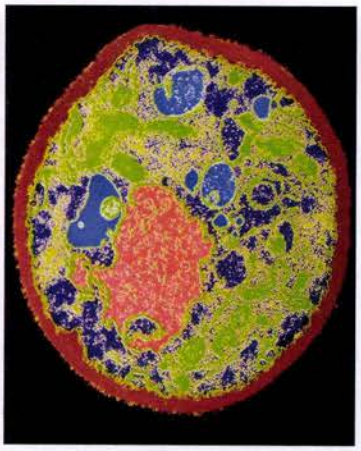
A2.2.8 – Different types of eukaryotic cells

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

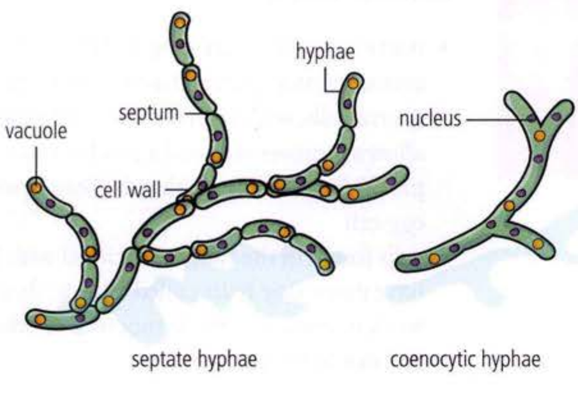
Most of the organelles discussed are present in all eukaryotic cells. When an organelle is present in each of the eukaryotic cell types, it usually has the same structure and function. For example, all three cell types contain mitochondria that possess cristae, a matrix and a double membrane. Also, in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

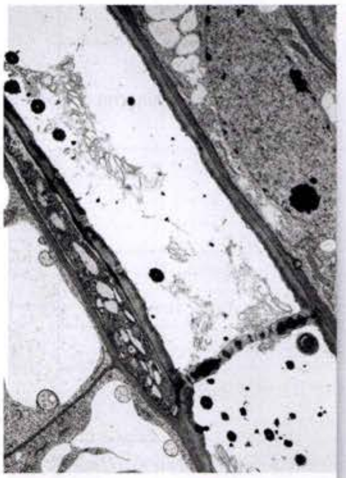
The structure of some eukaryotic cells is unique or atypical, which allows them to carry out specialized functions. One example of this atypical structure involves cell nuclei.

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.



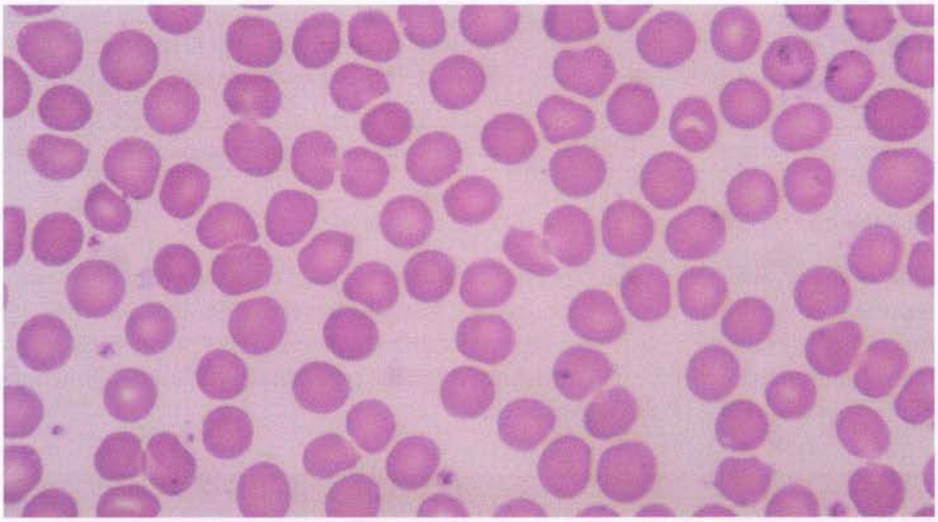
Notice the two types of hyphae shown in this image. The hyphae on the right do not contain cross-walls, while cross-walls are present in the hyphae on the left.

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.

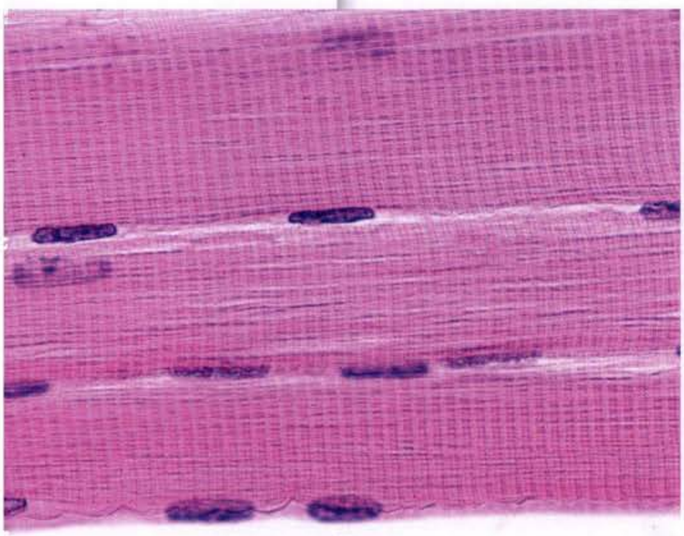


A2.2 Figure 5 A transmission electron micrograph (TEM) of a plant's sieve tube elements and associated companion cells. Notice the lack of substance in the sieve tube elements and the pores in the end wall.

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.



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

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.

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.

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.

SKILLS

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.

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.

HL

A2.2.12 – The origin of eukaryotic cells

A2.2.12 – Origin of eukaryotic cells by endosymbiosis
Evidence suggests that all eukaryotes evolved from a common unicellular ancestor that had a nucleus and reproduced sexually. Mitochondria then evolved by endosymbiosis. In some eukaryotes, chloroplasts subsequently also had an endosymbiotic origin. Evidence should include the presence in mitochondria and chloroplasts of 70S ribosomes, naked circular DNA and the ability to replicate. **NOS**: Students should recognize that the strength of a theory comes from the observations the theory explains and the predictions it supports. A wide range of observations are accounted for by the theory of endosymbiosis.

A common origin for all cells on Earth requires an explanation of how a cell could progress from a simple, non-compartmentalized prokaryote to a complex, highly compartmentalized eukaryote. The **endosymbiotic theory** presents a mechanism by which this progression may have occurred. The key points of the theory are:

- about 2 billion years ago a larger cell that had a nucleus and was capable of sexual reproduction engulfed a smaller prokaryotic cell that could produce energy
- these two cells developed a mutually beneficial (**symbiotic**) relationship, forming a single organism
- the smaller engulfed cell then went through a series of changes to become a mitochondrion.

With this process, the larger cell helped the bacteria prokaryote by providing protection and carbon compounds. The smaller prokaryote, after a series of changes, specialized so that it provided the now more complex larger cell with ATP.

There is much evidence to support this theory, including the characteristics of mitochondria. Mitochondria:

- are about the size of most bacterial cells
- divide by simple binary fission, as do most bacterial cells
- divide independently of the host cell
- have their own ribosomes, which are 70S in size, as prokaryote cell ribosomes are
- produce their own proteins with these ribosomes
- have their own DNA, which occurs in a circular ring, as in prokaryotic cells
- have two membranes on their exterior, which is consistent with an engulfing process
- have an inner membrane with a composition like that of prokaryote membranes, while the outer membrane is more like eukaryotic cell membranes
- have RNA present in mitochondrial ribosomes that closely resembles the RNA present in prokaryotic ribosomes.

Antibiotics used to inhibit protein synthesis in prokaryotes like bacteria also decrease protein production in mitochondria and chloroplasts.

Challenge yourself

2. On a sheet of paper, produce a series of drawings that represent how two membranes could have come to exist on mitochondria and chloroplasts through an engulfing process involving endocytosis.

In addition to the mitochondria, chloroplasts in plant cells also provide evidence for the theory of endosymbiosis. A modern-day protist called *Hatena arenicola* normally fulfils its nutritional needs by ingesting organic matter. However, when it behaves as a predator and ingests a green alga, it switches its method of fulfilling its nutritional needs to one that uses sunlight to convert organic molecules, that is the process known as photosynthesis. The two organisms, the *Hatena* and the green alga, thrive in a symbiotic relationship.

Another organism, *Elysia chlorotic,* demonstrates a similar adaptation. *Elysia* is a slug found in salt and tidal marshes and creeks. The early stage of its life, referred to as its juvenile stage, characteristically involves movement, and it derives its nutrition by ingesting nutrients found in its surroundings. During this juvenile stage it is brown. As *Elysia* develops, if it meets a specific type of green algae, it enters its adult phase, during which chloroplasts from the ingested algae are retained in its digestive tract. The adult stage of *Elysia* is therefore green in colour. This symbiotic relationship between *Elysia* and the green algae allows the adult form of *Elysia* to take on a more sedentary lifestyle, depending on light being available to carry out photosynthesis.

Another source of evidence for the endosymbiotic theory is DNA. DNA provides a code made up of 64 different "words". Interestingly, this code has the same meaning in nearly all organisms on Earth and is said to be "universal". There are only a few variations, which can be explained by changes since the common origin of life on our planet. As already mentioned, the mitochondria of eukaryotic cells have a DNA code that more closely resembles bacteria than eukaryotic cells. Most scientists believe that the more DNA two organisms have in common, the more closely related they are to one another.

TOK

Biology is the study of life, yet life is an emergent property. Under what circumstances is a **systems approach** productive in biology, and under what circumstances is a **reductionist approach** more appropriate? How do scientists decide between competing approaches? A systems approach involves study of the larger picture of organisms, while a reductionist approach looks at smaller parts of organisms and then attempts to tie them together to understand the total organism.

Nature of Science

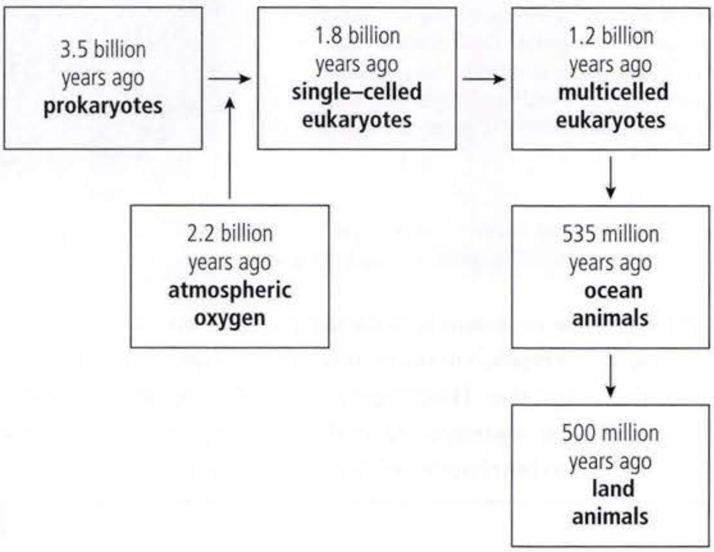
The endosymbiotic theory pulls together a wide range of observations. The strength of this theory results from the many observations as well as the numerous predictions it supports.

A2.2.13 and A2.2.14 – Cell specialization and multicellularity

A2.2.13 – Cell differentiation as the process for developing specialized tissues in multicellular organisms
Students should be aware that the basis for differentiation is different patterns of gene expression often triggered by changes in the environment.

A2.2.14 – Evolution of multicellularity
Students should be aware that multicellularity has evolved repeatedly. Many fungi and eukaryotic algae and all plants and animals are multicellular. Multicellularity has the advantages of allowing larger body size and cell specialization.

With evidence from the fossil record and the absolute dating techniques discussed in Chapter A2.1 a timeline can be constructed for life on Earth (Figure 8).



A2.2 Figure 8 A timeline of the major life-related events on Earth.

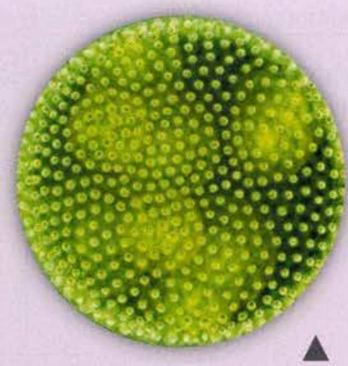
Endosymbiosis was one factor in the development of the cell. Another very important process that helped the development of the cell was **compartmentalization.** Membranes play a major role in the formation of compartments, enabling efficient reactions and processes to proceed. This compartmentalization resulted in specializations within the cell. One example of this is the nucleus, with a protective membrane, enabling the determiners of heredity, DNA molecules, to function without interference from other reactions taking place in the cytoplasm. Another specialized area of the cell is the mitochondria, where energy is produced so that the cell can perform the functions necessary for life.

Even with specialization, a single-celled organism has its limits, and it has not been successful in all environments. As shown in Figure 8, multicelled eukaryotes appear in the fossil record about 1.2 billion years ago. The presence of one eukaryotic organism possessing many cells eventually led to the differentiation of cells in that organism into highly specialized tissues and organs.

A tissue is made up of a group of similar cells working together to perform a common function. An organ is composed of two or more tissues working together to perform a common function.

The cells, tissues and organs that have developed in eukaryotic organisms coordinate and communicate with each other, resulting in organisms capable of thriving in most environments. This coordinated multicellularity appears to have evolved on more than one occasion, as many fungi and eukaryotic algae, and all plants and all animals, are multicellular.

It is not uncommon in nature to see aggregates of many cells. Often these aggregates are called colonies. Aggregates are not multicellular organisms. They have little differentiation of cells or coordination of function. An example of this is some types of *Volvox*. *Volvox* can exist as a spherical colony in which many green algae band together. The individuals are not organized into tissues or organs. There are also examples of bacteria that band together in a colony. However, each bacteria cell is genetically different and can exist individually.



This spherical colony of *Volvox* is composed of hundreds of individuals banded together. However, if the colony is disrupted, each individual organism can exist on its own.

All cells in a multicellular organism have the same genetic information. For specialization and differentiation to occur, mechanisms have developed that control and coordinate gene expression. Differing environments can alter gene expression in the cells of multicellular organisms. All of these developments have allowed most environments on Earth to be inhabited by some form of life.

HL end

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

HL

- evidence indicates that all eukaryotes evolved from a common ancestor
- endosymbiosis explains a mechanism for the development of some organelles of eukaryotic cells
- changes in gene expression result in differentiation of cells
- multicellularity appears to have evolved many times in various ways.

HL end

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.

HL

Q7. List three observations that provided a strong basis for the theory of endosymbiosis.

Q8. Compartmentalization was extremely important in the development of cell specialization. What cell organelle structure was instrumental in bringing about compartmentalization?

Q9. If all cells of a multicellular organism possess the same genetic information, how is specialization and differentiation of cells possible in that organism?

HL end

II. Continued research involving your chosen research question

(a) Research should involve a survey of the topic literature, keeping a detailed account of the sources from which ideas and/or data are used.

(b) Plan your procedure for any experimental work.

(c) Discuss your proposed research and procedure with your supervisor.

(d) It may be necessary to refine your topic and research question as more information is gathered. Proper focus on the research question is essential.

III. Experimental work and data collection

(a) Make certain your experimental procedure is safe and ethical in the opinion of your supervisor before beginning the procedure.

(b) Arrange for all necessary equipment, chemicals and specific needs before beginning the experimental work. This may involve sources outside your school. Be certain all sources of materials outside your school are acceptable to your supervisor.

(c) It is extremely important to consider the independent variables, the dependent variables, and the controlled variables in your procedure or procedures.

(d) An essential part of all experimental work is to ensure an adequate sample size. It is important to discuss sample size with your supervisor.

(e) Control groups and experimental groups must be carefully considered.

(f) A plan should be in place for recording the raw data before the procedure begins. Qualitative data and quantitative data should both be considered in the data collection and recording stage.

(g) Processing and presentation of data is an essential part of the experimental work. Careful consideration should be given to tables, graphs and statistical tests so that data will allow meaningful and proper conclusions to be reached.

(h) If taking a non-experimental approach to the Extended Essay, it is essential there is sufficient secondary data to research the topic effectively. It is also important with this approach to use the secondary data and manipulate or analyse it in an original way.

(i) Your supervisor may give general suggestions throughout this experimental work.

IV. Writing the essay

(a) Your essay should have a structure that allows for an acceptable and appropriate presentation. An acceptable Extended Essay organization is as follows.

- Title page
- Table of contents
- Introduction with research question stated early and clearly
- Hypothesis and explanation of hypothesis
- Background information
- Presentation of variables
- Materials used

- Protocol of experimental procedures
- Data collection and presentation
- Data analysis
- Evaluation
- Conclusion
- Bibliography
- Appendix (This is optional, and may include details of protocols, raw data, or any calculations using the raw data. It is important to note that the essay should be sufficient without the presence of an appendix.)

(b) A first draft should be submitted to your supervisor so that general directions may be given for writing the final draft.

(c) The first draft should be checked against the IB marking criteria by you and your supervisor.

(d) The bibliography style should be one used at your school. There is not a specific form of bibliography to use. It is important that some reference in the essay is made to each bibliography source provided. Information about any online sources used must be appropriate and complete.

V. Final draft

(a) Make changes generally suggested in the first draft by your supervisor.

(b) Proofreading is essential.

(c) Double check your final essay against the "presentation" criterion in the Extended Essay marking criteria.

(d) Arrange a meeting with your supervisor to submit your final essay. Your supervisor should go over the final essay with you, making certain the major sections have been included.

The Extended Essay criteria and advice for each criterion

Criterion	Advice
Criterion A: Focus and method – 6 marks possible	• Explain the topic in a clear and focused manner. • The research question must be effectively stated early in the paper. • The research question should lend itself to discussion and even debate within the Extended Essay. • A sound research question can only be presented when appropriate sources are utilized and properly cited. • The research question should be utilized to formulate a hypothesis, or hypotheses, that can be tested. • Methods used in the Extended Essay should be obviously well planned and allow gathering of data that is relevant to the research question. • Methods used should involve controls and allow adequate data collection.

Criterion	Advice
	• It is essential the research question and the method are biological in nature. • If an investigation is conducted in an external laboratory, you must clearly demonstrate your understanding of the methods and materials utilized. In this situation, you should also clearly present *your role* in choosing and applying any methods and materials utilized.
Criterion B: Knowledge and understanding – 6 marks possible	• The essay must demonstrate a thorough understanding of the topic. • Your essay should flow in a logical way towards the development of a proper conclusion concerning the research question. • Clearly demonstrate in the Extended Essay that you understand all aspects of the essay. • Your analyses should represent an obvious understanding of the topic and research question. • Sources utilized in the Extended Essay must be appropriate and contribute to analyses and the conclusion of the essay. • It is essential the terminology used in the essay is accurate, focused and relevant. • Any technical terms used in the essay should be explained and used appropriately within the text. • Symbols, equations, significant digits and International System of Units (SI) units should be utilized throughout the essay.
Criterion C: Critical thinking – 12 marks possible	• Be certain to present a convincing argument in your Extended Essay. • All arguments or data presented must relate logically to the research question. • It is wise to present alternative views as you develop your research question. • Carefully analyse all of the sources used in your essay. • Evaluate all aspects of the argument/experiment for appropriateness. • All data must be analysed. This analysis may involve mathematical transformations, statistical analysis, tables and/or graphs. • Tables and graphs should be presented logically and appropriately. Each table and graph used in the essay must relate to the research question and to the conclusion. • You must comment on the quality and quantity of the secondary sources and data used. • Limitations, validity and reliability of data should be critically commented on within the text of the essay.
Criterion D: Presentation – 4 marks possible	• Proper structure and layout are essential for high marks with this criterion. • The structure and layout of the essay should add to the presentation and development of the argument. • Scientific and annotated representations of equipment and experimental setups should be present and clear. • Procedural steps should be appropriately summarized. • Irrelevant details should be minimized. • Clarity of diagrams, graphs and tables is essential. They should add to the effective communication essential in the development of the analyses towards a logical conclusion.

Criterion	Advice
	• Raw and processed data tables must be clearly displayed in the most appropriate form. • Any mathematical processes used in analysing raw data should be illustrated/explained clearly. • The essay must not exceed 4,000 words. It is essential to include the following in your Extended Essay: title page, table of contents, page numbers, appropriate illustrations, proper citations and bibliography, and appropriate appendices, if needed. • Graphs, figures, calculations, diagrams, formulas and equations are not included in the word count. • Examiners will not assess any material presented after the 4,000 word upper limit.
Criterion E: Engagement – 6 marks possible	• The examiner will utilize your RPPF after the assessment of the essay to determine the marks achieved for this criterion. • Your reflections should explain how and why the topic was determined. • Your reflections should clearly demonstrate how methods and approaches were determined in developing the Extended Essay. • Reflections should demonstrate knowledge gained by performing this activity. It is essential that you explain suggested changes in further work on the topic chosen.

Final advice for your Extended Essay

1. Be cautious concerning plagiarism. Presenting someone else's ideas or work as your own is plagiarism. Be certain to give proper credit to all ideas or work that has been used in any way in your Extended Essay.
2. Your title page should include:
    - the title of the essay
    - the research question
    - the subject for which the essay is registered
    - the word count, within the 4,000 limit.
3. Neither your name nor your school's name should appear on the title page or any page headers.
4. The introduction must present a strong reasoning for pursuing a conclusion to the presented research question, which should be stated clearly and early. Why the research question is significant for your Extended Essay should also be stated.
5. Any experimental procedures must be clearly and appropriately presented in a way they can be easily replicated.
6. Ethical and safety factors must be thoroughly addressed. It must be obvious that ethical and safety factors have been seriously considered in pursuing the research question.
7. Pages should be clearly numbered. The title page is not numbered. Sections of the essay should be clearly and appropriately labelled.
8. Footnoting and the bibliography must be proper and consistent. Sources in the bibliography not specifically used in the paper should be minimal.

9. All visual presentations must be clear, labelled appropriately, and must pertain to the research question and conclusion.
10. The conclusion must be clearly related to the research question. Limitations to the conclusion should be discussed. It is suggested that you present a brief plan for possible further development of a conclusion to your research question.
11. Any appendices used must be appropriate. Large tables of raw data collected are best included in an appendix. However, a representative sample of collected raw data should be included in the core of the essay in a data table.
12. Be certain the essay is based on suitable biological topics. Stay away from psychology- or medicine-focused topics.
13. Remember that a strong evaluation includes a comparison of your results with that of the literature. This evaluation may be addressed at several points in the essay besides the conclusion. An evaluation only presented in the conclusion is often rather shallow and ineffective.
14. Be certain your Extended Essay does not duplicate any other work being submitted for the Diploma programme. The Extended Essay should not take the form of an internal assessment. The Extended Essay assesses the ability to analyse and evaluate scientific arguments.

Viva voce and the RPPF

The completion of your Extended Essay is signified by the viva voce (concluding interview). This is a 10–15 minute interview with your supervisor. It provides an opportunity to reflect on successes and what has been learned.

After completing the viva voce, you must complete your RPPF. This is your final reflections on the topic, methods, analyses and conclusion of the Extended Essay.

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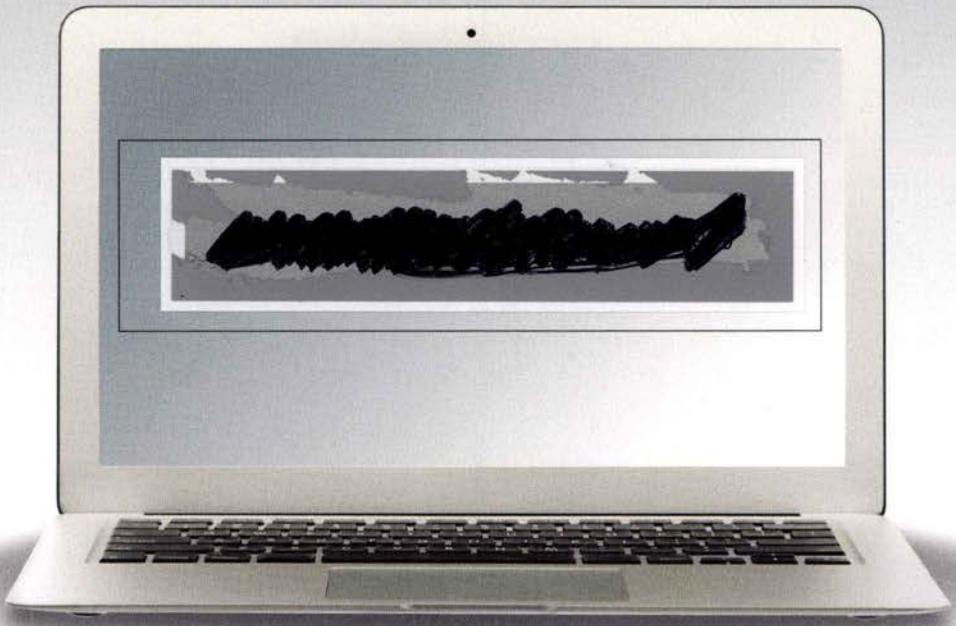

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Alan Damon has been teaching IB Biology and TOK at the École Jeannine Manuel in Paris since 1993. He is committed to integrating technology into the classroom and promoting critical thinking skills.

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.

William Ward taught for 41 years, spending 23 of those teaching IB Diploma Biology. He has led over 60 IB Biology workshops and consulted with many schools in establishing the IB curriculum or improving instruction at existing IB schools.

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