Edexcel

AS Level

Biology

CODE: (WBI11)

Topic 3

Cell structure, reproduction and development

3A Cell structure

1 Observing cells

▲ **fig A** As microscopes have developed, more and more has been revealed about cells, the key to understanding biology.

DISCOVERING CELLS

Robert Hooke, an English architect and natural philosopher, designed the first optical microscope in 1665, examining objects with tiny compartments called cells. Anton van Leeuwenhoek observed living unicellular organisms in water using lenses. Nehemiah Grew published accurate drawings of tissues. Matthias Schleiden and Theodor Schwann introduced cell theory in 1839, which proposed cells as the basic units of life. Cell theory is now accepted as a unifying concept in biology. Modern technologies like electron and confocal microscopes have improved our understanding of cells.

MICROSCOPES

The **light microscope or optical microscope** was the only tool for observing cells for many years and is still widely used today (see fig A). A good light microscope can magnify to 1500 times and still give a clear image. At this **magnification**, an average person would appear to be 2.5 km tall.
Since the mid-20th century, the **electron microscope** has enabled scientists to understand the inner workings of cells.

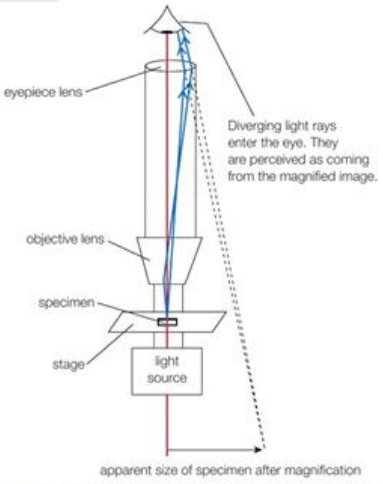
THE LIGHT MICROSCOPE

A specimen or thin slice of biological material is placed on the stage of a light microscope (see fig B). This is illuminated from underneath, either by sunlight reflected with a mirror or by a built-in light source. The objective lens produces a magnified and inverted image. The eyepiece lens focuses this image at the eye.

The total magnification of the specimen is calculated as follows:

magnification of objective lens × magnification of eyepiece lens = total magnification

e.g. ×10 × ×10 = ×100



▲ **fig B** Light passes through the specimen and on through the lenses to give an image that is magnified and upside down.

Providing you always record the magnification you are using, you can work out the actual size of a specimen by measuring it under the microscope:

$$\text{actual size} = \frac{\text{image size}}{\text{magnification}}$$

or $A = \frac{I}{M}$

THE ELECTRON MICROSCOPE

The electron microscope uses electrons to create images with a tiny wavelength, allowing resolution power to increase. Its specimens must be in a vacuum and prepared through a complex process including chemical preservation, freeze-drying, freeze-fracturing, dehydration, embedding, sectioning, and mounting on a metal grid. Heavy metal ions like lead and uranium are often used to improve electron scattering, producing clearer, easier-to-interpret images displayed on a monitor or computer screen.

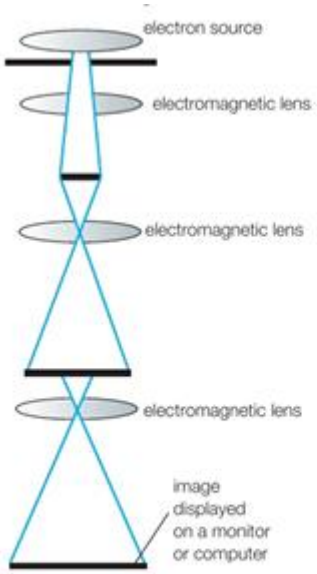
There are two main types of electron micrograph. Transmission electron micrographs (TEMs) are two-dimensional (2D) images similar to those from a light microscope (see fig E). Scanning electron micrographs (SEMs) have a lower magnification, but are three-dimensional (3D) and can be very striking (see fig F).

There are big advantages to using electron microscopes, but there are some disadvantages too (see **table B**).

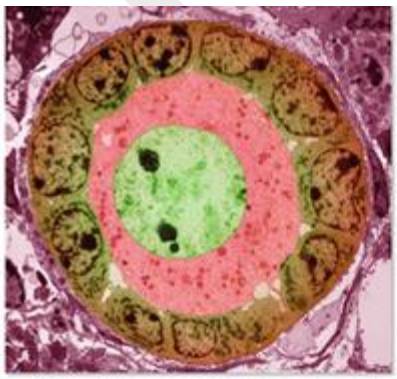
ADVANTAGES OF THE ELECTRON MICROSCOPE	DISADVANTAGES OF THE ELECTRON MICROSCOPE
• Huge powers of magnification and resolution. Many details of cell structure have been seen for the first time using an electron microscope.	• All specimens are examined in a vacuum – air would scatter the electrons and produce a blurred image of the tissue – so it is impossible to look at living material.
	• Specimens undergo severe treatment that is likely to result in artefacts. Preparing specimens for the electron microscope is very skilled work.
	• Extremely expensive.
	• The instrument is very large, must be kept at a constant temperature and pressure, and with an internal vacuum. Relatively few scientists outside research laboratories have easy access to this equipment.

table B The advantages and disadvantages of the electron microscope

▲ **fig F** Scanning electron micrographs introduce a 3D world of biology on a small scale.



▲ **fig D** In an electron microscope, a beam of electrons passes through the specimen and on through a series of electromagnetic or electrostatic lenses. This gives a greatly magnified image.



▲ **fig E** A transmission electron micrograph of a cell gives you much more detailed information than a light micrograph (see **fig C**).

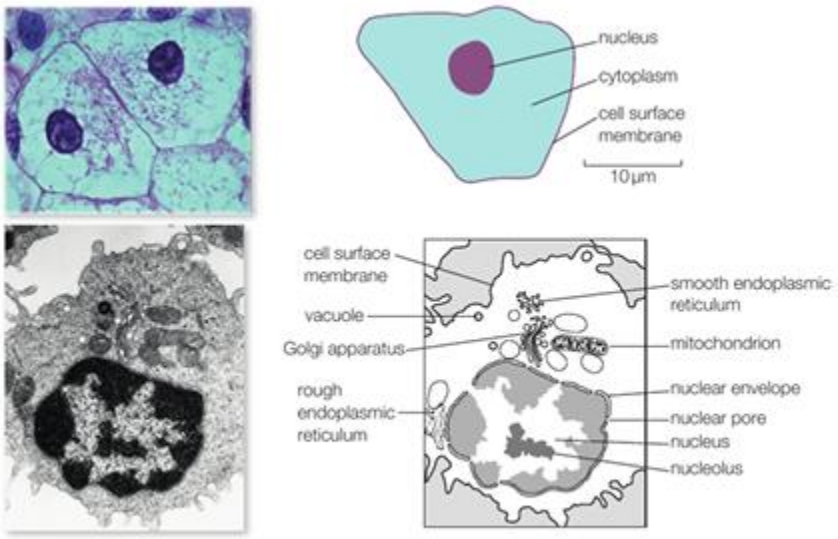
SUBJECT VOCABULARY

light microscope (optical microscope) a tool that uses a beam of light and optical lenses to magnify specimens up to 1500 times life size
magnification a measure of how much bigger the image you see is than the real object
electron microscope a tool that uses a beam of electrons and magnetic lenses to magnify specimens up to 500 000 times life size
resolution (resolving power) a measure of how close together two objects must be before they are seen as one
artefacts things observed in a scientific investigation that are not naturally present; they occur as a result of the preparation or investigation
graticule a series of lines in the eyepiece of a microscope which help you measure specimens accurately
transmission electron micrographs (TEMs) micrographs produced by the electron microscope that give 2D images like those from a light microscope, but magnified up to 500 000 times
scanning electron micrographs (SEMs) micrographs produced by the electron microscope that have a lower magnification than TEMs, but produce a 3D image

3A 2 Eukaryotic cells 1: common cellar structures

THE CHARACTERISTICS OF EUKARYOTIC CELLS

In eukaryotic organisms such as animals, plants and fungi, there is a very wide range of different types of cell, each with a different function. There are certain cell features that are common and which we can put together to represent a typical plant or animal cell. Remember that this typical cell does not really exist, but acts as a useful guide to what to look for in any eukaryotic cell (see fig A).

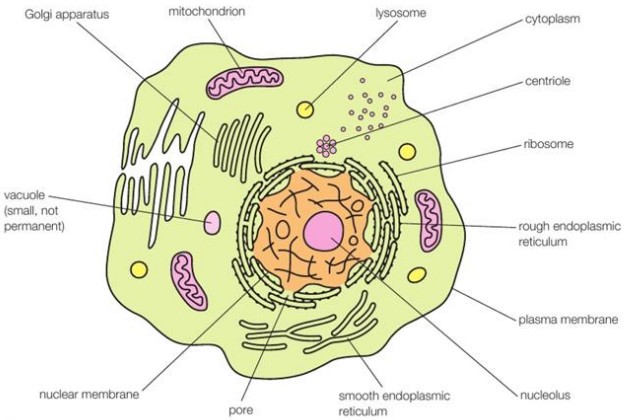


▲ **fig A** These images show clearly how introducing the electron microscope increased our detailed knowledge and understanding of structures within cells.

THE TYPICAL ANIMAL CELL

A typical animal cell contains many things that are found in all eukaryotic cells, including plants and fungi. A membrane known as the cell surface membrane surrounds the cell. Inside this membrane is a jelly-like liquid called the **cytoplasm** containing a **nucleus** - the two together are known as the **protoplasm**. The **cytoplasm** contains the components that perform the functions of the cell.

The **ultrastructure** of the cell are those structures that can only be observed in detail using the electron microscope (see fig B). You will never see a cell that looks like this, but it is a useful model to show how the different organelles are arranged in the cell and how they relate to each other. The structure of each part of the cell relates closely to its function.



▲ **fig B** This diagram shows a typical animal cell, drawn to show the ultrastructure visible with an electron microscope.

MEMBRANES

Membranes are important as an outer boundary to the cell and also as the many **intracellular**

(internal) membranes. In Chapter 2A. you looked at the importance of cell membranes for controlling the movement of substances, but membranes inside the cell also have other functions.

THE PROTOPLASM

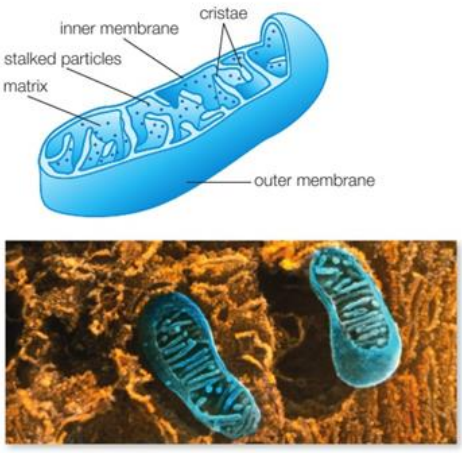
When the light microscope was the only tool that biologists had to observe cells, they thought that the cytoplasm was a relatively structureless clear jelly. But the electron microscope revealed the cytoplasm to be full of many structures, known as organelles, some of which are described below.

THE NUCLEUS

When the cell is not actively dividing, the DNA is bonded to the protein to form **chromatin**, which looks like tiny granules. Also in the nucleus is at least one **nucleolus** - an extra-dense area of almost pure DNA and protein. The nucleolus is involved in the production of ribosomes. Recent research also suggests that the nucleolus plays a part in the control of cell growth and division.

MITOCHONDRIA

The name **mitochondria** (singular mitochondrion) means 'thread granules' and describes the tiny rod-like structures that are 1 µm wide by up to 10µm long. They can be seen in the cytoplasm of almost all cells under a light microscope.

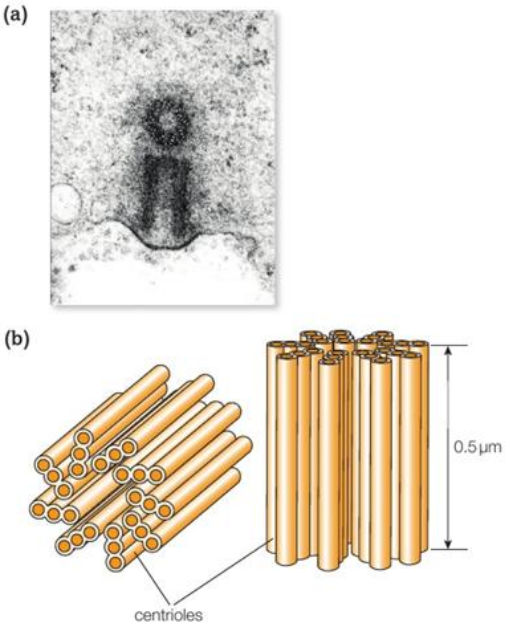


▲ **fig C** The 3D structure of the mitochondria (shown here in blue) is closely related to their functions in cellular respiration.

Mitochondria have an internal arrangement adapted for their function (see fig C). The inner membrane is folded to form **cristae**, which give a very large surface area, surrounded by a fluid matrix. This structure is closely integrated with the events in cellular respiration that occur in the mitochondrion .The fact that mitochondria (and chloroplasts) have their own DNA leads scientists to think that these organelles originated as symbiotic **eubacteria** living inside early eukaryotic cells. During millions of years, they have become an integral part of the eukaryotic cell.

THE CENTRIOLES

In each cell, there is usually a pair of **centrioles** near the nucleus (see fig D). Each centriole consists of a bundle of nine sets of tubules and is about 0.5 µm long by 0.2 µm wide. The centrioles are involved in cell division. When a cell divides, the centrioles pull apart to produce a **spindle** of microtubules that are involved in the movement of the chromosomes, as you will see later in this chapter.



▲ **fig D** **(a)** Transmission electron micrograph of centrioles and **(b)** diagram of centrioles

80S AND 70S RIBOSOMES

In **Section 2B.6** you encountered ribosomes. Protein synthesis occurs on these organelles in the cytoplasm of the cell. Ribosomes are made from ribosomal RNA and protein, and consist of a large subunit and a small subunit. The main type of ribosomes in eukaryotic cells are **80S ribosomes**. The S stands for Svedberg, a unit used to measure how quickly particles fall to the bottom of the tube (settle) in a centrifuge. The rate of settling depends on the size and shape of the particle. When 80S ribosomes are broken into their two units, they are made up of a 40S small subunit and a 60S large subunit. The ratio of RNA : protein in 80S ribosomes is 1 : 1.

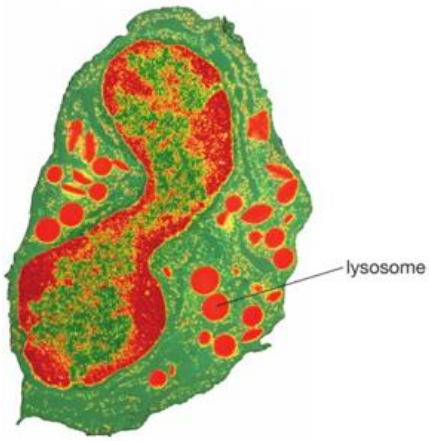
Eukaryotic cells also contain another type of ribosome. Scientists have discovered **70S ribosomes** in the mitochondria and in the chloroplasts of plant cells. These ribosomes are usually found in prokaryotic cells (bacteria and cyanobacteria). They consist of a small 30S subunit and a larger 50S subunit and the ratio of RNA : protein in 70S ribosomes is 2 : 1.

The 70S ribosomes are reproduced in the mitochondria and chloroplasts independently when a cell divides. This provides good evidence for the **endosymbiotic theory**.

LYSOSOMES

Food that is taken into the cell of single-celled protists such as *Amoeba* must be broken down into simple chemical substances that can then be used. Organelles in the cells of your body that are worn out need to be destroyed. These jobs are the function of the **lysosomes** (see **fig E**). The word 'lysis' means 'breaking down'.

Lysosomes can also self-destruct. When an entire cell is too old, needs to be removed during development, has a mutation or is under stress, then its lysosomes may rupture. They release their enzymes which then destroy the entire contents of the cell. This **programmed cell death** is known as **apoptosis**.



▲ **fig E** Good microscopic evidence of lysosomes, like those seen in this false colour electron micrograph, have helped scientists work out what they do in the cell.

SUBJECT VOCABULARY

cytoplasm a jelly-like liquid that makes up the bulk of the cell and contains the organelles
nucleus an organelle containing the nucleic acids DNA (the genetic material) and RNA, as well as protein, surrounded by a double nuclear membrane with pores
protoplasm the cytoplasm and nucleus combined
ultrastructure the detailed organisation of the cell, only visible using the electron microscope
intracellular inside the cell
chromatin the granular combination of DNA bonded to protein found in the nucleus when the cell is not actively dividing
nucleolus an extra-dense region of almost pure DNA and protein found in the nucleus; it is involved in the production of ribosomes and control of growth and division
mitochondria rod-like structures with inner and outer membranes that are the site of aerobic respiration
cristae the infoldings of the inner membrane of the mitochondria which provide a large surface area for the reactions of aerobic respiration
eubacteria true bacteria (prokaryotic organisms)
centrioles bundles of tubules found near the nucleus and involved in cell division by the production of a spindle of microtubules that move the chromosomes to the ends of the cell
spindle a set of overlapping protein microtubules running the length of the cell, formed as the centrioles pull apart in mitosis and meiosis
80S ribosomes the main type of ribosome found in eukaryotic cells, consisting of ribosomal RNA and protein, made up of a 60S and 40S subunit; they are the site of protein synthesis
70S ribosomes the ribosomes found in the mitochondria and chloroplasts of eukaryotic cells and in prokaryotic organisms
endosymbiotic theory a theory that suggests mitochondria and chloroplasts originated as independent prokaryotic organisms that began living symbiotically inside other cells as endosymbionts
lysosomes organelles full of digestive enzymes used to break down worn-out cells or organelles or digest food in simple organisms
apoptosis (programmed cell death) the breakdown of worn-out, damaged or diseased cells by the lysosomes

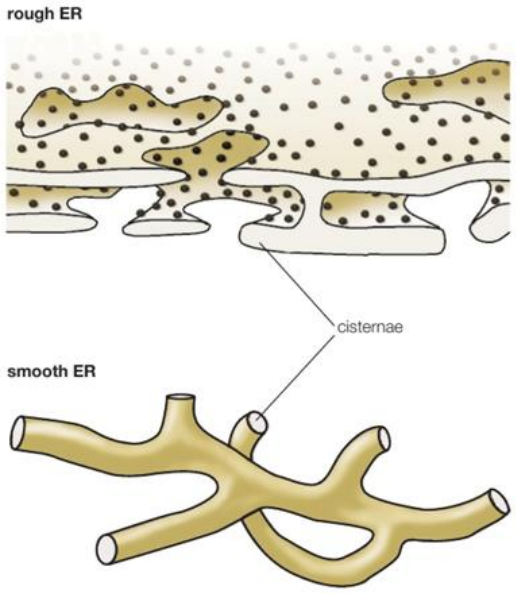
3A 3 Eukaryotic cells 2: protein transport

The cytoplasm of the cell contains the **endoplasmic reticulum (ER)**, a three-dimensional (3D) network of cavities surrounded by membranes. The electron microscope shows that some of the cavities are sac-like and some are tubular, and that the ER spreads through the cytoplasm. The ER network links with the membrane around the nucleus, and is a large part of the transport system within a cell as well as being the site of synthesis of many important chemical substances.

ROUGH AND SMOOTH ENDOPLASMIC RETICULUM

Electron micrographs show that much of the outside of the endoplasmic reticulum membrane is covered with granules, which are 80S ribosomes, so this is known as **rough endoplasmic reticulum** (RER) (see fig A). The function of the ribosomes is to make proteins. Cells that secrete materials have a large amount of RER. Examples include cells producing hormones or the digestive enzymes in the lining of the gut. These proteins must be secreted without interfering with the cell's own activities. This is an example of **exocytosis**.

Not all endoplasmic reticulum is covered in ribosomes (see fig A). **Smooth endoplasmic reticulum (SER**) is also involved in synthesis and transport, but in this case of steroids and lipids.



▲ **fig A** This is rough and smooth endoplasmic reticulum. Smooth ER is more tubular than rough ER and also lacks ribosomes on the surface.

THE GOLGI APPARATUS

Under the light microscope the **Golgi apparatus** looks like a rather dense area of cytoplasm. An electron microscope reveals that it is made up of stacks of parallel, flattened membrane pockets formed by vesicles from the endoplasmic reticulum fusing together.
The Golgi apparatus has a close link with, but is not joined to, the RER. It has taken scientists a long time to discover exactly what the Golgi apparatus does.

The Golgi apparatus was first reported over 100 years ago, in April 1898. An Italian scientist called Camillo Golgi (1843–1926) observed the flattened stack of membranes through a light microscope. For more than 50 years, scientists argued about what its function might be. Some thought it was an artefact from the process of fixing and staining during tissue preparation. The detailed structure of the Golgi apparatus could be seen for the first time when the electron microscope was introduced in the 1950s.

SUBJECT VOCABULARY

endoplasmic reticulum (ER) a 3D network of membrane-bound cavities in the cytoplasm that links to the nuclear membrane and makes up a large part of the cellular transport system as well as playing an important role in the synthesis of many different chemical substances

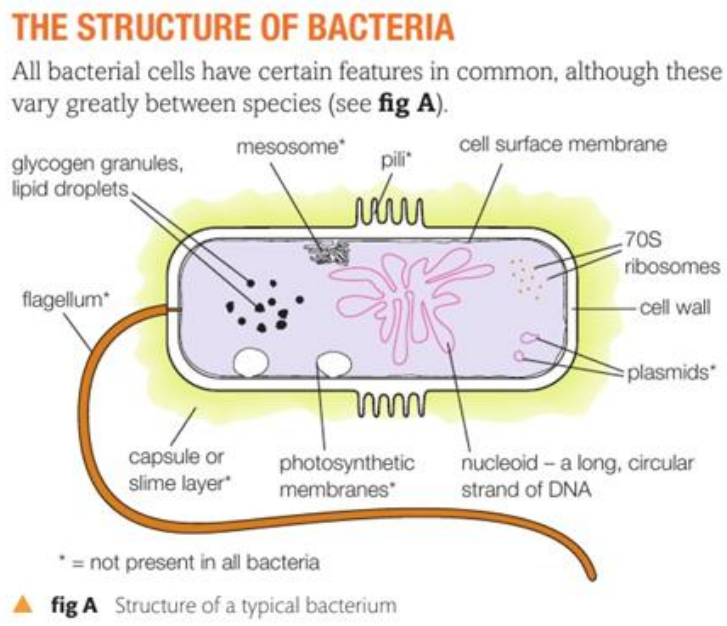
rough endoplasmic reticulum (RER) endoplasmic reticulum that is covered in 80S ribosomes and which is involved in the production and transport of proteins

exocytosis the movement of large molecules out of cells by the fusing of a vesicle containing the molecules with the surface cell membrane; the process requires ATP

smooth endoplasmic reticulum (SER) a smooth tubular structure similar to RER, but without the ribosomes, which is involved in the synthesis and transport of steroids and lipids in the cell

Golgi apparatus stacks of membranes that modify proteins made elsewhere in the cell and package them into vesicles for transport, and also produce materials for plant cell walls and insect cuticles

3A – 4 Prokaryotic cells



▲ **fig A** Structure of a typical bacterium

BACTERIAL CELL WALLS

All bacterial cells have a cell wall. The contents of bacterial cells are usually hypertonic to the medium around them, so water tends to move into the cells by osmosis. The cell wall prevents the cell swelling and bursting. It also maintains the shape of the bacterium, and gives support and protection to the contents of the cell. All bacterial cell walls have a layer of **peptidoglycan** that consists of many parallel polysaccharide chains with short peptide cross-linkages producing an enormous molecule with a net-like structure. Some bacteria have a **capsule** (or slime layer if it is very thin and diffuse) around their cell walls.

PILI AND FLAGELLA

Some bacteria have from one to several hundred thread-like protein projections from their surface. These are called the **pili** (singular pilus) and they are found on some well-known bacteria such as Escherichia coli (E. coli) species and Salmonella species. They seem to be used for attachment to a host cell and for sexual reproduction. However, they also make bacteria more vulnerable to virus infections, as a **bacteriophage** can use pili as an entry point to the cell.

Some bacteria can move themselves using **flagella** (singular flagellum). These are made of a many-stranded helix of the protein flagellin. The flagellum moves the bacterium by rapid rotations - about 100 revolutions per second.

CELL SURFACE MEMBRANE

The cell surface membrane in prokaryotes is similar in both structure and function to the membranes of eukaryotic cells. However, bacteria have no mitochondria, so the cell membrane is also the site of some of the respiratory enzymes. In some bacterial cells such as Bacillus subtilis, a common soil bacterium, the membrane shows infoldings known as **mesosomes**.

NUCLEOID

The genetic material of prokaryotic cells consists of a single circular strand of DNA, which is not contained in a membrane- bound nucleus. This is an important, identifying difference between prokaryotic and eukaryotic cells.

However, the DNA is folded and coiled to fit into the bacterium. The area in the bacterial cell where this DNA tangle is found is known as the **nucleoid** (see fig B). In an E.coli bacterium, it occupies about half of the cytoplasm. L

▲ **fig B** The nucleoid area of a bacterium

PLASMIDS

Some bacterial cells also contain one or more much smaller circles of DNA known as plasmids. A plasmid codes for a particular aspect of the bacterial phenotype in addition to the genetic information in the nucleoid.

70S RIBOSOMES

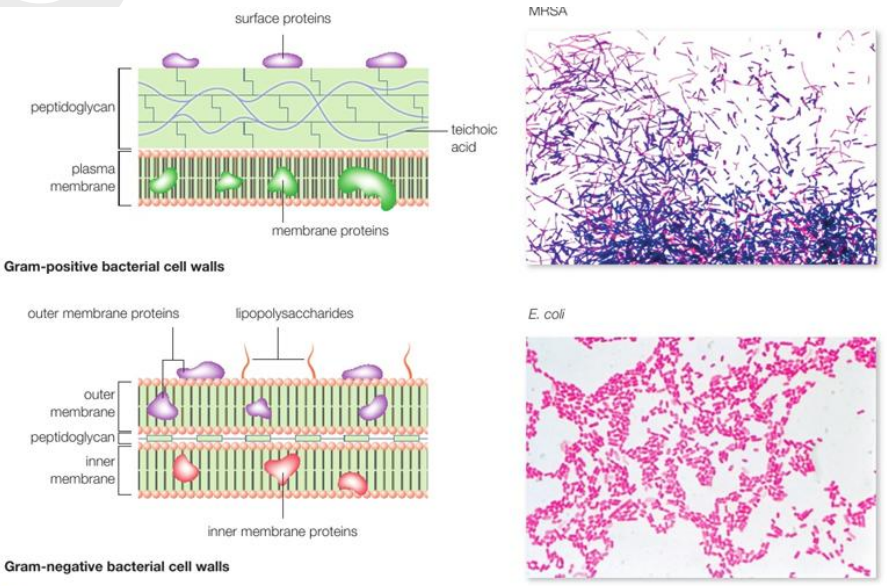
The bacteria, cyanobacteria and archaebacteria have no membrane-bound organelles, but they do have ribosomes where protein synthesis occurs. The ribosomes in bacterial cells are 70S, smaller than the 80S ribosomes which dominate in eukaryotes. They have two subunits. The smaller is 30S and the larger is 50S (see Section 3A.3). They are involved in the synthesis of proteins in a similar way to eukaryotic ribosomes.

GRAM STAINING AND BACTERIAL CELL WALLS

All bacterial cell walls contain peptidoglycan but there are two types which can be distinguished by **Gram staining**. This staining technique was developed in 1884 by Christian Gram (1853-1938) and is still used today. It is valuable because different types of disease-causing bacteria are vulnerable to different types of antibiotic and the type of cell wall they have is one of the factors that affects how vulnerable they are.

Before staining, bacteria are often colourless. The cell walls of **Gram-positive bacteria** (e.g. methicillin-resistant Staphylococcus aureus, MRSA) have a thick layer of peptidoglycan containing chemical substances such as **teichoic acid** within the net-like structure. The crystal violet/iodine complex in the Gram stain is trapped in the thick peptidoglycan layer and resists decolouring when the bacteria are dehydrated using alcohol.

The cell walls of **Gram-negative bacteria** have a thin layer of peptidoglycan with no teichoic acid between the two layers of membranes. The outer membrane is made up of lipopolysaccharides. This layer dissolves when the bacteria are dehydrated in ethanol. This exposes the thin peptidoglycan layer and the crystal violet/iodine complex is washed out. The peptidoglycan then takes up the red safranin counterstain. The cells appear red when viewed in a light microscope (see fig C).



▲ **fig C** The difference in the cell wall structure of the bacteria results in the different reactions with the Gram stain.

ALTERNATIVE WAYS OF CLASSIFYING BACTERIA

Grouping bacteria by the way their cell walls do or do not take up Gram stains is not very useful in classifying the different types. Another way in which bacteria can be identified is by their shape (see **fig D**). Some bacteria are spherical (**cocci**), some are rod-shaped (**bacilli**). Others are twisted (**spirilla**) or comma-shaped (**vibrios**).

▲ **fig D** The shapes of different types of bacteria can be seen clearly under powerful microscopes.

Bacteria are also sometimes grouped by their respiratory requirements. **Obligate aerobes** need oxygen for respiration. **Facultative anaerobes** use oxygen if it is available, but can manage without it. Many human pathogens are in this group. **Obligate anaerobes** can only respire in the absence of oxygen – in fact, oxygen will kill them.

SUBJECT VOCABULARY

peptidoglycan a large, net-like molecule found in all bacterial cell walls made up of many parallel polysaccharide chains with short peptide cross-linkages
capsule a layer formed from starch, gelatin, protein or glycolipid, found around the outside of some bacteria
pili thread-like protein projections found on the surface of some bacteria
bacteriophage virus that attacks bacteria
flagella many-stranded helices of the contractile protein flagellin found on some bacteria; they move the bacteria by rapid rotations
mesosomes infoldings of the cell membrane of bacteria
nucleoid the area in a bacterium containing the single circular loop of coiled DNA
plasmids small, circular pieces of DNA that code for specific aspects of the bacterial phenotype
Gram staining a staining technique used to distinguish types of bacteria by their cell wall
Gram-positive bacteria bacteria that contain teichoic acid in their cell walls and stain purple/blue with Gram staining
teichoic acid a chemical substance found in the cell walls of Gram-positive bacteria
Gram-negative bacteria bacteria that have no teichoic acid in their cell walls; they stain red with Gram staining
cocci spherical bacteria
bacilli rod-shaped bacteria
spirilla bacteria with a twisted or spiral shape
vibrios comma-shaped bacteria
obligate aerobes organisms that need oxygen for respiration
facultative anaerobes organisms that use oxygen if it is available, but can respire and survive without it
obligate anaerobes organisms that can only respire in the absence of oxygen and are killed by oxygen

3A 5 The organization of cells

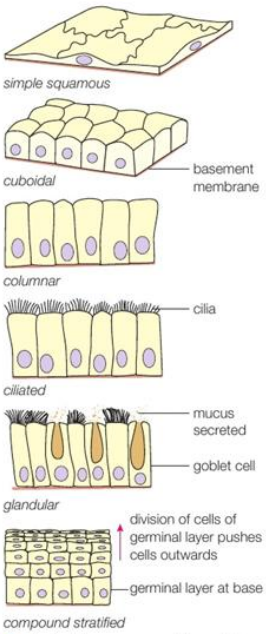
Multicellular organisms consist of specialised cells but these cells do not operate on their own. The specialised cells are organised into groups of cells known as **tissues**. These tissues consist of one or more types of cell all carrying out a function in the body. However, tissues do not operate in isolation. Many tissues are further organised into organs.

TISSUES

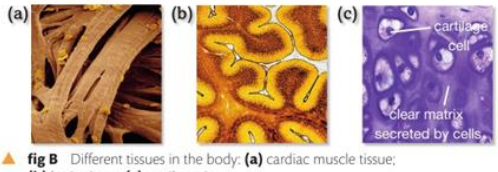
Tissues are groups of cells that all develop from the same kind of cell. Although there are many different specialised cells, there are only four main tissue types in the human body - **epithelial tissue**, connective tissue, muscle tissue and nervous tissue. Modified versions of these tissue types containing different specialised cells perform all the functions of the body. Fig A shows some different epithelial tissues, which are tissues that line the surfaces both inside and outside of the body.

ORGANS

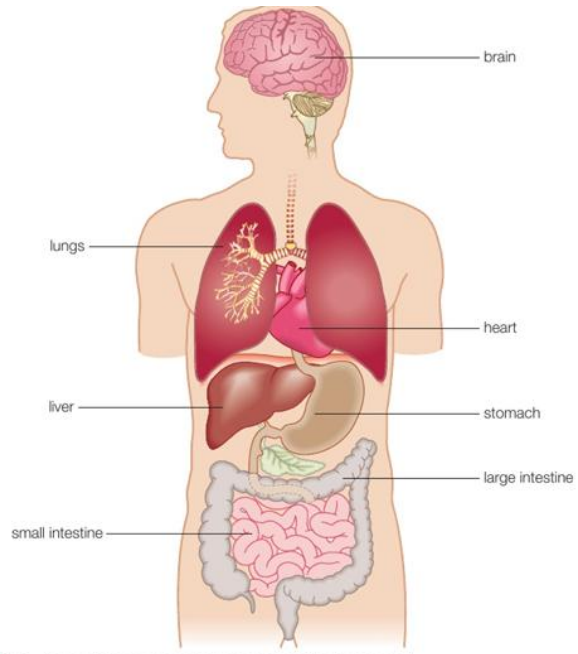
An organ is a structure made of several different tissues grouped into a structure so that they can work effectively together to carry out a particular function. There are many organs in the human body, some of which are shown in fig C.



▲ **fig A** There are many different kinds of epithelial tissue inside the human body.



▲ **fig B** Different tissues in the body: **(a)** cardiac muscle tissue; **(b)** brain tissue; **(c)** cartilage tissue

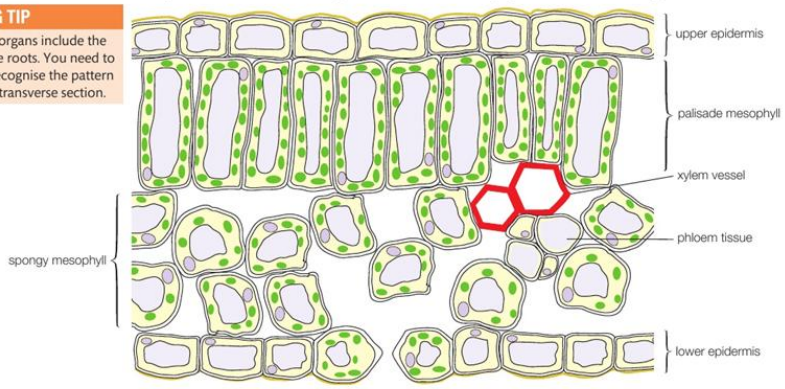


▲ **fig C** Some of the organs and organ systems of the human body.

Plants also have cells grouped into tissues and organs. For example, the leaf is an organ that is composed of vascular tissue, epithelial tissue and mesophyll tissue as shown in **fig D**.

LEARNING TIP

Other plant organs include the stem and the roots. You need to be able to recognise the pattern of tissues in transverse section.



▲ **fig D** Some of the tissues found in a leaf – the photosynthetic, food-making organ of a plant.

ORGAN SYSTEMS

In animals, often several organs work together as an organ system to perform large-scale functions in the body. For example, the digestive system includes the stomach, pancreas, and small and large intestines. The nervous system includes the brain, spinal cord and all peripheral nerves.

Most of the cells in tissues, organs and systems have differentiated (changed to become specialised) during their development so that they can perform their specific function. You will find out more about how this process happens in Chapter 3C.

SUBJECT VOCABULARY

tissues groups of specialised cells carrying out particular functions in the body
organs structures made up of several different types of tissue to carry out particular functions in the body
epithelial tissues tissues that form the lining of surfaces inside and outside the body
organ system a group of organs working together to carry out particular functions in the body

Topic 3B – Mitosis, meiosis and reproduction

3B 1 Cell cycle

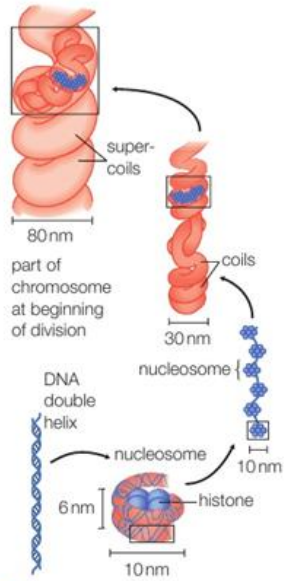
Most new biological material results from the process of nuclear division known as **mitosis**, followed by the rest of the cell dividing. **Asexual reproduction** (the production of genetically identical offspring from a single parent cell or organism) and growth (an increase in cell numbers) are both the result of mitotic cell division.

The production of offspring by **sexual reproduction** is also mostly dependent on mitosis to produce new cells after the gametes (sex cells) have fused.

The formation of the sex cells involves a different process of nuclear division called **meiosis** (see Section 3B.3).

What are chromosomes?

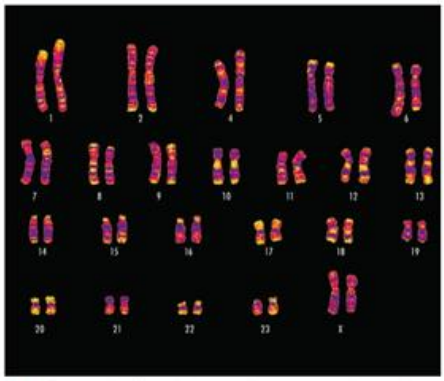
When the DNA molecules condense, they need to be packaged very efficiently. This is achieved with the help of positively charged basic proteins called **histones**. The DNA winds around the histones to form dense clusters known as **nucleosomes** (see fig A).



▲ **fig A** Histones play an important role in the organisation of DNA into orderly chromosomes that can be replicated.

In humans, each species has 46 chromosomes, which are divided equally between two new cells during mitosis. Before division, cells must duplicate the original set of chromosomes.

During active cell division, chromosomes become coiled and condensed, producing a **karyotype**, a display of all chromosomes.

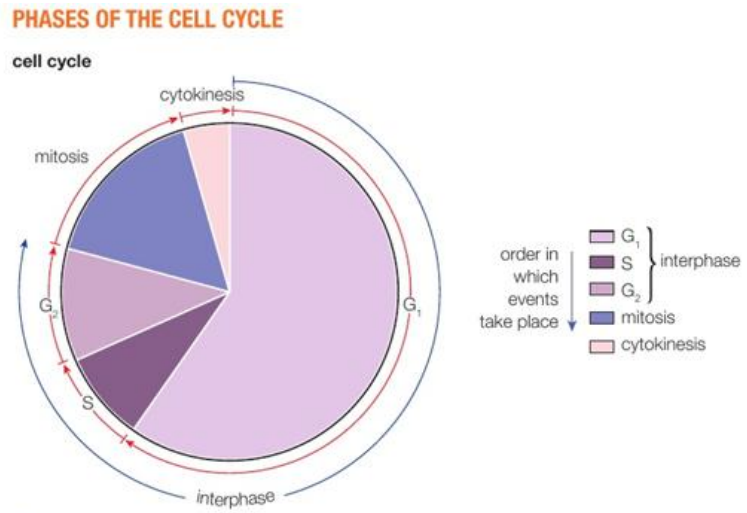


▲ **fig B** This female human karyotype shows the 22 pairs of autosomes and one pair of sex chromosomes found in every healthy human cell, except the eggs and sperm.

THE CELL CYCLE

Cells divide on a regular basis to bring about growth and asexual reproduction. They divide in a sequence of events known as the **cell cycle**, which involves several different phases, as you can see in fig C.

Interphase is a period of non-division when the cells increase in mass and size, carry out normal cellular activities and replicate their DNA ready for division. This is followed by mitosis, a period of active division, and **cytokinesis** when the new cells separate. The length of the cell cycle is variable. It can be very rapid, taking 24 hours or less, or it can take a few years.



▲ **fig C** In very actively dividing tissue, the cell cycle is repeated as fast as possible; in other tissues, the time between successive divisions may be years.

S is the stage when the chromosomes replicate and become double-stranded **chromatids** ready for the next cell division.

G2 (gap 2) is the time that the organelles and other materials needed for cell division are synthesised - before a cell can divide, it needs two of everything.

Mitosis is when the nucleus is actively dividing.

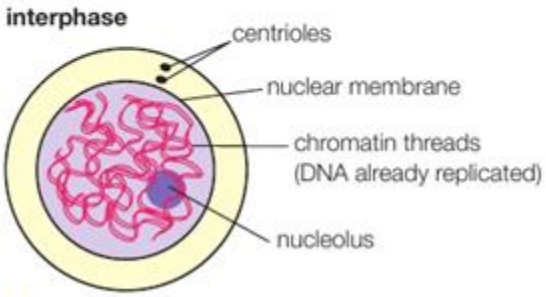
In multicellular organisms, the cell cycle is repeated very frequently in almost all cells during development. However, once the organism is mature, it may slow down or stop completely in some tissues. The cell cycle is controlled by chemical signals which are made in response to different genes. This control is brought about at checkpoints when the cell cycle moves from one phase to the next. The chemical substances which control this are small proteins called **cyclins**. These build up and attach to enzymes called **cyclin-dependent kinases (CDKS**). The cyclin-CDK complex that forms phosphorylates other proteins, changing their shape and bringing about the next stage in the cell cycle.

SUBJECT VOCABULARY

mitosis the process by which a cell divides to produce two genetically identical daughter cells
asexual reproduction the production of genetically identical offspring from a single parent or organism
sexual reproduction the production of offspring that are genetically different from the parent organism or organisms by the fusing of two sex cells (gametes)
meiosis a form of cell division in which the chromosome number of the original cell is halved, leading to the formation of the gametes
histones positively charged proteins involved in the coiling of DNA to form dense chromosomes in cell division
nucleosomes dense clusters of DNA wound around histones
karyotype a way of displaying an image of the chromosomes of a cell to show the pairs of autosomes and sex chromosomes
cell cycle a regulated process of three stages (interphase, mitosis and cytokinesis) in which cells divide into two genetically identical daughter cells
interphase the period between active cell divisions when cells increase their size and mass, replicate their DNA and carry out normal metabolic activities
cytokinesis the final stage of the cell cycle before the cell enters interphase again – division of the cytoplasm at the end of mitosis to form two independent, genetically identical cells
chromatid one strand of the replicated chromosome pair that is joined to the other chromatid at the centromere
cyclins small proteins that build up during interphase and are involved in the control of the cell cycle by their attachment to cyclin-dependent kinases
cyclin-dependent kinases (CDKs) enzymes involved in the control of the cell cycle by phosphorylating other proteins, activated by attachment to cyclins

3B 2 Mitosis

A cell is in the interphase stage of the cell cycle for much of its life. This used to be called the resting phase, but this is not a good description. During interphase, the normal metabolic processes of the cell continue and new DNA is produced as the chromosomes replicate. New proteins, cytoplasm and cell organelles are also made so that the cell is prepared to produce two new cells. ATP production is stepped up at times to provide the extra energy needed as the cells divide. **Fig A** shows a cell in interphase. When everything the cell needs is present, and the parent cell is large enough, interphase ends and mitosis begins. You will mainly consider mitosis in animal cells.



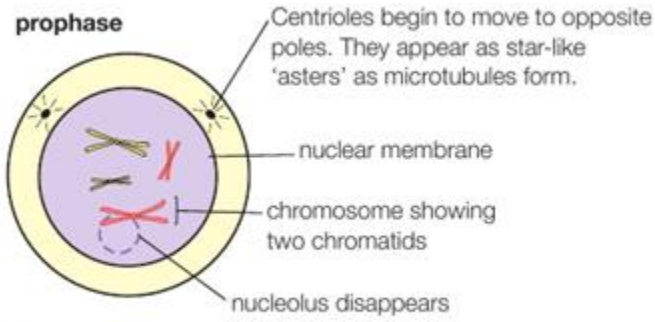
▲ **fig A** Interphase

THE STAGES OF MITOSIS

As in many biological processes, the events of mitosis are continuous, but it is easier to describe what is happening by considering the sequence of events as a series of phases. These are known as **prophase, metaphase, anaphase and telophase.**

PROPHASE

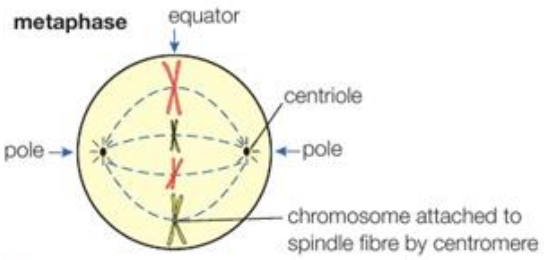
Before mitosis begins, the genetic material replicates to produce exact copies of the original chromosomes. By the beginning of prophase, both the originals and the copies are referred to as chromatids. In prophase, the chromosomes coil up and can take up stains to become visible. At this point, each chromosome consists of two daughter chromatids that are attached to each other at a region known as the **centromere**. The nucleolus breaks down and the centrioles begin to pull apart to form the spindle (see fig B).



▲ **fig B** Prophase

METAPHASE

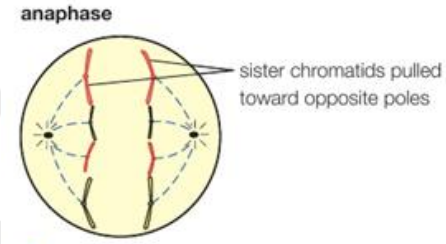
The nuclear membrane has broken down and the centrioles have moved to opposite poles of the cell. In moving apart, the centrioles have formed between them a set of microtubules that is known as the spindle. The chromatids appear to compete for position on the **metaphase plate (equator**) of the spindle during metaphase.



▲ **fig C** Metaphase

ANAPHASE

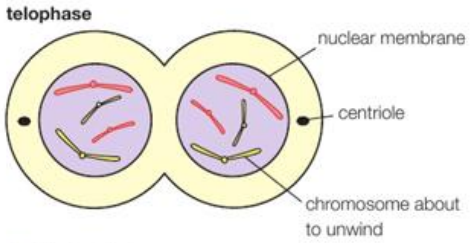
The centromeres split so that the two identical linked chromatids become separate entities (see fig D overleaf). They are now new chromosomes. The chromatids from each pair are pulled, centromere first, towards opposite poles of the cell. This separation occurs quickly, taking only a matter of minutes. At the end of anaphase, the two sets of chromatids have been separated to opposite ends of the cell.



▲ **fig D** Anaphase

TELOPHASE

During telophase, the spindle fibres break down and nuclear envelopes form around the two sets of chromosomes (see fig E). The nucleoli and centrioles are also re-formed. The chromosomes begin to unravel and separate, becoming less dense and harder to see.



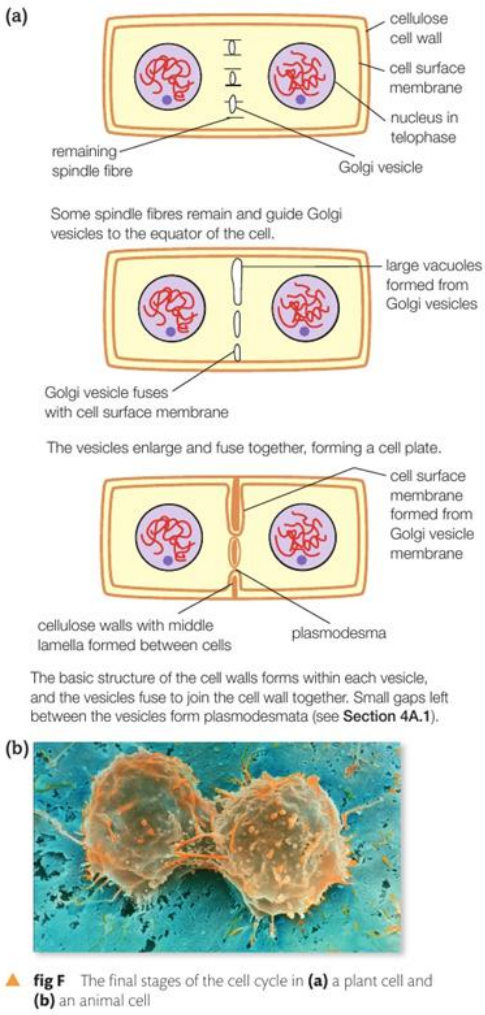
▲ **fig E** Telophase

CYTOKINESIS

The final phase of the cell cycle is cytokinesis, when the cytoplasm divides (see fig F).

In animal cells, a ring of contractile fibres tightens around the centre of the cell similar to a belt tightening around a sack of flour. These fibres seem to be the same as those found in animal muscle cells. They continue to contract until the two cells have been separated.

In plant cells, the division of the cell occurs differently. A cellulose cell wall builds up from the inside of the cell outwards.



▲ **fig F** The final stages of the cell cycle in **(a)** a plant cell and **(b)** an animal cell

THE IMPORTANCE OF MITOSIS

Mitosis is how organisms grow and replace old cells. It is also the method which organisms use for asexual reproduction. Asexual reproduction involves only one parent individual and it results in genetically identical individuals or **clones**. It has many advantages for an organism. It does not rely on finding a mate and can give rise to large numbers of offspring very rapidly.

The mitotic index

The mitotic index is a measure of how actively the cells in a tissue are dividing. It is the ratio between the number of cells in a tissue sample that are in mitosis and the total number of cells in the sample.

▲ **fig H** Once the cell leaves interphase and enters mitosis, the chromosomes can be seen. You can use this when counting cells to work out the mitotic index.

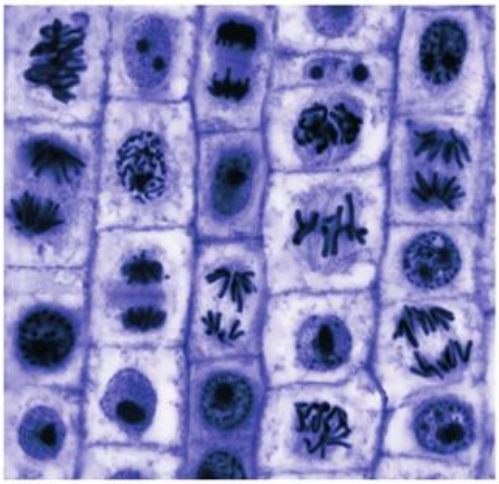
We can then calculate the mitotic index by dividing the number of actively dividing cells by the total number of cells (see **fig I**):

$$\text{mitotic index} = \frac{\text{cells in mitosis}}{\text{total number of cells}}$$

Cells with visible chromosomes: 12

Total number of cells: 25

$$\text{Mitotic index} = \frac{12}{25} = 0.48$$



▲ **fig I** Calculating the mitotic index

SUBJECT VOCABULARY

prophase the first stage of active cell division where the chromosomes are coiled up and consist of two daughter chromatids joined by the centromere; the nucleolus breaks down

metaphase the second stage of active cell division where a spindle of overlapping protein microtubules forms and the chromatids line up on the metaphase plate

anaphase the third stage of active cell division where the centromeres split so chromatids become new chromosomes; they are moved to the opposite poles of the cell, centromere first, by contractions of the microtubules of the spindle

telophase the fourth stage of active cell division where a nuclear membrane forms around the two sets of chromosomes, the chromosomes unravel and the spindle breaks down

centromere the region where a pair of chromatids are joined and which attaches to a single strand of the spindle structure at metaphase

metaphase plate (equator) the region of the spindle in the middle of the cell along which the chromatids line up

clones genetically identical individuals resulting from asexual reproduction in a single parent

mitotic index the ratio between the number of cells in a tissue sample that are in mitosis and the total number of cells in the sample

3B 3 sexual reproduction and meiosis

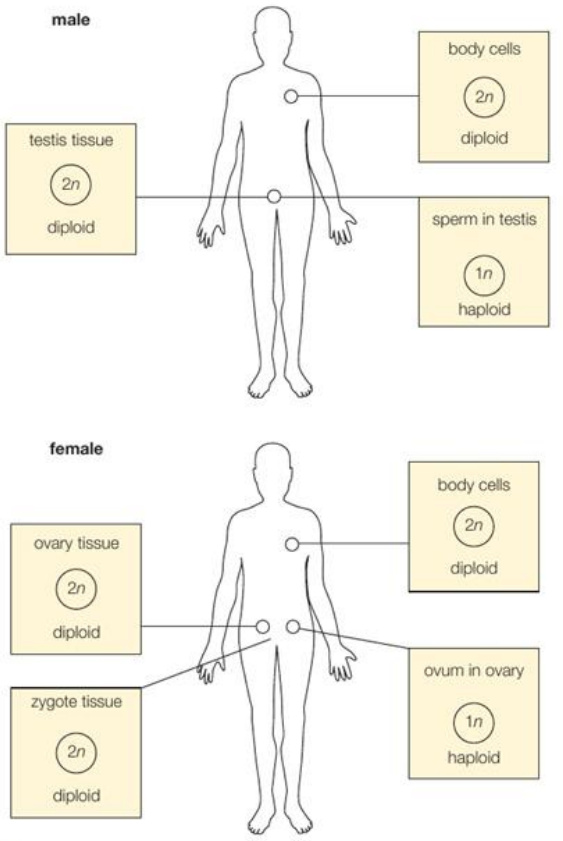
Sexual reproduction is the production of a new individual resulting from the joining (fusion) of two specialised cells known as gametes. Sexual reproduction produces individuals that are not genetically the same as either of their parents, but contain genetic information from both (see **fig A**). Sexual reproduction relies on two gametes meeting and fusing. It is not always easy to find a mate, particularly if you are a solitary predator. It also uses more bodily resources because it usually involves special sexual organs. However, the great advantage of sexual reproduction is that it increases genetic variation because gametes from two different individuals are fused together. In a changing environment, this gives a greater chance that one or more of the offspring will have a combination of genes that improves their chance of surviving and going on to reproduce.

▲ **fig A** The genetic variation in offspring produced by sexual reproduction can be very easy to see.

WHAT ARE GAMETES?

The nucleus of a cell contains the chromosomes. In most of the cells of any individual, the chromosomes occur in pairs. A cell containing two full sets of chromosomes is called **diploid (2n**) and the number of chromosomes in a diploid cell is characteristic for that species.

Each new generation would get more genetic material until eventually the cells would break down and fail to function. To avoid this, **haploid (n**) nuclei are formed with one set of chromosomes (half of the full chromosome number), usually within the specialised cells called gametes. Sexual reproduction occurs when two haploid nuclei fuse to form a new diploid cell called a **zygote** (see fig B overleaf). This process is called **fertilisation**.



	TISSUE TYPE	DIPLOID OR HAPLOID
Male	body tissue	diploid
	testis tissue	diploid
	sperm in testis	haploid
Female	body cells	diploid
	ovary tissue	diploid
	ovum in ovary	haploid
	zygote tissue	diploid

▲ **fig B** The only cells in the human body that are haploid are the gametes.

THE FORMATION OF GAMETES

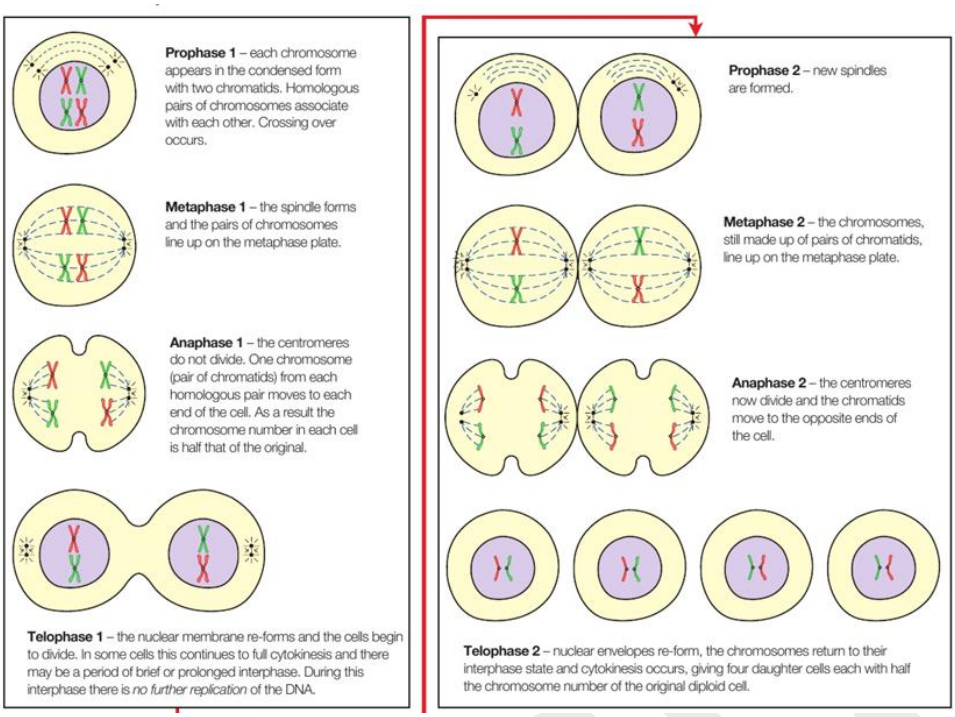
Gametes are formed in special sex organs. In simpler animals and plants, the sex organs are often temporary, formed only when they are needed. In more complex animals, the sex organs are usually more permanent structures that we sometimes call the **gonads**. In flowering plants, the female sex organs are the **ovaries** and the male ones are the **anthers**. The female gametes, **ovules**, are made in the ovaries. The male gametes are produced in the anthers: the gamete cells are contained within a spore which we know as **pollen**. In animals, the male gonads are the **testes**, which produce the male gametes known as **spermatozoa**, or more commonly, **sperm**. The female gonads are the ovaries and they produce the female gametes known as **ova**. The male gametes are often much smaller than the female ones, but they are usually produced in much larger quantities.

MEIOSIS

Meiosis is a reduction division and it occurs only in the sex organs. In animals, the gametes are formed directly from meiosis. In flowering plants, meiosis forms special male cells called **microspores** and female cells called **megaspores**, which then develop into the gametes. Meiosis is of great biological significance - it is the basis of the variation that allows species to evolve.

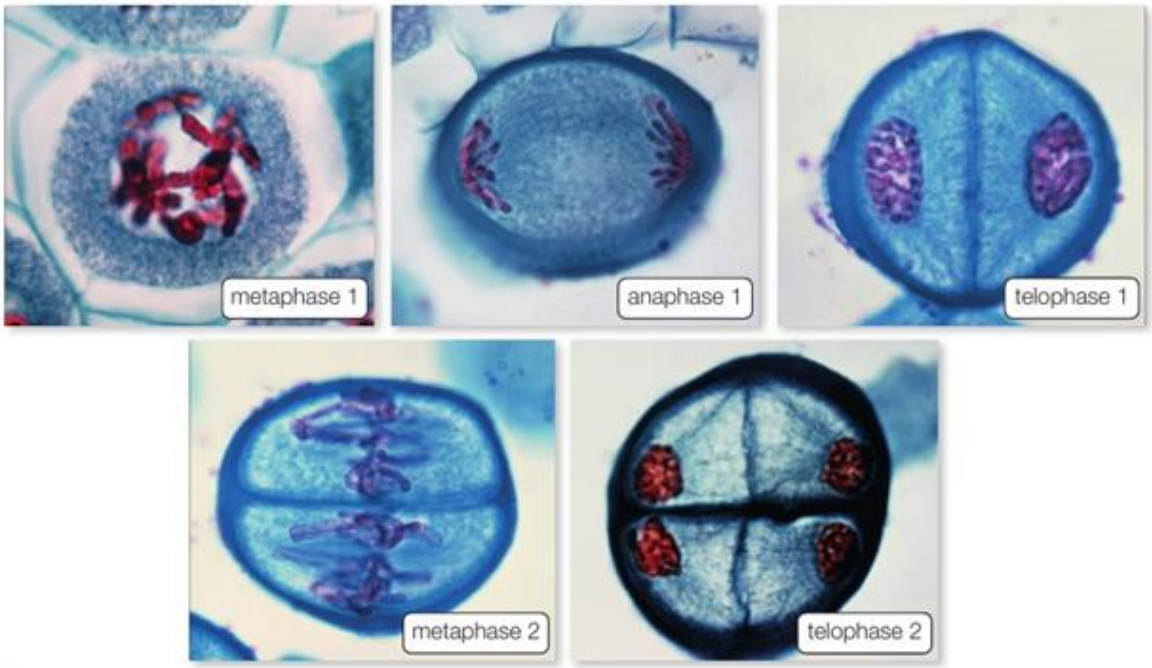
THE CHROMOSOMES IN MEIOSIS

In meiosis, two nuclear divisions produce four haploid daughter cells, each with its own unique combination of genetic material (see fig C). The events of meiosis are continuous although we describe the stages as separate phases. As in mitosis, the contents of the cell, in particular the DNA, are replicated while the cell is in interphase. When the cell has all the materials it needs, it can enter meiosis.



▲ **fig C** These are the main steps in the process of meiosis, which results in the formation of haploid gametes. This is a simplified version of meiosis shown in a cell with only two pairs of chromosomes, to make it easier to see what is happening.

In prophase 1 of meiosis the two chromosomes of each pair, known as **homologous pairs**, stay close together. At this stage, **crossing over (recombination**) introduces genetic variation as the chromatids may break and recombine (see fig E). Just as in mitosis, the nuclear membrane and nucleolus break down and the centrioles pull apart to form the spindle.



▲ **fig D** The stages of meiosis are not easy to see in cells, but these images, taken from the testis of a locust and the anther of a plant, show you some of them.

THE IMPORTANCE OF MEIOSIS

miosis reduces the chromosome number in gametes from diploid to haploid. This means that sexual reproduction is possible without each following generation having more and more genetic material. It is also the main way in which genetic variation is introduced to a species. This variation is introduced in two main ways.

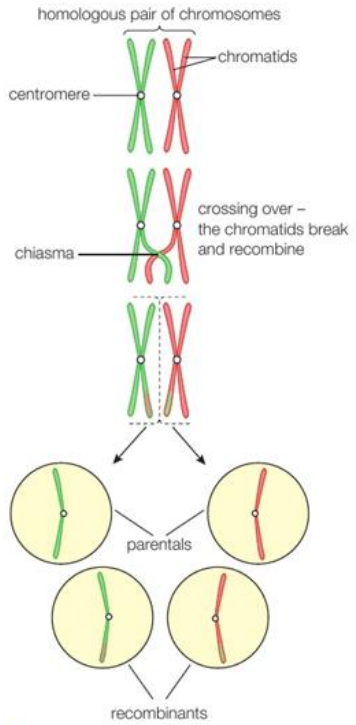
• **Crossing over (recombination**): this process occurs in prophase 1 of meiosis when large, multi-enzyme complexes 'cut and join' bits of the maternal and paternal chromatids together (see fig E). The points where the chromatids break are called **chiasmata**.

These are important in two ways. First, the exchange of genetic material leads to added genetic variation. Second, errors in the process lead to **mutation** and this is a further way of introducing new combinations into the genetic make-up of a species.

• **Independent assortment (random assortment):** the maternal and paternal chromosomes are distributed into the gametes completely at random.

SUBJECT VOCABULARY

diploid (2*n*) a cell with a nucleus containing two full sets of chromosomes
haploid (*n*) a cell with a nucleus containing one complete set of chromosomes
zygote the cell formed when two haploid gametes fuse at fertilisation
fertilisation the fusing of the haploid nuclei from two gametes to form a diploid zygote in sexual reproduction
polyploidy a cell or an organism with more than two sets of chromosomes
gonads the sex organs in animals
ovaries the female sex organs in both animals and plants; they produce the female gametes called ovules in plants and ova in animals
anthers male sex organs in plants that produce the male gametes contained in the pollen
ovules the haploid female gametes in plants
pollen the spore which contains the haploid male gametes of plants
testes the male sex organs in animals that produce the male gametes – sperm
spermatozoa (sperm) the haploid male gametes in animals
ova the haploid female gametes in animals (singular = ovum)
microspores the result of meiosis in plants that develop into the spore (pollen) containing the male gametes
megaspores the result of meiosis in plants that develop into the female gametes, ovules
homologous pairs matching pairs of chromosomes in an individual which both carry the same genes, although they may have different alleles
crossing over (recombination) the process by which large multi-enzyme complexes cut and re-join parts of the maternal and paternal chromatids at the end of prophase I, introducing genetic variation
chiasmata the points where the chromatids break during recombination
mutation a permanent change in the DNA of an organism
independent assortment (random assortment) the process by which the chromosomes derived from the male and female parent are distributed into the gametes at random



▲ **fig E** Chromosomes crossing over in meiosis. This process introduces more variation into the gametes.

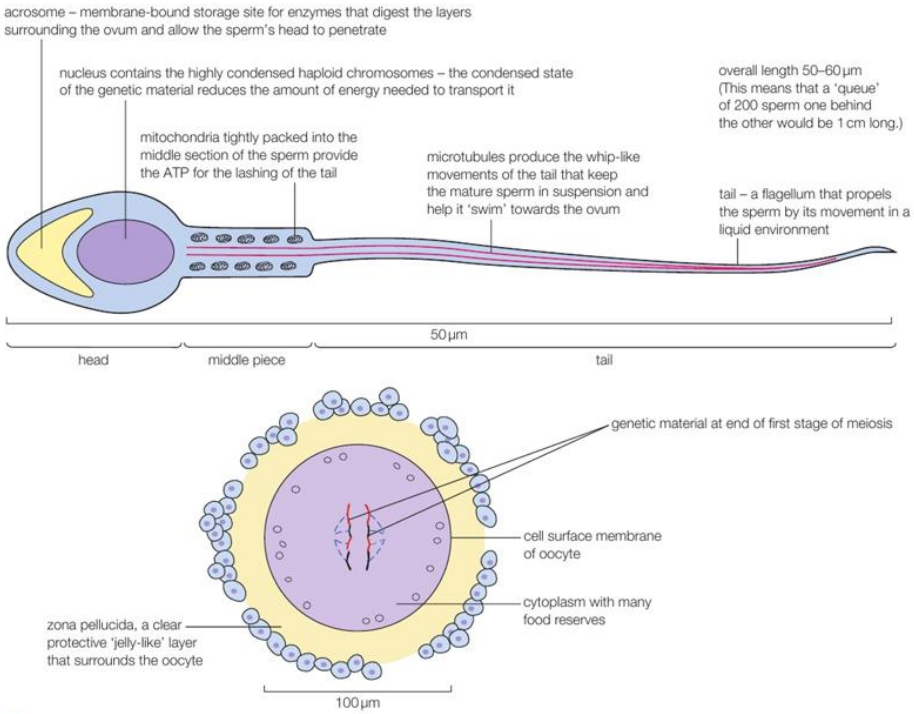
3B 4 Gametes: structure and function

The gametes that make sexual reproduction possible are formed in a process called **gametogenesis**. Meiosis is just one stage in gamete formation, which produces different male and female sex cells.

GAMETE FORMATION IN MAMMALS

Many millions of sperm are released every time a male mammal ejaculates. The eggs in a sexually mature female are usually numbered in thousands and will eventually run out. Special cells (the primordial germ cells) in the gonads divide, grow, divide again and then differentiate into the gametes.

In human males, the process of gametogenesis involving meiotic and mitotic cell divisions happens constantly from puberty onwards. In females, mitotic divisions occur before birth to form diploid primary **oocytes**, which remain inactive until after puberty. The second meiotic divisions are only completed if the ovum is fertilised.



▲ **fig A** Human gametes – the sperm and ova show clear specialisations that fit them for their function.

CHARACTERISTICS OF THE GAMETES

SPERMATOZOA: MANY, MINI, MOTILE

The male gametes or spermatozoa of most mammalian species, including humans, are around 50 µm long. They have several tasks to fulfil.

- They must carry the genetic information in the nucleus.
- They must remain in suspension in the semen so they can be transported through the female reproductive tract. For this, they need a long, beating tail.
- They must be able to penetrate the protective barrier around the ovum and deliver the male haploid genome safely inside. They penetrate the protective barrier of the egg using enzymes contained in the **acrosome**.

OVA: FEW, FAT, FIXED

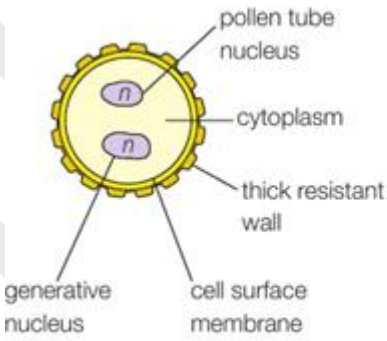
Although spermatozoa of most animals are very similar in size, the same is not true for ova. These vary tremendously in both their diameter and their mass. The human ovum is about 0.1 mm across, while the ovum in an ostrich egg is around 6mm in diameter. Eggs do not move on their own, so they do not need contractile proteins, but they usually contain food for the developing embryo. They have a protective layer of jelly around them known as the **zona pellucida.**

THE GAMETES IN PLANTS

The formation of gametes in flowering plants is more complex because plants have two phases to their life cycles. The **sporophyte generation** is diploid and produces spores by meiosis. The resulting **gametophyte generation** is haploid and produces the gametes by mitosis. In plants such as mosses and ferns, these two phases exist as separate plants. In flowering plants, the two phases have been combined into one plant. The main body of the plant that we see is the diploid **sporophyte**.

POLLEN

The anthers of flowering plants are equivalent to the testes of animals. Meiosis occurs here, resulting in vast numbers of pollen grains that carry the male gametes. The male gametes in plants are known as **microgametes**. Each pollen grain contains two haploid nuclei: the **tube nucleus** and the **generative nucleus** (see fig B). The tube nucleus has the function of producing a **pollen tube** that penetrates through stigma, style and ovary and into the ovule.

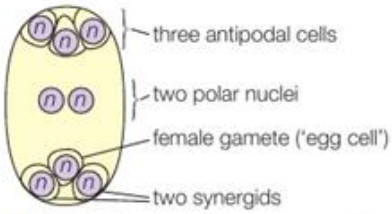


▲ **fig B** Pollen grain containing two haploid nuclei

OVULES

The ovary of the plant is equivalent to the animal ovary. Meiosis results in the formation of a relatively small number of ova contained within ovules inside the ovary. Some plants - an example is the peach - produce only one ovule (egg chamber), while others such as peas produce several. The ovule is attached to the wall of the ovary by a pad of special tissue called the **placenta**. Inside the ovule, the embryo sac forms the gametophyte generation (see fig D).

A combination of meiotic and mitotic cell divisions results in an egg cell, known as the **megagamete**. It contains two polar nuclei and other small cells, some of which degenerate.



▲ **fig D** Mature embryo sac containing the egg cell, which is the female gamete in flowering plants.

SUBJECT VOCABULARY

gametogenesis the formation of the gametes by meiosis in the sex organs
oocyte a cell in an ovary which may form an ovum if it undergoes meiotic division
acrosome the region at the head of the sperm that contains enzymes to break down the protective layers around the ovum
zona pellucida a layer of protective jelly around the unfertilised ovum
sporophyte generation the diploid generation in plants that produces spores by meiosis
gametophyte generation the haploid generation in plants that gives rise to the gametes by mitosis
sporophyte the diploid main body of the plant
microgametes the male gametes produced in plants, the pollen grains
tube nucleus the male nucleus that will control the production of the pollen tube in fertilisation
generative nucleus the male nucleus that will fuse with the female nucleus
pollen tube a tube that grows out of a pollen grain down the style, into the ovary and through the micropyle of the ovule to carry the generative nucleus (which divides to form two male nuclei) to the ovule
placenta (plant) the pad of special tissue that attaches the plant ovule to the ovary wall
megagamete the female gamete, the egg cell, in plants

3B 5 Fertilization in mammals and plants

GETTING TOGETHER

In plants, some flowers attract other organisms such as insects, birds or mammals. The other organism transfers the pollen from one plant to another, known as **pollination**. Other plants rely on the wind to carry their pollen from plant to plant.

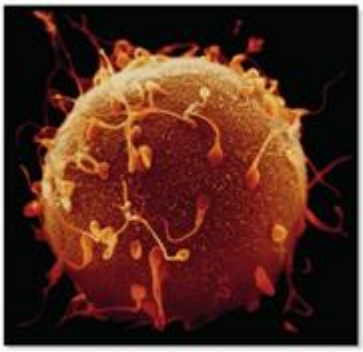
Animals use a wide variety of strategies to make sure the gametes meet. They fall into two main categories.

• **External fertilisation** occurs outside the body, with the female and male gametes discharged directly into the environment where they meet and fuse. External fertilisation is usually seen in aquatic species, because spermatozoa and ova are very vulnerable to drying and are rapidly destroyed in the air. Simpler animals such as jellyfish release copious amounts of male and female gametes into the sea. It is largely a matter of chance whether fertilisation takes place.

• **Internal fertilisation** involves the transfer of the male gametes directly to the female. This does not guarantee fertilisation, but makes it much more likely. More complex animals such as insects and some of the vertebrates have evolved a system whereby the male gametes are released directly into the body of the female during **mating**.

FERTILISATION IN HUMANS

For sexual reproduction to be successful in humans, as in any other species, the gametes must meet and fuse. Fig A is a scanning electron micrograph of an ovum surrounded by sperm, which gives you a good idea of the scale of the male and female gametes.



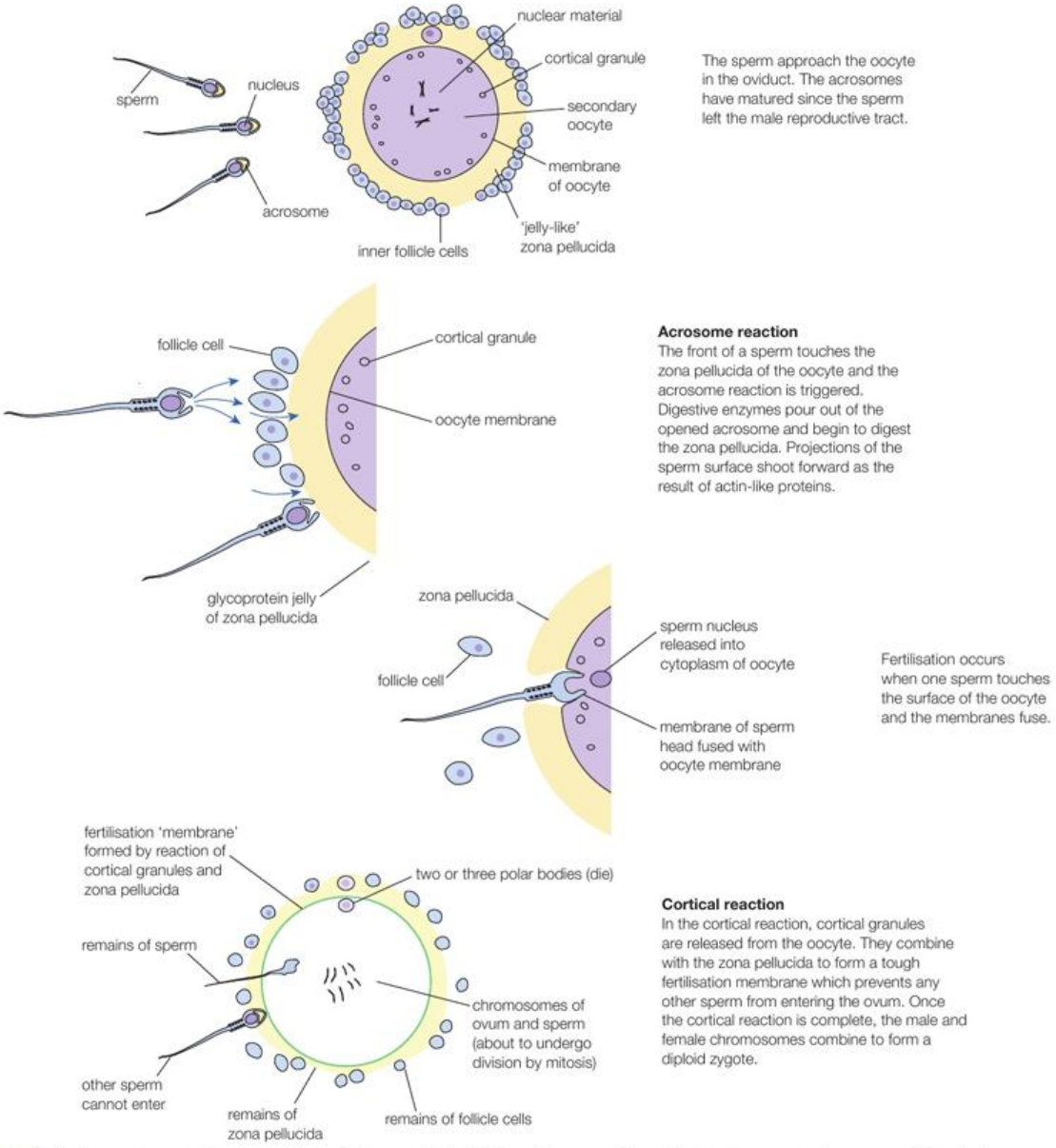
▲ **fig A** The fertilisation of a human ovum

The ovum is fully viable and able to receive the male gamete for only a few hours. The sperm will survive a day or two in the female reproductive tract.

The ovum released at ovulation has not fully completed meiosis. It is surrounded by a protective jelly-like layer known as the zona pellucida and some of the follicle cells. Many sperm cluster around the ovum and, as soon as the heads of the sperm touch the surface of the ovum, the **acrosome reaction** is triggered (see fig B).

Eventually, one sperm will wriggle through the weakened protective barriers and touch the surface membrane of the oocyte. This has several almost instantaneous effects. The second meiotic division takes place providing a haploid ovum nucleus to fuse with the haploid male nucleus.

It is essential that no other sperm enter now, as this would result in **polyspermy** (fertilisation by more than one sperm) and would produce a nucleus containing too many sets of chromosomes.



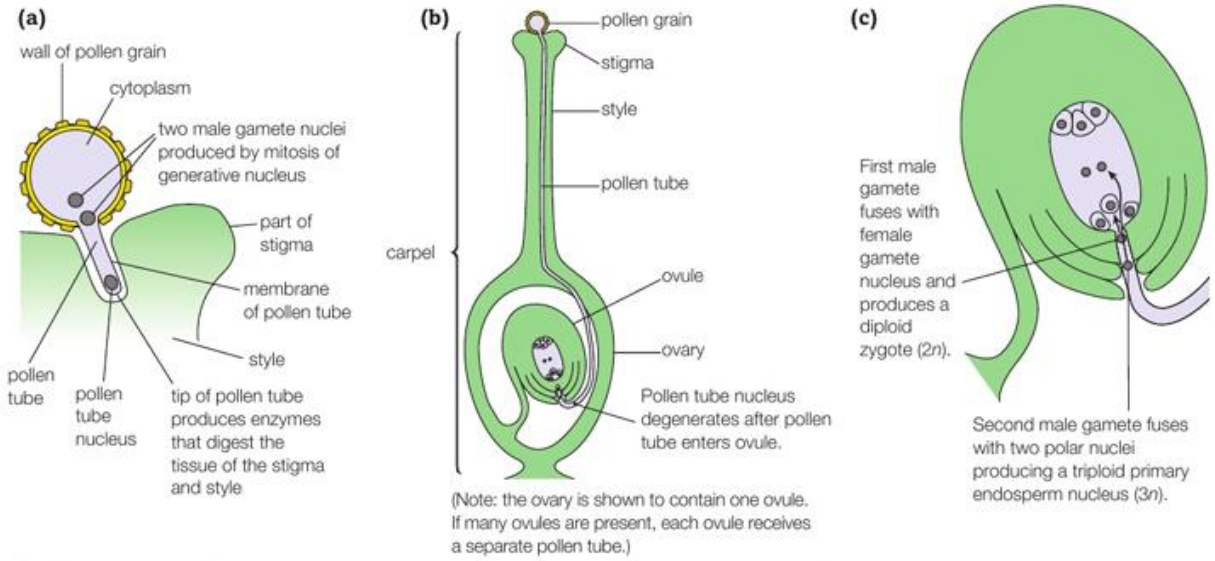
▲ **fig B** The acrosome reaction plays a vital role in the successful fertilisation of the egg and the cortical reaction ensures only one sperm is involved.

The events that follow fertilisation prevent polyspermy. Ion channels in the cell membrane of the ovum open and close so that the inside of the cell, instead of being electrically negative with respect to the outside, becomes positive. This alteration in charge blocks the entry of any further sperm. It is a temporary measure until the **cortical reaction** takes place. In the cortical reaction, cortical granules in the cytoplasm of the ovum release enzymes into the zona pellucida. These enzymes destroy the sperm-binding sites and also thicken and harden the jelly of the zona pellucida. This then forms a tough **fertilisation membrane** around the fertilised ovum. The fertilisation membrane now repels other sperm as the electrical charge returns to normal.

The head of the sperm enters the oocyte, but the tail region is left outside. Once the head is inside the ovum it absorbs water and swells, releasing its chromosomes to fuse with those of the ovum and forming a diploid zygote. At this point, fertilisation has occurred and a new individual has formed. Fertilisation is also referred to as **conception** in the case of humans.

Fertilization in plants

Pollen grains **germinate** when they recognize each other as being from the same species. This process prevents self-fertilisation and reduces variety. Pollen grains from the same plant may germinate but cannot penetrate the carpel. A pollen tube grows from the grain cell through the stigma into the style, digesting the tissue to reach the ovule. The generative nucleus divides by mitosis, forming two male gametes. The tube passes through the micropyle of the ovule, allowing fertilisation. Flowering plants undergo **double fertilisation**, with one male nucleus forming the triploid endosperm and the other forming the diploid zygote. This completes fertilisation and allows seed and embryo development.



▲ **fig C** A summary of the events that follow pollination in a flowering plant and lead to fertilisation of the ovule.

SUBJECT VOCABULARY

pollination the transfer of pollen from the anther to the stigma, often from one flower to another
external fertilisation the process of fertilisation in which the female and male gametes are released outside of the parental bodies to meet and fuse in the environment
internal fertilisation the fertilisation of the female gamete by the male gamete, which takes place inside the body of the female
mating the process by which a male animal transfers sperm from his body directly into the body of the female
acrosome reaction the reaction seen when the sperm reach the oocyte and enzymes are released from the acrosome and digest the follicle cells and the zona pellucida
polyspermy the fertilisation of an egg by more than one sperm
cortical reaction the reaction seen when cortical granules in the cytoplasm of the ovum release enzymes into the zona pellucida; these enzymes destroy the sperm-binding sites and also thicken and harden the jelly of the zona pellucida
fertilisation membrane the tough layer that forms around the fertilised ovum to prevent the entry of other sperm
conception the term used for fertilisation of the ovum in humans
germinate (of pollen) the process by which a pollen tube starts to grow out of the pollen grain to transfer the male nuclei to the ovule
double fertilisation the process that occurs in plants in which one male nucleus fuses with the two polar nuclei to form the triploid endosperm nucleus and the other fuses with the egg cell to form the diploid zygote

3C Development of organisms

3C 1 Cell differentiation

GENE EXPRESSION IN ACTION

In a multicellular organism, every cell contains the same genetic information, but different cells perform different functions. They differentiate and develop into different tissues and organs. As this **cell differentiation** occurs, different types of cells produce more and more proteins which are specific to their cell type. Their shape and arrangement of the organelles also differ.

At the same time, almost all cells have a number of 'housekeeping' proteins in common. These are the proteins found in the structures which are common to most cells. Examples of such proteins include the structural proteins of the membranes, and the enzymes needed in cellular respiration.

HOW DO GENES CONTROL THE PHENOTYPE?

In Chapter 2C, you discovered that each chromosome has several genes each of which codes for a particular protein. Each gene is found at a particular place on the chromosome and this location is known as the **locus** of the gene. Each gene has at least two different forms, known as alleles.

MULTIPLE ALLELES

In the examples you have studied so far, you have only looked at traits that are inherited as genes with just two possible alleles - for example, for pea shape and colour and the inheritance of cystic fibrosis and colour blindness. However, some features are determined by **multiple alleles**. This means there are more than two possible variants. No matter how many possible alleles there are, any one diploid individual will only inherit two of them.

These have a different pattern of dominance as well. Both A and B are dominant to O, so the O blood group is recessive, but A and B are **codominant**. This means both alleles are expressed and produce a protein. So different combinations of alleles give you different blood groups (see table A and fig A).

GENOTYPE	PHENOTYPE
OO	blood group O
AO or AA	blood group A
BO or BB	blood group B
AB	blood group AB

table A ABO blood groups – an example of inheritance through multiple alleles

fig A Blood donations save lives. It is vital to know the blood group of each donor so the blood can be matched to the patient who needs it.

GENE LINKAGE

In the simple models of inheritance you have looked at so far, you considered a single trait inherited by a pair of alleles on the autosomes.

However, all this is a very long way from the real mechanisms by which inheritance takes place. Hundreds and thousands of genes go to make up the genotype of any one individual and they are all passed on at the same time. Scientists have discovered that there are many cases where characteristics inherited on single genes are always associated with other characteristics, also carried on single genes. These genes are said to be linked. So how does **gene linkage** work?

POLYGENIC TRAITS

Monohybrid genetic crosses involve only one gene locus. It is important to remember, however, that most traits in living organisms are determined not by a single gene but by several or many interacting genes. They are **polygenic**. Characteristics such as eye colour, weight and intelligence are determined by several different genes at different loci and, in many cases, interactions with the environment add further variety. So when you think about how genes affect the phenotype of an organism, remember monohybrid crosses are a very simple model that helps us to understand a much more complex reality.

Looking at how two different genes are inherited completely independently in a process called **digenic (dihybrid) inheritance** will help you understand gene linkage (see **fig B**). Digenic crosses are breeding experiments involving the inheritance of two pairs of contrasting characteristics at the same time. Although still a very long way from the complexity of real events, this goes one step closer to the living cell.

There are some occasions when the ratios are not what you expect. There can be several explanations for this:

- small sample size
- experimental error – especially when working with organisms such as *Drosophila*, which can escape or die relatively easily
- the process is random and so sometimes the unexpected happens
- unexpected ratios can mean the genes being examined are both on the same chromosome (they are linked).

You are now going to look at the process of gene linkage.

RATIOS IN DIHYBRID INHERITANCE

In the fruit fly *Drosophila*, grey bodies are dominant to ebony bodies, and long wings are dominant to very short vestigial wings. For a cross between two heterozygotes, you can use a Punnett square to determine the results of digenic inheritance. The crossing of two non-linked heterozygotes in a dihybrid cross always results in a 9 : 3 : 3 : 1 ratio of phenotypes (see **fig B**).

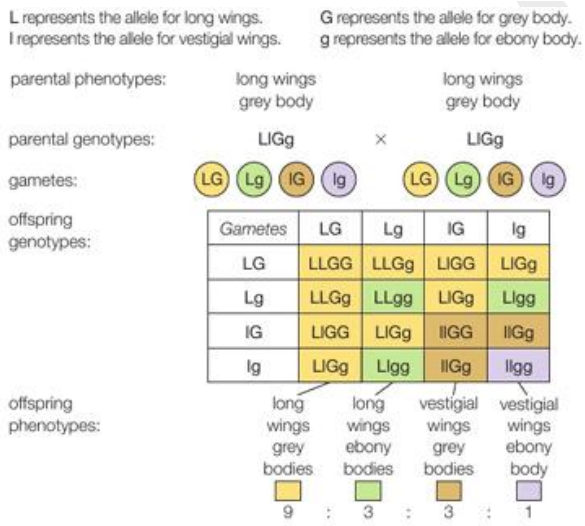


fig B Crossing two heterozygotes in a dihybrid cross always results in a typical 9 : 3 : 3 : 1 ratio of parental phenotypes (the same as the parents) and recombinant phenotypes (different combinations of the phenotypes which result from inheriting the different alleles independently).

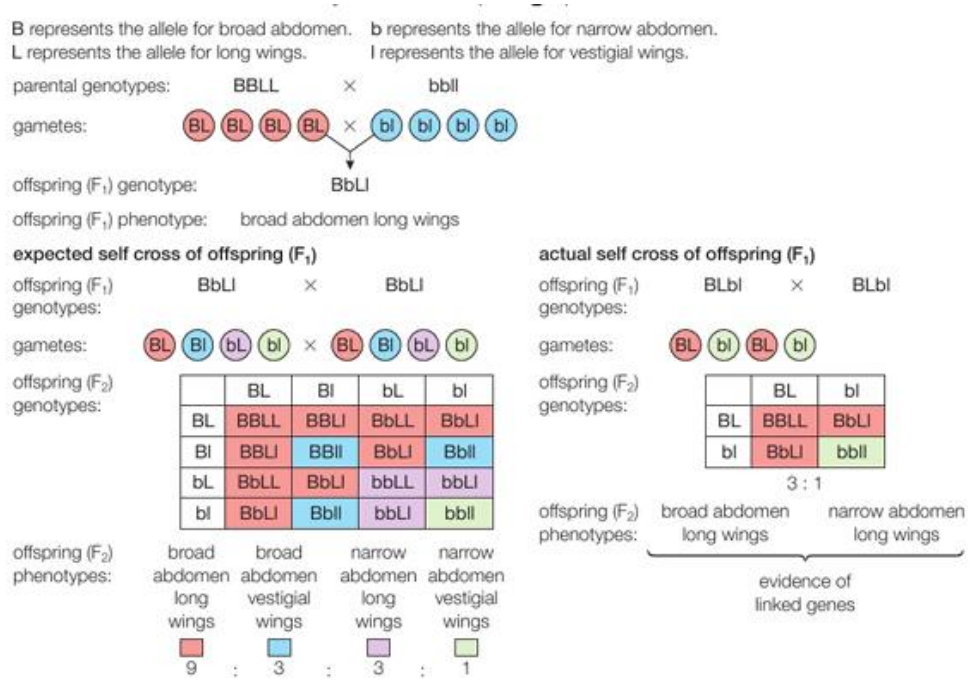
LEARNING TIP

Remember this ratio, and remember it is a ratio. Results of a cross may not look exactly like this ratio but will be similar.

LINKAGE IN FRUIT FLIES

When homozygous Drosophila with dominant broad abdomens and long wings are crossed with flies displaying recessive narrow abdomens and vestigial wings, all the offspring show the dominant phenotype, but possess the heterozygote genotype.

When the heterozygous flies are crossed, it is expected that a normal 9:3:3:1 ratio would be observed. This is the ratio of parental phenotypes (they look the same as the parents) and recombinant phenotypes (different combinations of appearance which result from inheriting the different alleles independently).

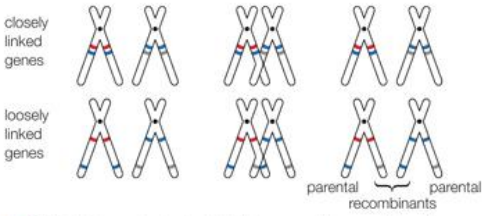


▲ **fig C** These two genes are linked. They are inherited as if they are one unit because they are positioned close together on the same chromosome.

IDENTIFYING LINKED GENES

Linked genes are found on the same chromosome and are inherited as a single gene. Closely linked genes rarely occur during meiosis, while loosely linked genes increase the number of recombination events. The tightness of a pair of genes' linkage is related to the proximity of the linked genes on the chromosome. Genes close together are less likely to be split during the crossing over stage.

linked that they are never split up during meiosis and so the gametes formed will always be of the parental types. If the genes are further apart, crossing over between them is more likely to occur. Although in the majority of cases they will be passed on as a parental unit, sometimes they will be mixed and recombinant gametes produced, which will, in turn, be reflected in the offspring (see **fig D**).



▲ **fig D** During meiosis, closely linked genes will be passed into the gametes as a single unit. Genes on the same chromosome but positioned further apart will form some recombinant gametes, with different mixtures of the alleles.

SUBJECT VOCABULARY

cell differentiation the process by which a less specialised cell becomes more specialised for a particular function
locus place on a chromosome where any particular gene is found
multiple alleles more than two possible variants at a particular locus
codominant both alleles are expressed in the phenotype
gene linkage when genes for two different characteristics are found on the same chromosome and are close together so they are linked and inherited as a single unit
polygenic phenotypic characters determined by several interacting genes
digenic (dihybrid) inheritance the inheritance of two pairs of contrasting characteristics at the same time

3C 2 Interactions between genes and environment

Genetic makeup influences an organism's appearance, but environmental factors also play a role. Genetically identical plants grow differently under different light, water, and soil conditions, demonstrating the impact of environment on an organism's appearance. Animals' growth depends on factors like food availability, but studying the impact of environment on phenotypes is challenging due to ethical concerns and the difficulty in producing large cloned organisms. Siamese cats and certain rabbit breeds have dark points on their ears, muzzle, and paws due to a mutation.

▲ **fig A** The environment of the animal's body interacts with the genotype to give the unique markings of a Siamese cat.

STUDYING VARIATION IN HUMANS

The environment in the uterus impacts a fetus's development before birth, with malnutrition, ineffective placenta, smoking, and certain illnesses affecting the fetus's growth. The genotype also plays a role in determining a fetus's phenotype, but polygenic inheritance can result in complex characteristics like intelligence and appearance. Studying the interaction between genotype and environment in humans is challenging, as imposing similar conditions is impossible. Scientists need alternative approaches to understand the interaction between nature and nurture.

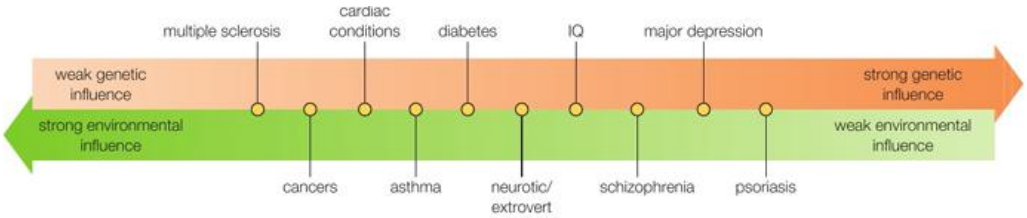
TWIN STUDIES

Twin studies are used to separate the effects of genes and environment on genetically identical individuals. Identical twins have the same genetic material, while non-identical twins have closely related but not identical DNA. Height has a strong genetic component, while body mass is affected by external factors like family eating habits. IQ is a combination of both, with environment playing a distinct role. A 2008 study found that 77% of variation in BMI and waist circumference was caused by genes.

TRAIT	IDENTICAL TWINS REARED APART	IDENTICAL TWINS REARED TOGETHER	NON-IDENTICAL TWINS	NON-TWIN SIBLINGS
Height difference	1.8 cm	1.7 cm	4.4 cm	4.5 cm
Mass difference	4.5 kg	1.9 kg	4.6 kg	4.7 kg
IQ score difference	8.2	5.9	9.9	9.8

table A These data show the results from a US study based on 19 pairs of identical twins reared apart, along with 50 pairs each of identical twins reared together, non-identical twins and non-twin siblings, by Newman, Freeman and Holzinger at the University of Chicago in 1937. Although these data are old, they are still relevant today.

We do not know everything about how genes influence human traits, but work like these twin studies helps improve our understanding. **Fig C** shows some conclusions about relative genetic and environmental influences taken from several similar studies.



▲ **fig C** Nature versus nurture – the evidence suggests that both influence many of our characteristics.

DISCONTINUOUS AND CONTINUOUS VARIATION

In any population of organisms there are two types of variation - **discontinuous variation** and **continuous variation.** Discontinuous variation is shown by features that are either present or not, such as blood groups or sex (male or female). These features are generally determined by one or at most a very few genes, and the environment does not usually have an effect - you are either male or female, and your blood group is either A, B, AB or O.

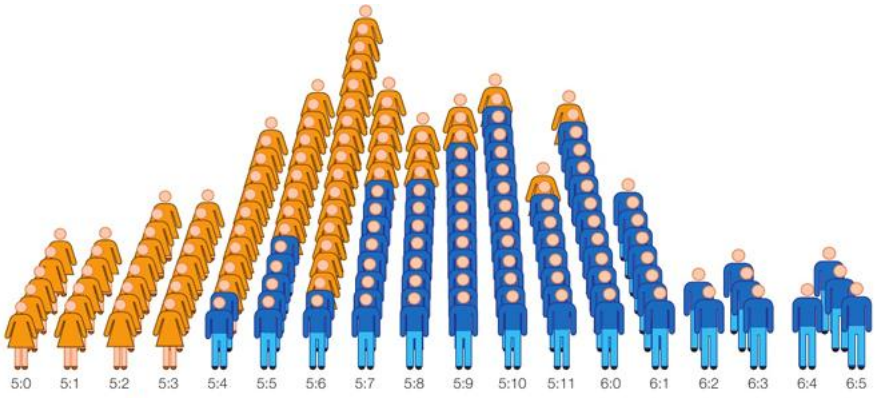


fig E Height is a feature showing continuous variation, with clear sex differences but with overlap between taller women and shorter men.

STUDYING CONTINUOUS VARIATION

Height in humans is a complex phenomenon influenced by genetics, environmental factors, and environmental factors. Tall parents tend to have taller children, and genetic factors affect factors like gender, leg length, vertebrae size, growth hormone production, and bone growth rate. However, a balanced diet can help individuals achieve their genetic height potential, while malnutrition can hinder this. To study continuous variation in a population, large samples are needed, as chance can affect results. Data can be displayed using graphs or histograms to show the frequency distribution of the characteristic.

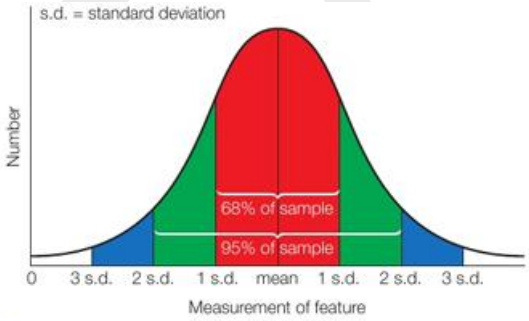


fig F Most of the measurements in a normal distribution – for example, human height – are within three standard deviations from the mean of the sample. Graphs like these are very useful in biology.

SUBJECT VOCABULARY

operon a unit consisting of linked genes which is thought to regulate other genes responsible for protein synthesis

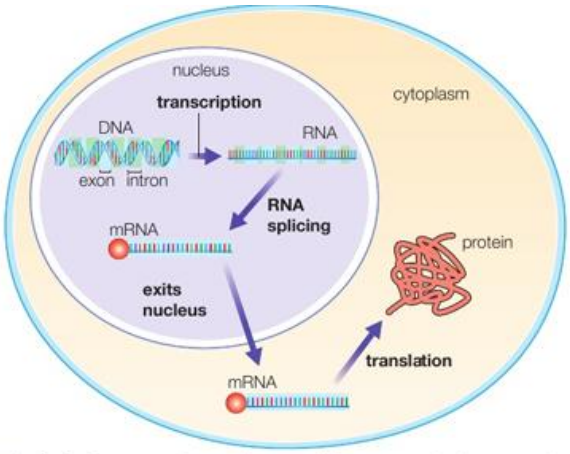
discontinuous variation phenotypic features which are either present or not, usually inherited on one or at most a small number of genes.

continuous variation phenotypic features which show a huge range of values; they are usually polygenic and are also affected by environmental factors

3C 3 Controlling gene expression

CONTROLLING GENE EXPRESSION

Cells have around 20,000-25000 individual genes on their chromosomes, with 10,000-20000 actively expressed in differentiated cells. Gene expression involves transcription from DNA to mRNA and translation from mRNA to proteins. Control over gene expression is achieved through controls at any stage. Different proteins determine cell type and function, and can be altered post-synthesis.

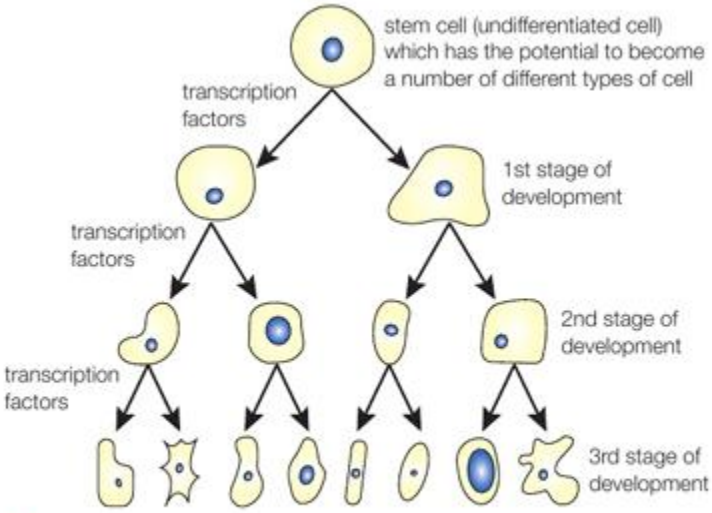


▲ **fig A** Gene expression can be controlled at any stage in the process of protein synthesis.

TRANSCRIPTION FACTORS AND THE CONTROL OF GENE EXPRESSION

Transcription factors are proteins that bind to the DNA in the nucleus and affect the process of transcribing the genetic material. All transcription factors have regions that enable them to bind to specific regions on the DNA known as promoter sequences. Promoter sequences are usually found just above the starting point for transcription upstream of the gene. (See Section 2B.6 to remind yourself of how DNA is transcribed in the nucleus of the cell.) Some transcription factors stimulate the transcription of a region of DNA simply by binding to a DNA **promoter sequence**.

This stimulates the start of transcription of that area of the DNA. Other transcription factors bind to regions known as **enhancer sequences** and regulate the activity of the DNA by changing the structure of the chromatin, making it more or less open to RNA polymerase. An open chromatin structure is associated with active gene expression; closed chromatin structures are associated with gene inactivity.



▲ **fig B** The wide variety of cells in an organism is the result of different transcription factors allowing different genes to be expressed or repressed in each cell type. This diagram gives you an idea of how many different types of cell can result from a single original as many different transcription factors are switched on and off.

RNA SPLICING

The mRNA produced in the nucleus results from the transcription of all the DNA making up a gene, including the **exons** and **introns** (the non-coding DNA). We now know that this mRNA is not quite finished when it is first transcribed. Several processes occur which modify it before it lines up on the ribosomes, so it is referred to as **pre-mRNA.** The

modifications to the pre-mRNA always involve the removal of the introns and, in some cases, some of the exons are removed as well. Enzyme complexes called **spliceosomes** join together the exons that are to be transcribed and produce the mature, functional mRNA.

fig C The hearing mechanism of chicks like these is based on 576 proteins that are all produced by RNA splicing from a single gene.

POST-TRANSLATION CONTROL

Further modification of proteins may also occur after they have been synthesised. A protein that is coded for by a gene may remain intact or it may be shortened or lengthened by enzymes to give a variety of other proteins.

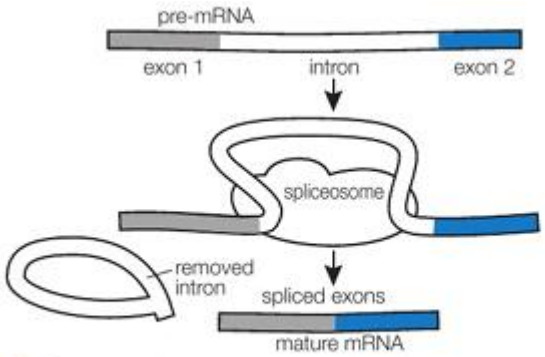


fig D RNA splicing to remove introns, and sometimes rearrange exons, enhances the expression of some genes.

EPIGENETICS

Epigenetics is a relatively new area of research in biology. It studies genetic control by factors other than the base sequences on the DNA. So in a way, RNA splicing is a form of epigenetic control because it changes the mRNA and proteins produced from the original genetic code. Scientists are becoming increasingly aware of the role of epigenetic control in the normal development of specialised cells.

DNA METHYLATION

DNA methylation has been found to be extremely important in controlling gene expression and has a major role in many processes including embryonic development and X chromosome inactivation. In many specialised cells in adults, many genes are silenced by DNA methylation most or all of the time.

DNA demethylation is equally important. The removal of the methyl group enables genes to become active so they can be transcribed.

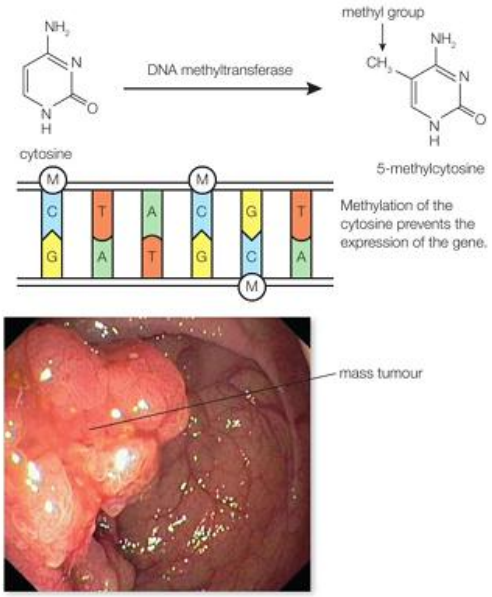


fig E DNA methylation silences many genes. Scientists are finding demethylation of DNA may well be a factor in the growth of the tumour in some cancers, including ovarian and bowel cancers.

HISTONE MODIFICATION

Histones can be modified in a number of ways to affect the transcription of DNA and therefore gene expression. This DNA-protein complex makes up the chromosomes. The histones determine the structure of the chromatin. When the chromatin is densely supercoiled and condensed, the genes are not available to be copied to make proteins and this is known as **heterochromatin**.

Many different factors affect the modification of the histones, including steroid hormones. Modification processes include the following

- **Histone acetylation** - an acetyl group (-COCH3) is added to one of the lysines in the histone structure. Adding an acetyl group usually opens up the structure and activates the chromatin, allowing genes in that area to be transcribed. Removing an acetyl group produces heterochromatin again.

- **Histone methylation** - a methyl group (-CH,) is added to a lysine in the histone. Depending on the position of the lysine, methylation may cause inactivation of the DNA or activation of a region. Methylation is often linked to the silencing of a gene and even whole chromosomes.

NON-CODING RNA

About 90% of the human genome is transcribed into mRNA, but only about 2% of those RNA molecules code for proteins. Much of the rest of the **non-coding RNA (ncRNA**) seems to affect the transcription of the DNA code or modifies the products of transcription. Both genes and whole chromosomes can be silenced by ncRNAs. In female mammals, one of the X chromosomes in every cell is inactivated at random. This is largely due to the presence of an ncRNA called X-inactive specific transcript (Xist), which is produced by the active Xist gene on the inactive chromosome.

CELL DIFFERENTIATION

Cell differentiation occurs when unspecialised cells switch different genes on and off as needed to become specialised cells. Scientists are now aware that most of these changes are the result of epigenetic modification of the genetic material. Epigenetic modifications ensure that a wide range of very specific proteins are made within the cell as it differentiates for a specific function.

These epigenetic changes may be in response to internal stimuli from the cell itself or in response to changes outside the cell (an external stimulus) which affect the inside of the cell. For example, the sex hormones produced at puberty trigger changes in many cells in the body through DNA methylation in the nuclei of the cells. The production of these hormones is a response to many factors including body mass which is affected by the environment – for example, by how much food is available. Once epigenetic changes have occurred within a cell, the modifications – the genes which are switched on or switched off – are passed on when the cell divides by mitosis. The process of cell differentiation can be summarised as follows:

- chemical stimulus (e.g. demethylation)/transcription factor
- certain genes activated/switched on
- mRNA produced from these genes
- translation of mRNA to form polypeptide/protein
- permanent modification of the cell.

SUBJECT VOCABULARY

transcription factor protein that binds to the DNA in the nucleus and affects the process of transcribing DNA into RNA
promoter sequence specific region on the DNA to which transcription factors bind to stimulate transcription
enhancer sequence specific region of DNA to which transcription factors bind and regulate the activity of the DNA by changing the structure of the chromatin
exons segments of a DNA or RNA molecule containing information coding for a protein or peptide sequence
introns segments of a DNA or RNA molecule containing information which does not code for a protein or peptide sequence
pre-mRNA mRNA that is transcribed directly from the DNA before it has been modified
spliceosomes enzyme complexes that act on pre-mRNA, joining exons together after the removal of the introns
DNA methylation methylation of DNA (addition of a methyl $-CH_3$ group) to a cytosine in the DNA molecule next to a guanine in the DNA chain and prevents the transcription of a gene
DNA demethylation removal of the methyl group from methylated DNA enabling genes to become active so they can be transcribed
heterochromatin densely supercoiled and condensed chromatin where the genes are not available to be copied to make proteins
histone acetylation addition of an acetyl group ($-COCH_3$) to one of the lysines in the histone structure, which opens up the structure and activates the chromatin, allowing genes in that area to be transcribed
histone methylation addition of a methyl group ($-CH_3$) to a lysine in the histone; methylation may cause inactivation or activation of the region of DNA, depending on the position of the lysine
non-coding RNA (ncRNA) 98% of the RNA, which does not code for proteins but affects the transcription of the DNA code, modifies the chromatin structure or modifies the products of transcription

3C 4 Stem cells

Fertilisation starts a complex series of events that will eventually lead to the birth of a fully formed new individual. In humans, the zygote (fertilised egg cell) has the potential to form all of the 216 different cell types needed for an entire new person. It is said to be **totipotent**. The future roles of individual cells are decided quite early in the life of an embryo.

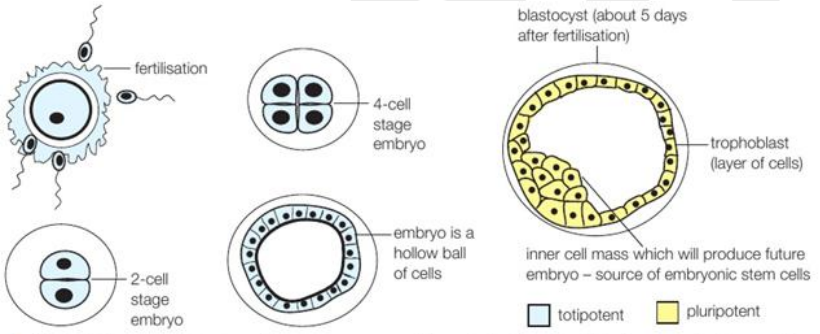
THE EARLY STAGES OF DEVELOPMENT

The first stage of embryonic development is known as cleavage. Cleavage involves a special kind of mitosis where cells divide repeatedly without the normal interphase for growth between the divisions. The result of cleavage is a mass of small, identical and undifferentiated cells forming a hollow sphere known as a **blastocyst** (see fig A).

In humans, this process takes about 5-6 days, and it takes place as the zygote is moved along the oviduct towards the uterus. One large zygote cell forms many small cells in the early embryo. The tiny cells of the early human embryo are known as **embryonic stem cells**. Stem cells are undifferentiated cells that have the potential to develop into many different types of specialised cell from the instructions in their DNA.

The very earliest cells in an embryo are totipotent like the zygote. By around the fourth day after fertilisation, they become a solid ball of 10-30 cells known as a **morula**. Each of the cells in the morula is still totipotent and has the potential to form every type of adult human cell.

The inner layer of cells can form almost all of the cell types needed in future, but not tissue such as the placenta. These cells are known as **pluripotent** embryonic stem cells. They have become pluripotent as a result of some genes already being permanently switched off.



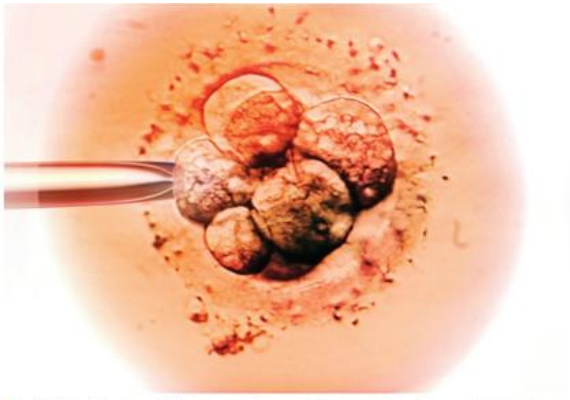
▲ **fig A** In the very earliest stages of pregnancy any one of the cells has the potential to form an entire human being, but this ability is lost by the blastocyst stage.

TYPES OF STEM CELL

Stem cells come in a number of different types, with different levels of potency.

EMBRYONIC STEM CELLS

The earliest embryonic cells, such as those shown in fig B, are totipotent. By the blastocyst stage, when the embryo is implanted in its mother's uterus, the inner cells of this ball are pluripotent. Pluripotent stem cells change to become more specialised as the embryo develops.



▲ **fig B** A 3-day-old human embryo: at this stage the cells are still totipotent.

UMBILICAL CORD STEM CELLS

The blood that drains from the placenta and umbilical cord after birth is a rich source of pluripotent stem cells. If this blood is frozen and stored, in theory those stem cells will be available throughout the life of the child should they or their family need them later for stem cell therapy. It may become possible to store stem cells from every newborn baby ready for when they might need them.

SUBJECT VOCABULARY

totipotent an undifferentiated cell that can form any one of the different cell types needed for an entire new organism
blastocyst an early embryo consisting of a hollow ball of cells with an inner cell mass of pluripotent cells that will eventually form a new organism
embryonic stem cells the undifferentiated cells of the early human embryo with the potential to develop into many different types of specialised cell
morula an early embryo made up of a solid ball of 10–30 totipotent cells
pluripotent an undifferentiated cell that can form most of the cell types needed for an entire new organism
adult stem cells (somatic stem cells) undifferentiated cells found among the normal differentiated cells in a tissue or organ that can differentiate when needed to produce any one of the major cell types found in that particular tissue or organ
multipotent a cell that can form a very limited range of differentiated cells within a mature organism

ADULT STEM CELLS

An adult human consists of many different types of highly specialised cell. However, some **adult stem cells (somatic stem cells**) remain as undifferentiated cells and are found among the normal differentiated cells in a tissue or organ. They can differentiate when needed to produce any one of the major cell types found in that particular tissue or organ.

There are only a very small number of adult stem cells in each different tissue. They are difficult to extract and most of them form a very limited range of differentiated cells. They are said to be **multipotent**. They are difficult to grow in the laboratory.

THE DEVELOPMENT OF AN ORGANISM

Totipotent stem cells in embryos transform into pluripotent stem cells in the blastocyst and fully differentiated somatic cells in mature organisms. Gene expression is controlled through transcription factors and epigenetic mechanisms like DNA methylation, histone modification, and ncRNAs.

AN EXAMPLE OF EPIGENETIC CONTROL IN HUMAN DEVELOPMENT

Haemoglobin, an essential molecule for oxygen transport, is switched on and off during human development from embryo to fetus to baby. Different versions of globin genes are activated in different tissues, with globin production moving from the yolk sac to the liver, spleen, and bone marrow.

The mechanism which controls the genes that code for the different chains is still the subject of much active research. If scientists can work out how to reactivate the fetal haemoglobin gene in children and adults, they may be able to overcome the problems presented in genetic conditions such as sickle cell anaemia and thalassaemia, which affect the structure of adult haemoglobin. So far scientists have found evidence of some epigenetic control mechanisms.

- Histone acetylation appears to activate the gamma globin gene in the fetus.
- DNA methylation appears to be important in silencing the fetal gamma globin genes just before and after birth.
- Histone methylation appears to complement DNA methylation in silencing the fetal gamma globin.
- Non-coding RNAs have been associated with the process, but scientists are not yet sure what they do.
- A number of transcription factors are very important in the switch to the production of beta globin in the spleen and bone marrow as the fetus approaches full term and birth.

As we understand more about the control of cell differentiation, our ability to control stem cells will increase too.

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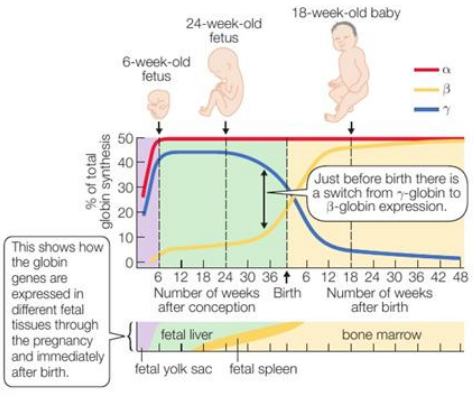


fig C Different genes for the production of globin molecules are switched on and off in different tissues during the development of a human being from an embryo to a fetus to a baby.

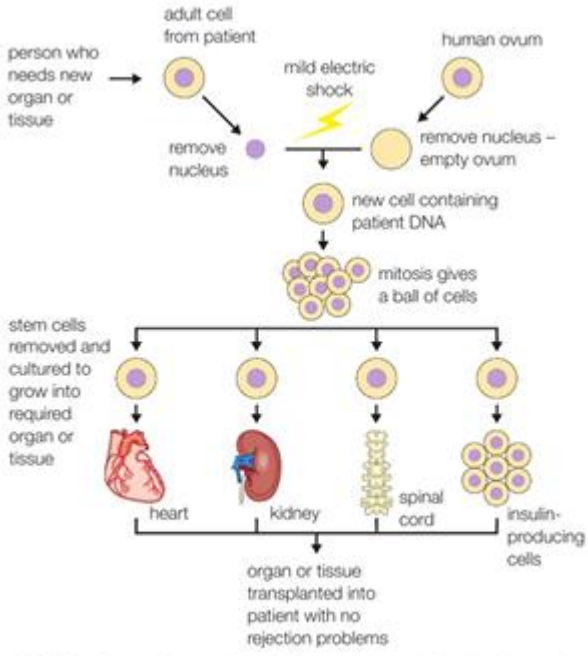
3C 5 Using stem cells

STEM CELL THERAPY

When stem cells were first cultured, scientists hoped that they could be used to produce new tissues but this has not yet been successful. It is very difficult to control the differentiation of the cells. Some of the early treatments did result in patients being cured of one condition, but they then developed cancer.
Much of the early work carried out by scientists on stem cells used cells harvested from early embryos. This process is allowed in many countries, but is unacceptable in others. The use of stem cells derived from embryos to develop new medical treatments has raised both practical and ethical difficulties.

THERAPEUTIC CLONING

Somatic cell cloning or **therapeutic cloning** is an experimental technique that scientists hope to use in the future to produce large quantities of healthy tissue. This is one of the main ways in which scientists are using stem cells to develop new medical therapies. It is hoped that this could be used to treat people with diseases caused by faulty cells, such as type 1 diabetes or Alzheimer's disease.



▲ **fig B** Therapeutic cloning is still very experimental but this diagram shows how scientists and doctors hope it will be used in the future.

PITFALLS AND POTENTIAL BENEFITS OF STEM CELL THERAPY

There are problems that relate to the uses of all kinds of stem cell to develop new medical therapies. Society has to rely on the scientific knowledge presented to it to make decisions about the use of stem cells in this way. For example, at the moment no one is quite sure how the genes in cells are switched on or off to form specific types of tissue.

INDUCED PLURIPOTENT STEM CELLS

In 2006, a team of researchers in Japan made an astonishing breakthrough. They took adult mouse cells and, using genetic engineering techniques, reprogrammed them to become pluripotent again. Effectively, they produced stem cells without using an embryo. What is more, the **induced pluripotent stem cells (iPS cells**) renew themselves. The next stage was to repeat the process in humans. The team used harmless, genetically modified viruses to carry a group of four genes for specific transcription factors into skin cells taken from a 36-year-old and synovial fluid taken from a 69-year-old.

WHO COULD BENEFIT FROM STEM CELL THERAPY?

Stem cell therapy has the potential to treat a wide range of diseases caused by faulty cells. Here are some examples of areas where scientists feel pluripotent stem cells could give real therapeutic value.

PARKINSON'S DISEASE

Parkinson's disease is a global brain disorder causing tremors and rigidity. Despite improved drug treatments, there is no long-term cure. Scientists are exploring stem cell transplants to replace lost brain cells and restore dopamine production. Mouse stem cells have been transplanted into rats with Parkinson's symptoms, improving movement control. Pluripotent stem cells are considered the best hope for a long-term treatment, as they can replace damaged cells.

TYPE 1 DIABETES

Type 1 diabetes usually develops when people are young. The glucose-sensitive, insulin-secreting cells from the islets of Langerhans in the pancreas are destroyed or stop making insulin. This means the blood glucose concentration is uncontrolled. This can be very serious or even fatal. Although insulin injections work well enough, people affected by type 1 diabetes must monitor their food intake and blood glucose concentration and inject insulin regularly. Stem cell therapy could give them working pancreas cells again, restoring insulin production and therefore blood glucose control.

DAMAGED NERVES

No medical cure exists for damaged brain and spine nerves. Stem cells have been transplanted into mice and rats with damaged spines, allowing them to regain control and movement. Examining spinal cords showed stem cells growing into working adult nerve cells, suggesting potential for future human treatments. Although not stem cells, progress in humans is possible.

ORGANS FOR TRANSPLANTS

Many people die because their organs no longer function properly. Hearts, kidneys, livers and many other organs can be replaced by transplant, but only if there is a suitable donor organ available. There is a desperate need for new organs, preferably ones that will not cause rejection problems when they have been transplanted. In 2013, a team of researchers in Australia produced stem cells from human skin cells. They then manipulated the differentiation of these stem cells into minute functioning kidney units.

STEM CELL SUCCESS

So far, the number of successful therapies using pluripotent stem cells has been very small. Many ideas are being developed and trialled in animals. Not many of these have had any impact on human health although recent results with age-related muscular degeneration are very positive. Scientists and doctors expect that numbers of successful treatments will increase dramatically in the next 10 years.

ETHICAL QUESTIONS

There have been some very powerful reactions to stem cell technology. As well as the many practical problems to be overcome before stem cell therapy becomes a standard treatment, society has many ethical issues to deal with.
The four ethical principles are as follows.

- Respect for autonomy - this means respect for individuals, by not performing procedures without consent.
- Beneficence - this means the aim of doing good, by giving medicine to relieve suffering, etc.
- Non-maleficence - this means doing no harm.
- Justice - this means treating everyone equally and sharing resources fairly, to avoid discrimination.

THERAPEUTIC CLONING

In therapeutic cloning, the cloned cells created from adult cells are produced to provide pluripotent stem cells. Therefore, many people are very optimistic about the future potential of this new
technology and see no major ethical issues to overcome. However, other people fear that if the cloning is allowed for therapeutic purposes it could be taken further, to produce a cloned baby.

iPS CELLS

iPS cells are pluripotent so they can be turned into most cell types by carefully manipulating transcription and epigenetic factors. They come from the individual patient so there are no issues of rejection. They do not come from embryos and they are not capable of forming a new embryo. The ethical issues are all answered by using this technology. The biggest problem is that these cells are not so easy to grow and manipulate as natural pluripotent stem cells. Societies around the world will consider the scientific evidence to make decisions about the use of stem cells in medical therapies. However, in this field of science, the ethical views of a society will also affect their attitude to, and acceptance of, new stem cell treatments.

SUBJECT VOCABULARY

therapeutic cloning an experimental technique used to produce embryonic stem cells from an adult cell donor
induced pluripotent stem cells (iPS cells) adult cells that have been reprogrammed by the introduction of new genes to become pluripotent again

Revision questions

Q1.

The photograph shows a Baird's tapir.

Source: https://www.biolib.cz/IMG/GAL/171566.jpg

(a) Baird's tapir is endemic to countries in Central America.

State what is meant by the term **endemic.**

(b) Baird's tapir is classified as endangered.

In 2006, it was estimated that there were 5500 Baird's tapirs. This number had fallen to 3000 in 2016.

(i) Calculate the percentage decrease in the number of Baird's tapirs from 2006 to 2016.

(2)

Answer ..... %

(ii) Explain how human activity, other than hunting, could have caused this decrease in the number of Baird's tapirs.

(c) Preservation of sperm collected from Baird's tapir may help captive breeding programmes.

Scientists investigated the effect of freezing on sperm from Baird's tapir.

The sperm were frozen and then thawed.

The results of this investigation are shown in the table.

Sperm	Percentage of sperm capable of moving (%)	Ability of sperm to swim in a straight line / a.u.	Percentage of sperm with an undamaged acrosome (%)
Freshly collected	63	3.5	80
Frozen and then thawed	38	2.5	48

(i) Describe how each of these effects of freezing could be determined.

(ii) Explain how freezing sperm could affect the success of captive breeding programmes.

Q2.

Organisms can be classified into one of three domains.

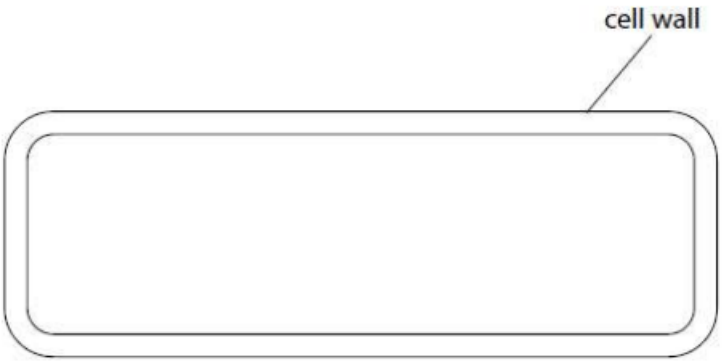
(a) Organisms belonging to two of these domains have prokaryotic cells.

(i) Bacteria are one of these domains.

Name the other domain that has prokaryotic cells.

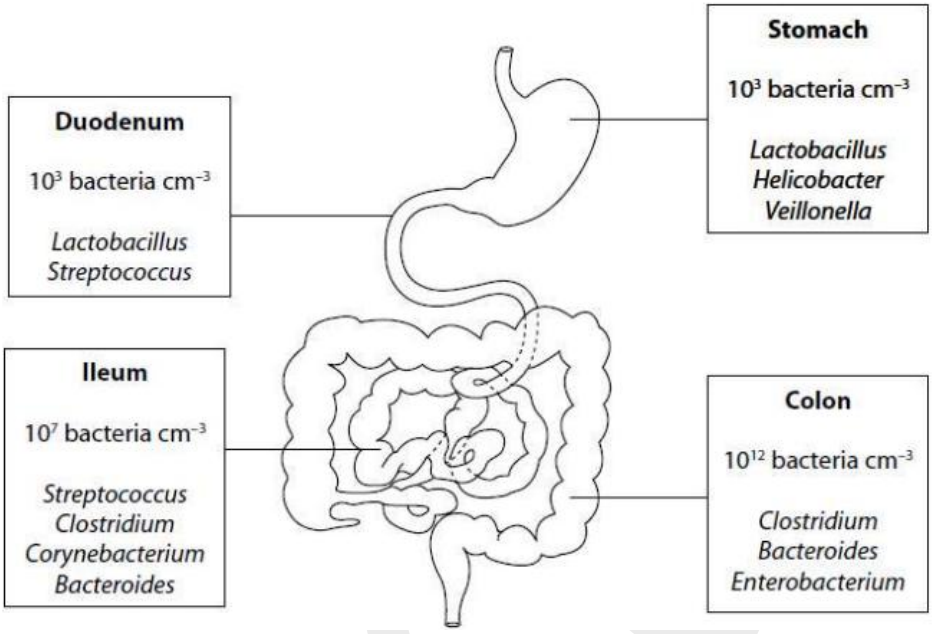
(ii) The diagram shows the outline of a bacterial cell.

Draw **three** labelled features on this diagram that may be found in a prokaryotic cell.



*(b) A variety of different types of bacteria is found in the human digestive system.

The diagram shows part of the human digestive system and the number and types of bacteria that can be found in each organ.



The table gives some information about conditions in the digestive system.

Organ	pH	Oxygen content
Stomach	1 to 3	High ↓ Low
Duodenum	6 to 7	
Ileum	6 to 8	
Colon	5 to 7	

Explain the distribution of bacteria in the digestive system. Use the information in the diagram and table to support your answer.

Q3.

The phenotype of an organism is affected by a number of factors.

(a) State what is meant by the term **phenotype.**

(b) Coat colour in rabbits is determined by multiple alleles.

The table gives some information about coat colour in rabbits.

Type of rabbit	Coat colour of rabbit	.....
Black 	black all over	CC
Chinchilla 	grey all over	$c^{ch}c^{ch}$
Himalayan 	white body black ears, face, feet and tail	$c^{h}c^{h}$
Albino 	white all over	cc

(i) Complete this table by writing a suitable heading for the right-hand column.

(ii) Which row of the table gives the correct number of genes and alleles for coat colour in these rabbits?

(1)

	Number of genes for coat colour	Number of alleles for coat colour
☐ A	1	1
☐ B	1	4
☐ C	4	1
☐ D	4	4

(c) Height is one phenotype of an elephant.

The photograph shows an African elephant.

Source: Caroline Wilcox

Male African elephants range in height from 3.2 m to 4.0 m.

Female African elephants range in height from 2.2 m to 2.6 m.

(i) Which row of the table names the types of graph that should be drawn to show sex and height variation in a population of African elephants?

(1)

	Sex	Height
☐ A	bar chart	bar chart
☐ B	bar chart	histogram
☐ C	histogram	bar chart
☐ D	histogram	histogram

(ii) Calculate how many times bigger the male African elephant is than the female African elephant.

Q4.

Red blood cells are produced from pluripotent stem cells found in bone marrow.

(a) Which statement about these stem cells is correct?

(1)

☐ **A** they can produce all types of cell

☐ **B** they can produce all types of cell except extraembryonic cells

☐ **C** they can produce some types of cell

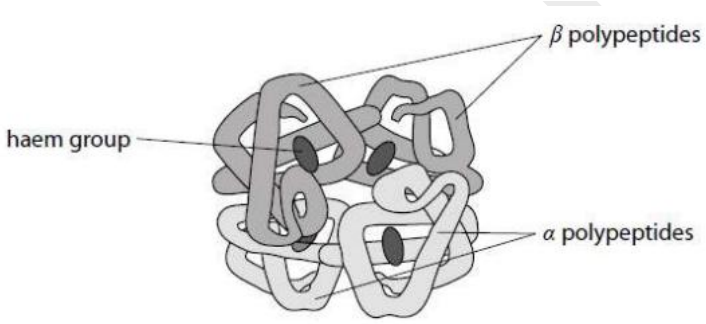
☐ **D** they can produce red blood cells only

(b) Red blood cells contain haemoglobin.

A molecule of haemoglobin is made of four polypeptides. Each polypeptide has a haem group attached to it. The haem group is **not** made of amino acids.

In most adult haemoglobin, there are two α polypeptides and two β polypeptides.

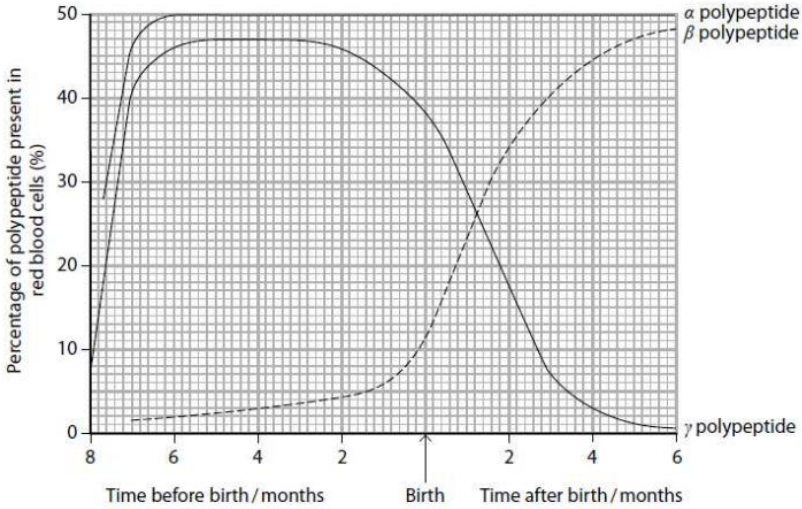
The diagram shows the structure of adult haemoglobin.



Describe the role of the rough endoplasmic reticulum in the synthesis of haemoglobin.

(c) Fetal haemoglobin has a similar structure to adult haemoglobin. Fetal haemoglobin has two α polypeptides and two γ polypeptides.

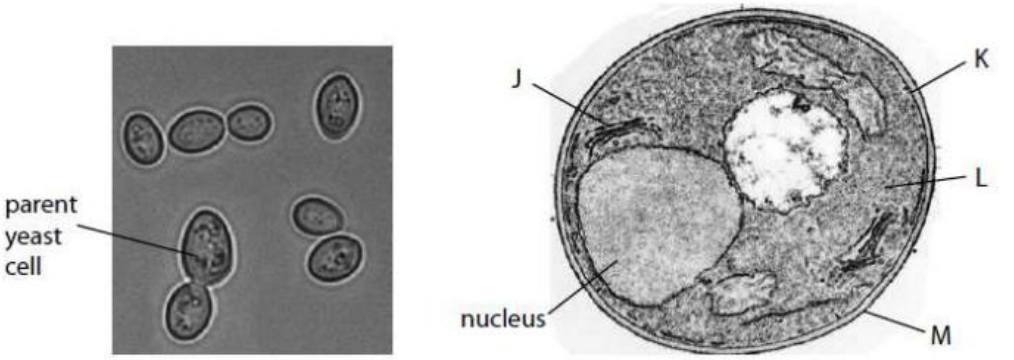
The graph shows the percentage of each polypeptide present in red blood cells in an individual before and after birth.



(i) Describe the changes in the percentages of polypeptides present in red blood cells. Use the information in the graph to support your answer.

Q5.

The photographs show yeast cells, seen using a light microscope and an electron microscope.



Yeast cells seen using a light microscope Yeast cell seen using an electron microscope

(a) Which structure identifies yeast as a eukaryotic organism?

(a) Which structure identifies yeast as a eukaryotic organism?

(1)

- ☐ **A** J
- ☐ **B** K
- ☐ **C** L
- ☐ **D** M

(b) Explain why structure J can be seen using the electron microscope but not the light microscope.

(c) Explain why the nuclear envelope cannot be seen as two membranes using this electron microscope.

(d) Yeast cells reproduce asexually by a process called budding.

The parent yeast cell produces a bud.

(i) Explain the importance of mitosis in budding.

(ii) Once the bud is large enough, it separates from the parent yeast cell.

The rate at which budding happens depends on the availability of oxygen and nutrients.

Suggest why the availability of oxygen and nutrients determines the rate of budding.

6. There are 18 species of puffer fish found in the Maldives.

The photograph shows one of these species, *Canthigaster valenti*.

© kaschibo/Shutterstock

Magnification ×0.5

(a) The markings on the skin of *Canthigaster valenti* are warnings to predators. It also protects itself from predators by producing poisons and by inflating its body.

Which row of the table describes these types of adaptations?

Which row of the table describes these types of adaptations?

	Markings on the skin	Production of poison	Inflating the body
☐ A	anatomical	behavioural	physiological
☐ B	anatomical	physiological	behavioural
☐ C	physiological	anatomical	behavioural
☐ D	physiological	behavioural	anatomical

(b) Another fish found in the Maldives is *Paraluteres prionurus*.

This fish is not poisonous. It grows to about 10 cm in length.

The photograph shows *Paraluteres prionurus*.

Source: http://www.underwaterkwaj.com/uw-misc/file/Paraluteres-prionurus.htm

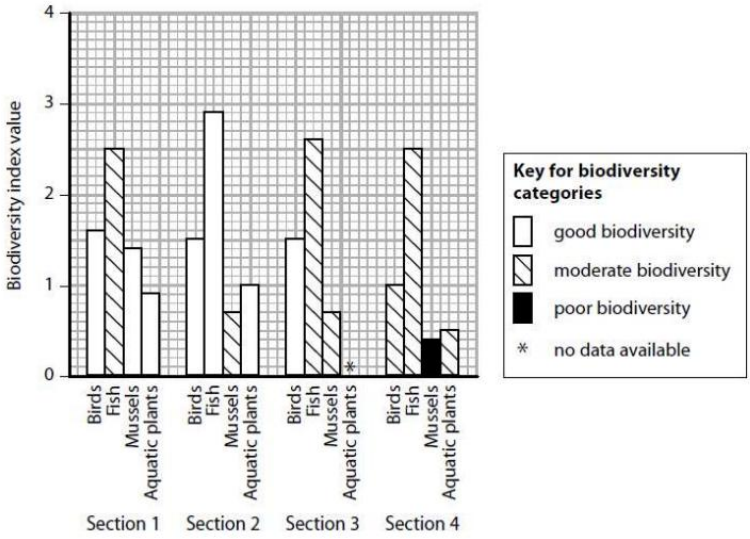
Explain how the appearance of *Paraluteres prionurus* shows it is adapted to its habitat.

(c) Explain why *Canthigaster valenti* and *Paraluteres prionurus* are unable to reproduce with each other.

7. The biodiversity of four groups of organisms – birds, fish, mussels and aquatic plants – was studied along four sections of the Rideau River in Canada.

A biodiversity index value was calculated for each group of organisms.

The graph shows the results of this study.



The biodiversity index value can be used to compare biodiversity within one group of organisms.

The biodiversity categories (good, moderate and poor) can be used to compare biodiversity between different groups of organisms.

(a) Which statement describes biodiversity?

(1)

☒ **A** species richness of only the endemic species within a habitat

☒ **B** species richness of all the species within a habitat

☒ **C** the role of only the endemic species within a habitat

☒ **D** the role of all the species within a habitat

*(b) Describe the changes in biodiversity along the Rideau River. Use the information in the graph to support your answer.

(c) In Section 1, birds have a biodiversity index value of 1.6 and fish have a biodiversity index value of 2.5.

Suggest why the fish are considered to have a moderate biodiversity and the birds have a good biodiversity, but the biodiversity index value of the fish is greater.