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BIOLOGY SL

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Biology SL
Study Guide

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INTRODUCTION

Welcome to the IB Academy Study Guide for Biology Standard Level.

We are proud to present our study guides and hope that you will find them helpful. They are the result of a collaborative undertaking between our tutors, students and teachers from schools across the globe. Our mission is to create the most simple yet comprehensive guides accessible to IB students and teachers worldwide. We are firm believers in the open education movement, which advocates for transparency and accessibility of academic material. As a result, we embarked on this journey to create these study guides that will be continuously reviewed and improved. Should you have any comments, feel free to contact us.

In this Biology SL guide we present everything that is vital for your final exam. Each section is clearly marked relating to the topics of the syllabus. The material is summarised in short texts that include various definitions, images, examples and labelled diagrams which will help you with your studies. This study guide also contains useful tips and info boxes that will assist you along the way, telling you which components are important for your exams.

For more information and details on our revision courses, be sure to visit our website at ib-academy.nl. We hope that you will enjoy our guides and best of luck with your studies.

IB Academy Team

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CELL BIOLOGY

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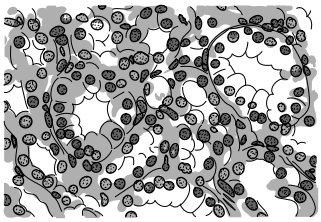
1.1 Cell theory

A



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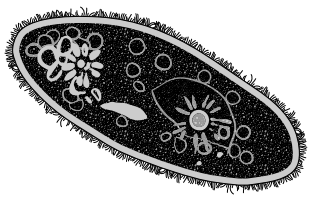

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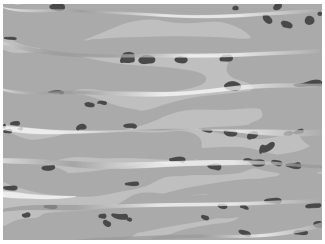

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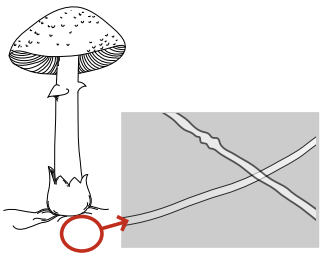


1. **All organisms are composed of cells:** microscopic examination of many organisms has shown that they are all composed of cells; unicellular organisms are still composed of one cell that performs all functions of life.
2. **Cell is the basic unit of life:** cell as a whole can perform the functions of life, while its individual components cannot.
3. **All cells originate from a pre-existing cell:** spontaneous generation of cells is not possible; a cell needs to divide to create another cell.

Even though most organisms fit well into the first two points of the cell theory (A and B), some organisms and tissues seem to contradict it. Muscle fibres are fused, elongated cells with multiple nuclei and as such differ from the common definition of a cell (C). Similarly, fungal hyphae often don't contain dividing walls and are made up multiple fused thread-like cells (D).

7 Functions of life carried out by cells

1. Nutrition
2. Metabolism
3. Excretion
4. Response
5. Homeostasis
6. Growth
7. Reproduction

If these are hard to remember, think about the following:

Every living being has to eat①, process the food it has eaten② and excrete the waste③, take in the signals from the environment and respond to them④, accordingly make sure that it is well balanced⑤ (food-wise, heat wise, etc.) and finally, use all that to grow⑥ and pass on its genes⑦.

Example.

Example: Paramecium is a unicellular organism widely used as an example of a functional unit of life.

The Paramecium:

- Is surrounded by cilia that allows it to move. *(Response)*
- Engulfs food via a specialized membranous feeding groove called a cytostome. *(Nutrition)*
- Encloses food particles in small vacuoles with enzymes for digestion. *(Metabolism)*
- Removes solid waste via an anal pore and liquid wastes are pumped out through contractile vacuoles. *(Excretion)*
- Allows essential gases to enter and exit the cell via diffusion. *(Homeostasis)*
- Grows in size and divides asexually (fission) *(Reproduction and growth)*

1.1.1 Sizes of cells

Surface area to volume ratio

Surface Area: of a cell is related to the rate of exchange of materials or how fast/slow a cell takes in food/gasses and excretes wastes products.

- The higher the surface area, the higher the exchange rate as there is more physical membrane where exchange can happen.

Volume: of a cell is related to the rate of metabolic reactions occurring in a cell or how much nutrient processing and waste production is occurring in a cell at a given time.

- The higher the volume of a cell, the higher the metabolic rate as the more nutrients are needed/used and thus more waste produced.

Cell growth is limited by two features of the cell: *surface area* and *volume*.

When the cell volume increases, the surface area increases comparably less. This limits the size of a cell because:

- the cell must be able to transport enough food/waste through the surface
- compared to the food needs/excrement production, which is determined by the cell volume.

This is linked to cell division, as following a period of growth a cell will divide in order to increase the surface area to volume ratio and function more effectively. In addition, some cells increase their surface area to volume ratio by creating folds in the plasma membrane, which creates more surface area to cope with a large exchange of materials. This can be seen in the cells of the intestinal lining.

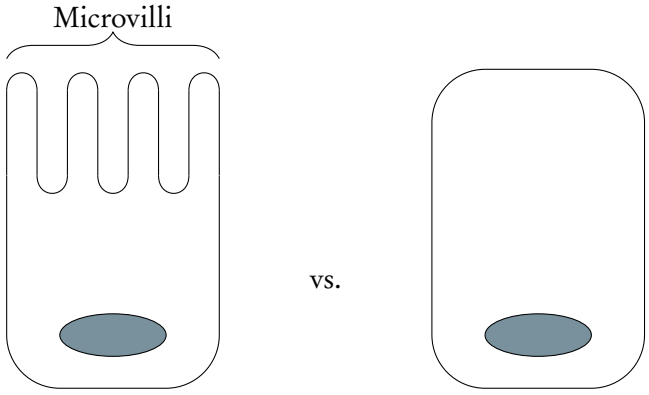
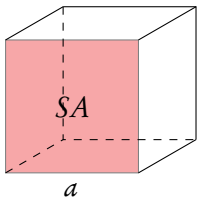


Figure 1.1: Microvilli increases surface area for exchange.

Example.

Example surface area (SA) and volume (V) calculation



Imagine a cell as a cube with sides of length a. The surface area (SA) can be calculated by adding the SAs of the six faces of the cube and the volume (V) by multiplying the sides.

$$SA = 6 \times a^2 \qquad \text{and} \qquad V = a^3$$

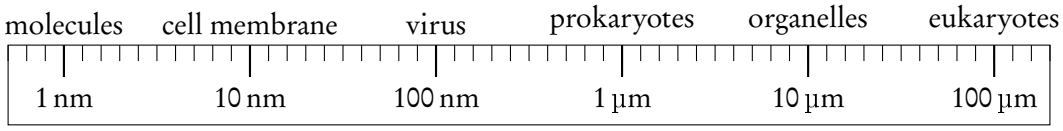
Now, compare the growth of cells, starting with $a = 1$, $a = 5$ and $a = 10$.

	size of 1	size of 5	size of 10
side= a	$a = 1$	$a = 5$	$a = 10$
$SA = 6 \times a^2$	$SA = 1$	$SA = 150$	$SA = 600$
$V = a^3$	$V = 1$	$V = 125$	$V = 1000$

Up to a certain size the SA still exceeds the V, and the cell would be able to import and export enough materials to sustain its life. But as the cell grows bigger the volume will exceed the SA, at which point the cell cannot transport enough materials in and out of the cell to keep up with its food needs/waste production.

Typical cell sizes

Cells have different sizes, from one organism to another as well as within an organism. This difference arises from the different cell functions and needs. The following scheme should help you compare the sizes of different cells:



Calculating magnification

Most cells are invisible to the naked eye therefore we use microscope magnification to be able to see them.

$$\text{Image of the cell} = \text{real cell size} \times \text{magnification}$$

Example.

Real cell size
Exam question: *Image of a cell, measurable by a ruler. Magnification in the corner.*

Calculate the real size of the cell in the picture or the magnification factor

Solution:

$$\text{Image of the cell} = \text{real cell size} \times \text{magnification}$$

therefore

$$\text{Real cell size} = \frac{\text{Image of the cell}}{\text{magnification}}$$

Numbers worked out.

Remember to always use the same units

- 1 mm = 1000 micrometers (µm)

Microscopes

An electron microscope has a far greater resolving power than a conventional light microscope, meaning an electron microscope can be used to create images of smaller objects with greater resolution.

The limit of resolution is determined by the wavelength of the incident light/electrons. And since the wavelength of electrons is much smaller than that of visible light, they can be used to view objects much smaller and in much more detail.

1.1.2 Cell properties

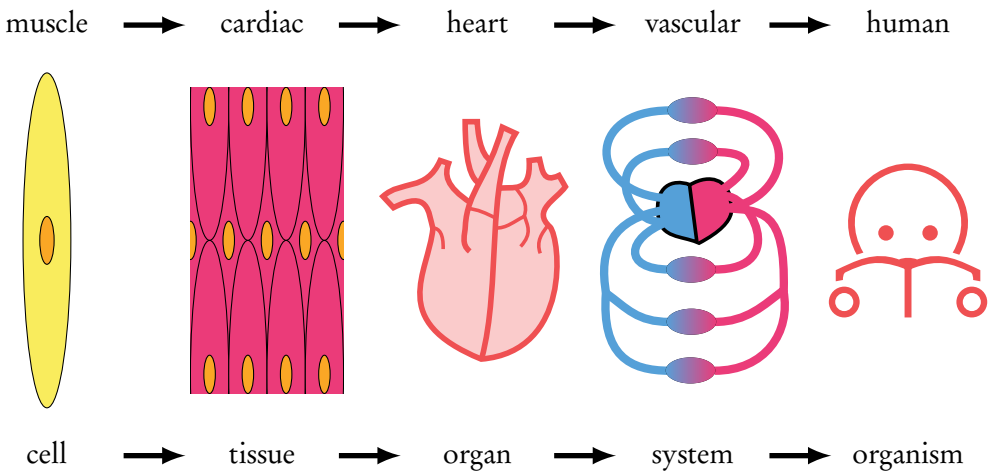
In multicellular organisms, each cell has its own function and cooperates with other cells to form an organism.

Emergent properties

Emergent properties are properties that emerge from the interaction of the individual cell components creating new functions. Multicellular organisms can realize a number of complex functions that individual cells cannot perform on their own by collaborating with one another.

Example.

You can easily visualize this by thinking about how individual cardiac cells form tissues that work together to create an organ (the heart). Then the heart together with tissues that formed vessels can function as the vascular system, transporting blood across the body. The latter cannot be done by one single cell, but is possible by the collective actions of many cells together. Finally, different systems can create an organism, like a human, who can also perform several functions that a single cell could not do on its own.



Cell differentiation

Although all cells possess the same genes, expressed genes are the ones that are "switched on" while all other genes are "switched off". Cell differentiation is the process whereby different genes are put on "lockdown" to reach a very specific cell type with particular functions brought by the available active genes.

Stem cells

Undifferentiated cells that can divide and have the capacity to differentiate into any cell type and thus acquire any function. Therapeutic sources of stem cells include umbilical cord blood, bone marrow and human embryonic stem cells

1.1.3 Examples of stem cell use

Example.

Stargardt disease

Stargardt disease is a degenerative disease of the eye (retinal cells) leading to blindness. Human embryonic stem cells are obtained from unsuccessful in vitro fertilizations. These cells are differentiated in the lab towards retinal cells and injected into the eye of patients. The new cells replace the degenerate cells in the retina and restore vision

Example.

Leukaemia

Leukaemia is the cancer of white blood cells (immune cells). Human cord blood is collected after childbirth. The cord blood contains stem cells that differentiate into white blood cells. A patient with leukaemia is irradiated and given chemotherapy to kill all cancerous white blood cells. The killed cells are then replaced by the matching cord blood cells which are able to differentiate into all kinds of white blood cells in the patient

1.2 Cells and membrane transport

1.2.1 Eukaryotic and prokaryotic cells

The main distinctions between the eukaryotic and prokaryotic cells relate to their size and complexity. Prokaryotes, also known as bacteria, are unicellular organisms with a simple, non-compartmentalized structure. Eukaryotes, which can be unicellular or multicellular organisms, are usually bigger with a complex organelle based function and compartmentalization.

Compartmentalization means to have structures wrapped around a membrane, creating different discrete compartments. This allows regions in the cell to have specific functions and environments.

Example.

Lysosomes

Lysosomes are membrane bound organelles responsible for the digestion of materials. In order to break down materials they need to have a very acidic pH of around 4.5–5. This pH is achieved with hydrogen pumps in the organelle's membrane that pump protons inside the organelle. Without compartmentalization, this specific concentrated acidic environment would not be possible, and would disrupt normal cell functioning.

Prokaryotic cells

Make sure you can draw and clearly label this yourself!

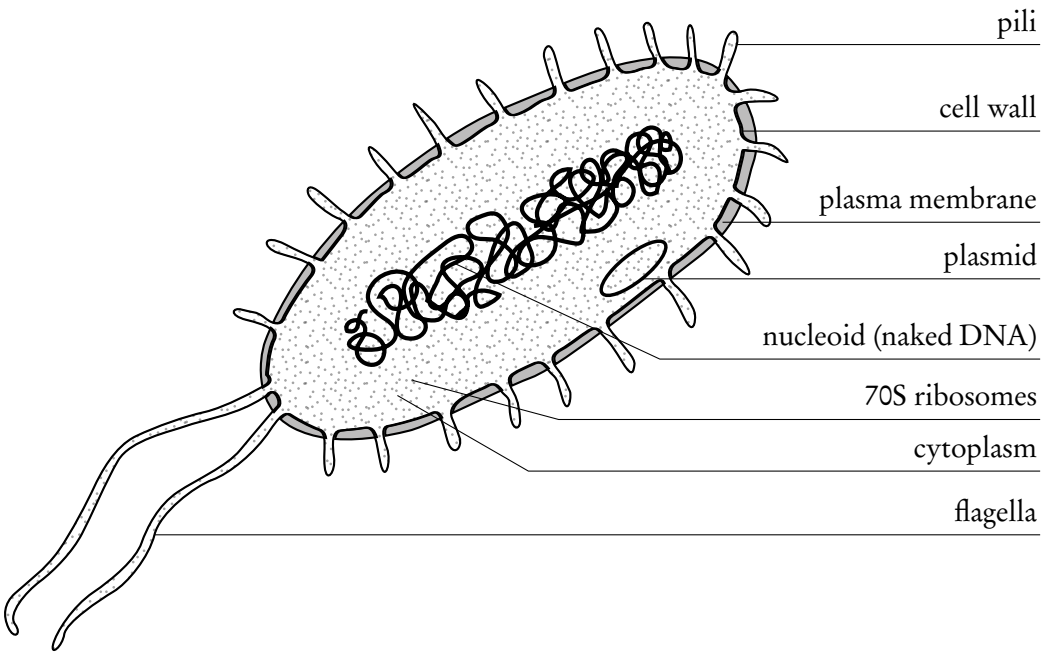


Figure 1.2: Prokaryotic cell.

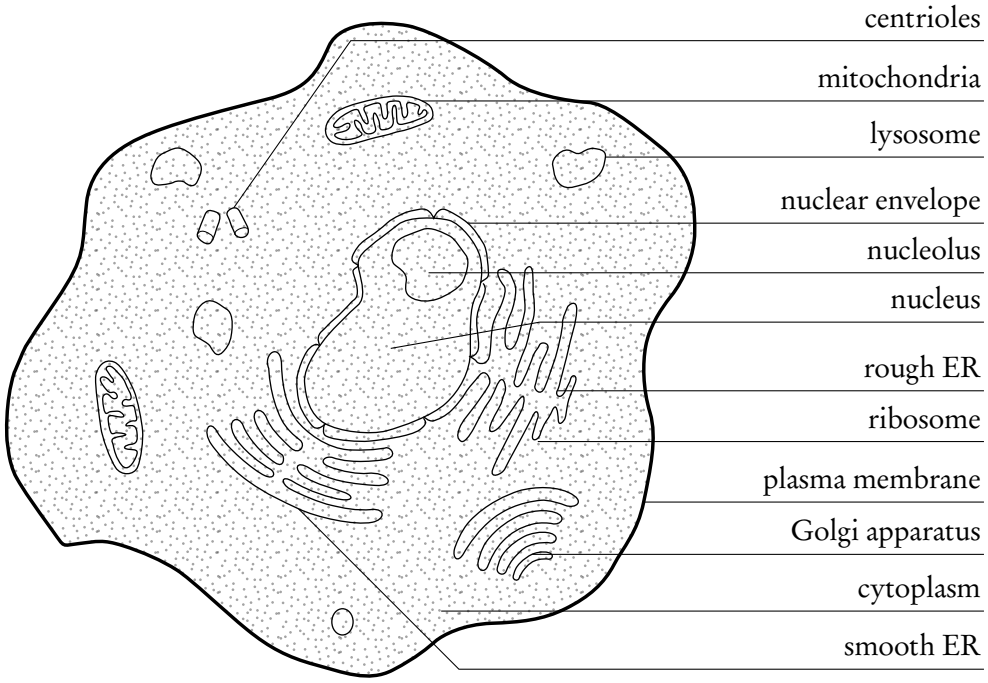
The bold structures in the table are shared between the prokaryotic and eukaryotic cells.

Table 1.1: Functions of prokaryotic cells.

Structure	Function
Capsule	Protection
Cell wall	Protection and pressure maintenance
Cell membrane	Transport of materials
Cytoplasm	Contains enzymes, food…, medium for cellular processes
Ribosomes	Protein synthesis
Nucleoid	DNA containing area not enclosed by a membrane
Plasmid	Extra genetic material (e.g., antibiotic resistance genes)
Pili	Communication, DNA exchange, attachment
Flagellum	Movement

Eukaryotic cells

eu = good/true
karyon = nucleus
} → organisms with a nucleus



Make sure you can draw and label this yourself!

Figure 1.3: Eukaryotic Cell.

There are two types of eukaryotic cells: pancreatic cell (animal) and mesophyll cell (plant).

Table 1.2: Comparison of animal cell and plant cell.

	Structure	Function	Animal cell	Plant cell
	Ribosome	Protein synthesis	✓	✓
	Rough endoplasmic reticulum	Protein modifications	✓	✓
	Golgi apparatus	Protein packaging	✓	✓
*	Mitochondrion	Site of cell respiration	✓	✓
*	Nucleus	Contains chromosomes (DNA)	✓	✓
	Lysosome	Degradation enzyme storage	✓	✓
	Centrioles	Chromosome separation during mitosis	✓	✗
	Vacuole	Food and water storage	✓	✓
	Cell Wall	Maintenance of cell pressure	✗	✓
*	Chloroplast	Site of Photosynthesis (food production)	✗	✓
*	Centrosomes	Contain microtubules, move to opposite poles during mitosis division	✓	✓

* indicates double membrane bounded organelles.

Comparison of eukaryotic cells and prokaryotic cells

Table 1.3: Comparison of prokaryotic cells and eukaryotic cells.

Prokaryotic Cell	Eukaryotic Cell
Naked DNA	DNA wrapped around
DNA in nucleoid	DNA enclosed by a nuclear region
DNA circular	DNA linear
No membrane bound structures	Membrane bound structures such as mitochondria, ER, Golgi apparatus present which compartmentalize functions
Plasmids present	No plasmids
Mitochondria not present	Mitochondria always present
Ribosomes smaller (70S)	Ribosomes larger (80S)

Remember that in a **compare and contrast** question in the exam, you only get a point for differences if you give the alternative for each thing being compared. So it is not enough to say Prokaryotes have DNA at the nucleoid region, but you must also mention that Eukaryotes have DNA enclosed in the nuclear membrane.

Besides in their structure, the two types of cells also differ in their mode of division. Eukaryotic cells divide by **mitosis** (discussed later) while prokaryotic cells divide by **binary fission**.

1.2.2 Cell membrane

Cell membrane Cell membranes are an assembly of different components that encloses cells. This includes phospholipids, cholesterol, proteins, and lipoproteins.

Phospholipids molecules composed of a glycerol head with a negatively charged phosphate group and two hydrocarbon lipid tails. This makes phospholipids amphipathic, meaning that they have two opposite properties:

- Their heads are hydrophilic (water loving) making them polar.
- Their tails are hydrophobic (water hating) making them non-polar.

Make sure you can draw and label a phospholipid diagram (Figure 1.4).

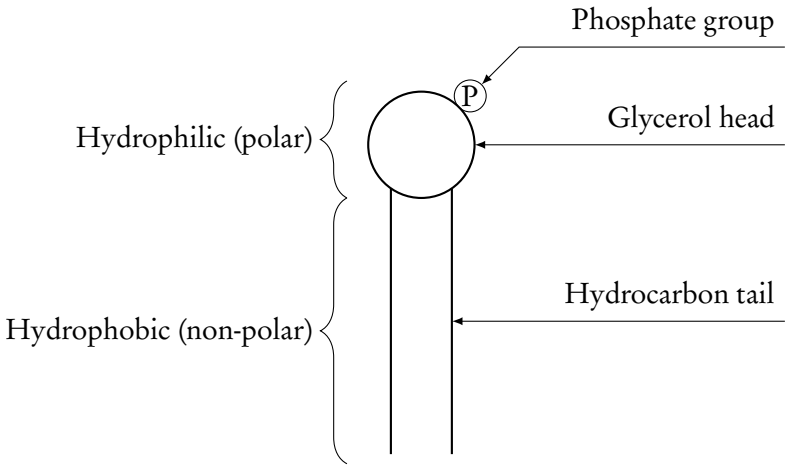


Figure 1.4: Phospholipid diagram.

This will usually give you an extra point in essay questions concerning the plasma membrane.

Notice the head / tail structure of the phospholipid: their amphipathic properties cause them to spontaneously arrange into a bilayer in an aqueous environment. This is due to the fact that water is polar, and therefore the hydrophobic, non-polar portion of the phospholipids will want to be shielded from water by the hydrophilic, polar heads of the phospholipids.

Due to these interactions, the plasma membrane is very stable but is said to be **fluid**. This means that the tails will always be facing tails, and the heads will always face outside, but the position of individual phospholipids in a layer may change.

This property of the membrane also allows it to hosts a variety of other molecules, like proteins and cholesterol. This makes it look like a **mosaic**.

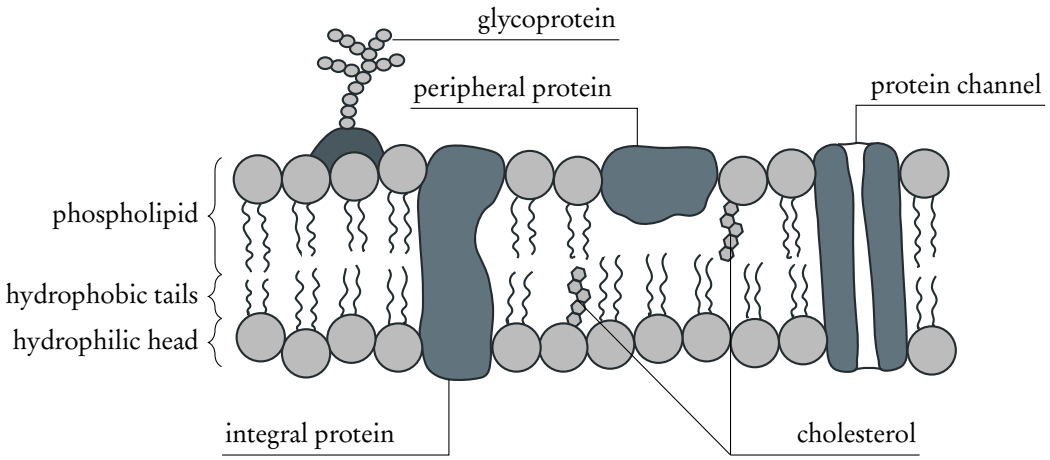


Figure 1.5: Phospholipid molecules form a phospholipid bilayer, which together with proteins and cholesterol forms cell membranes.

Cholesterol keeps the fluidity of the membrane constant at a variety of temperatures. When it is cold, it increases fluidity and when hot, it makes the membrane more rigid. This is important to maintain a constant environment for cellular processes to occur.

Integral Proteins span the lipid bilayer and are permanently attached to it by polar interactions with the phospholipid heads and nonpolar interactions with the tails. These can be for example receptors or transport proteins.

Peripheral Proteins are attached to the inner or outer side of the membrane by non-covalent interactions with the surface of the membrane or other integral proteins. These are for example enzymes attached to the outside of cells.

Membrane proteins fulfill various functions:

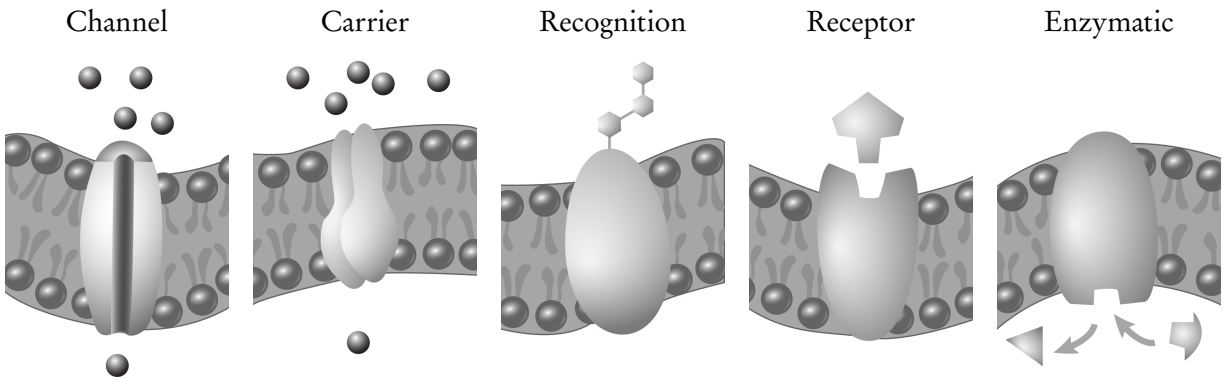


Figure 1.6: Phospholipid molecules form a phospholipid bilayer, which together with proteins and cholesterol forms cell membranes.

1.2.3 Membrane transport

The lipid bilayer membrane is semi-permeable and selective, which means that

Semi-permeable: only certain molecules (small, polar) can freely cross the membrane
Selective: with the use of transport proteins, it can select what comes in and out and what does not

Recall that the main function of the plasma membrane is transport. Generally, transport is defined as passive or active.

Active transport movement of molecules from an area of lower concentration to an area of higher concentration, with the use of energy (against the concentration gradient)

Passive transport movement of molecules from an area of higher concentration to an area of lower concentration (down the concentration gradient)

Passive transport is further divided into two types of diffusion, simple and facilitated.

Simple diffusion passive transport of molecules through a membrane, without the need of protein channels (oxygen diffusion)

Facilitated diffusion passive transport of molecules **facilitated** by channel or carrier proteins (sodium transport, calcium transport)

Osmosis is a form of passive transport that only refers to the movement of water. The water, like other particles in passive transport, moves from the area where there is more of it, to the area where there is less of it. However, osmosis is defined in terms of the concentration of dissolved molecules:

Osmosis movement of water from the area of low solute concentration to the area of high solute concentration.

Active transport, like (passive) facilitated diffusion requires proteins. However, these proteins use energy in form of ATP to pump molecules against their concentration gradient. There are two types of active transport:

Primary: direct use of metabolic energy for transport of molecules against concentration gradient.

Secondary: coupling the movement of one molecule against the concentration gradient with the movement of another along the concentration gradient of the second molecule, often created by primary active transport.

Sodium-potassium pump is such a protein, and can be found in many cells including neurons. This pump is described in more detail in the "Human physiology" chapter, but now consider the following points:

- sodium potassium pump is an integral protein that uses ATP to transport molecules across a membrane;
- it transports sodium out of the cell, and potassium into the cell;
- it works against the concentration gradients of both sodium and potassium;
- for every three sodium molecules it transports out, two potassium molecules are transported in.

You should consider two more types of active transport that involve vesicle transport, rather than protein pumps.

Exocytosis Exocytosis: Transport of molecules in secretory vesicles that fuse with the plasma membrane upon contact to release the contents outside of the cell

Endocytosis transport of molecules into the cell through invagination of the plasma membrane and formation of the phospholipid vesicle containing the molecule.

1.2.4 Osmolarity

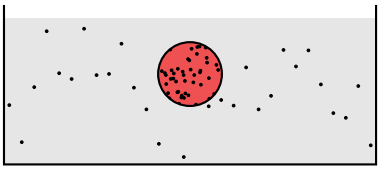
Osmolarity Is a measure of solute concentration (osmol/L) in a given system. A system can be a Petri dish, a cell, an organism, etc.

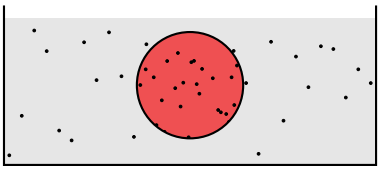
Hypotonic low osmolarity, or low solute concentration, meaning that the system loses water

Hypertonic high osmolarity, or high solute concentration, meaning that the system will gain water

Imagine a potato cube in a water bath. Mind you that the potato has a much smaller volume compared to that of the water tank.

Hypotonic





The ratio of solutes to water inside the potato is much higher than that same ratio in a water bath.

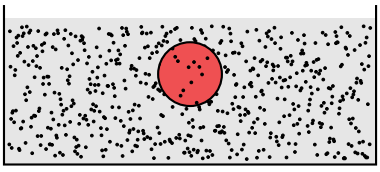
The bath is *hypotonic* compared to the potato.

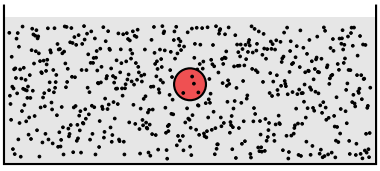
The water moves from the bath into the potato, making the potato swell.

The ratio of water to solute in the potato is the same as the one in the bath.

Recall that in osmosis, the water moves from where there is more of it to where there is less of it

Hypertonic





The water bath is more saturated with its solute compared to the potato.

The bath is a *hypertonic* solution compared to the potato.

The water inside the potato will pass into the water bath, trying to dilute it to the same concentration as in the potato.

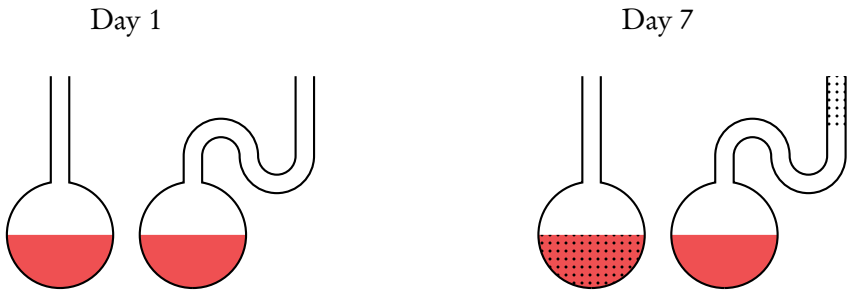
The potato will shrink, its ratio of solute to water will increase and the osmolarities will be balanced.

1.3 Origin of cells

1.3.1 Pasteur's soup

A prior belief was that cells could spontaneously arise from the assembly of inorganic matter. However, Louis Pasteur disputed the belief of spontaneous formation of life in the 19th century.

In his simple experiment, he filled two flasks with nourishing soup, a medium highly nutritious for microorganisms to thrive, and then sterilized them. One flask had a straight open neck, while the other had a curved opened neck. Within a week, the straight-necked soup was spoiled and the curved-necked soup was as good as it was on the first day.



The germs found in the spoiled soup, could be found at the entrance of the curved necked, where they got stuck. Therefore, the mould, fungi and bacteria were able to enter the soup from the environment, but were not able to assemble from thin air in the sealed container.

1.3.2 Formation of organic molecules

In order to form cells, first we have to form (relatively) complex molecules.
The Miller–Urey experiment showed that:

- water vapour, ammonia and methane, all found in the early atmosphere, could have spontaneously assembled into amino acids and carbon compounds, in the presence of electricity (lightning);
- if some of the compounds formed at that time on earth were phospholipids, they would have naturally assembled into bilayers, forming early membranes;
- the formation of nucleic acids such as RNA would have given rise to early enzymatic activities, protein assembly and the first genetic information.

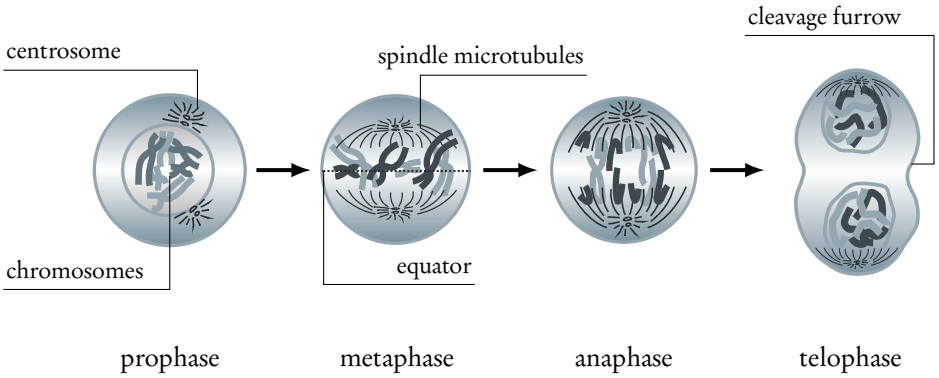
1.3.3 Endosymbiotic theory

Next, this theory assumes that more complex eukaryotic cells have evolved from the prokaryotic cells through a symbiotic process.

- Symbiosis is a mutually favourable coexistence of two organisms.
- The theory suggests that a larger anaerobic prokaryotic cell could have engulfed a smaller aerobic cell, and started coexisting with it.
- The large cell was supplying the smaller one with food, while the smaller cell was converting the food into energy for the larger cell → symbiosis.This would have given rise to mitochondria and chloroplasts.
- Unlike the rest, these organelles are bounded by a double membrane. The two membranes would be the vesicle from endocytosis and the cell membrane of the engulfed cell.
- Mitochondria and chloroplasts contain plasmid-like, circular DNA (characteristic of prokaryotes) that has genes independent from those found in the eukaryotic nucleus. These are thought to be conserved genes from the original engulfed cell.

1.4 Cell division

Mitosis is the division of the cell's nucleus into two identical daughter nuclei containing the same number of chromosomes as the mother cell.



The function of mitosis is to create two genetically identical daughter cell with the genome of the mother cell. The process involves replication (=duplication) of DNA (all chromosomes). In order for separation of duplicated DNA to work, the DNA (normally

a very long molecule) needs to *supercoil*. Replication is said to be proofread and checked for errors by the cell's machinery.

Remember that mitosis occurs only in eukaryotic cells, while prokaryotic cells divide by binary fission.

Cytokinesis is the division of the cell's cytoplasm and organelles that directly follows mitosis

In plant and animal cells, the process of cytokinesis differs. In plant cell, the kinesis results from the transport of vesicles to the cell equator leading to their eventual fusion and formation of the plasma membrane. The vesicles bring cellulose to form the cell wall around the newly formed plasma membrane. In animal cells, the division of cytoplasm is a result of an invagination of the plasma membrane. Actin and myosin are the contractile fibres that create this invagination called cleavage furrow.

1.4.1 Cell cycle

From its formation, until division, each cell goes through several phases of the life cycle.

- G1 is the phase in which cells spend the majority of their lifespan: this is the period of growth and performance of its daily functions.
- S is the phase that occurs once the cell has decided to undergo mitosis: this is the period of DNA synthesis (replication)
- G2 is the phase where the cell does its last preparations for mitosis: during G2, the cell duplicates its organelles and prepares enzymes and proteins needed for mitosis
- A tip to remember the phases is to know them as G(rowth)1, S(ynthesis of DNA), and G(rowth)2.

Cyclins are proteins that regulate the cell cycle.

The name cyclin should help you remember that the concentrations of these proteins go through cycles or vary throughout the cell cycle in response to internal and external signals. An increase or decrease in the concentration of cyclins will influence the progression of the cell cycle.

- Cyclins comprise the cell cycle checkpoints

- The first cell cycle check point occurs between G1 and S phase
- Another checkpoint occurs during S phase before the beginning of DNA replication
- If the cyclins are not produced or activated, the cell cannot pass a cell cycle checkpoint

Cyclin dependent kinases (CDKs) are enzymes whose activity is dependant on the concentrations of cyclins. It is CDKs which ultimately allow progression through a stage of the cycle via phosphorylation specific molecules.

Despite this tightly regulated cell cycle system, some cells manage to escape the checkpoints and form tumours.

Cancer is the result of uncontrollable cell division and tumours are the aggregates of cancerous cells.

- Mutagens are agents that cause mutations in the DNA.
- Some of these mutations can be missed by proofreading machinery leading to gene mutations
- UV light is a known mutagen that cause high rate of DNA mutations that can often not be repaired
- Oncogenes are genes of each cell that are responsible for normal cell division. They are called oncogenes, because a mutation in these genes can lead to the formation of cancer
- If these genes are mutated, they often lead to cancer
- Proto-oncogenes are oncogenes that in their mutated state become overactivated and promote cell division leading to tumour formation
- Tumour suppressor genes are genes that negatively regulate the cell cycle, so when mutated, they fail to prevent uncontrollable cell divisions
- Metastasis refers to the movement of the primary cancerous cells to a new formation where they continue to form tumours.

1.4.2 Phases of mitosis

Mitosis consists of 4 phases that can be distinguished under the microscope. Due to supercoiling of the DNA, the chromosomes become visible and can be tracked during these phases.

Prophase

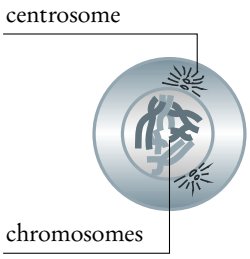


Figure 1.7: Prophase: nuclear envelope is fractured, chromosomes are becoming thick, centrioles are located and the poles of the cell.

- DNA supercoils, chromosomes condense and become visible.
- Nuclear envelope breaks down.
- Spindle microtubules start forming at the poles of the cell.
- The cell contains double the DNA compared to its G1 phase, the same number of chromosomes.
- Begins after S phase has occurred

Metaphase

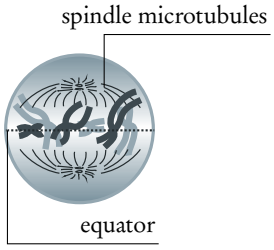


Figure 1.8: Metaphase: chromosomes located at the equator of the cell, each X representing a chromosome, and they're ordered in one single row. Spindle fibres originate at the poles and attach to centres of X-es each pole, with one chromosome having one spindle from each pole.

- Chromosomes align at the equator of the cell.
- Spindle microtubules attach to the centromeres (centres of the chromosome).

Anaphase

Figure 1.9: Anaphase: fibres are shortening towards the poles, and dragging one leg of the X towards the pole. Equal number of chromosome legs are moving to each pole.

- Sister chromatids (legs of each chromosomes, containing identical copies of DNA) are pulled to opposite poles by spindle microtubules.
- Now there is an equal number of chromosomes (DNA molecules) at each pole, but overall, the cell now has double the number of chromosomes compared to prophase.

Telophase

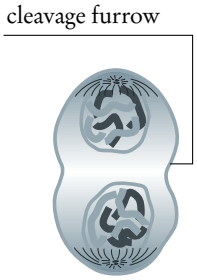


Figure 1.10: Telophase: two nuclei beginning to form at each pole, and the chromosomes uncoiling and becoming longer.

- Chromosomes begin to uncoil as the nuclear envelope reforms around them.
- The cell contains two identical nuclei and awaits the division of cytoplasm and organelles (= Cytokinesis).

When observing a tissue or a group of cells under a microscope, it is easy to calculate the rate of division of the cells/tissue in question. This is done by the following formula:

$$\text{Mitotic index} = \frac{\text{number of cells undergoing mitosis}}{\text{total number of cells}}$$

MOLECULAR BIOLOGY

2

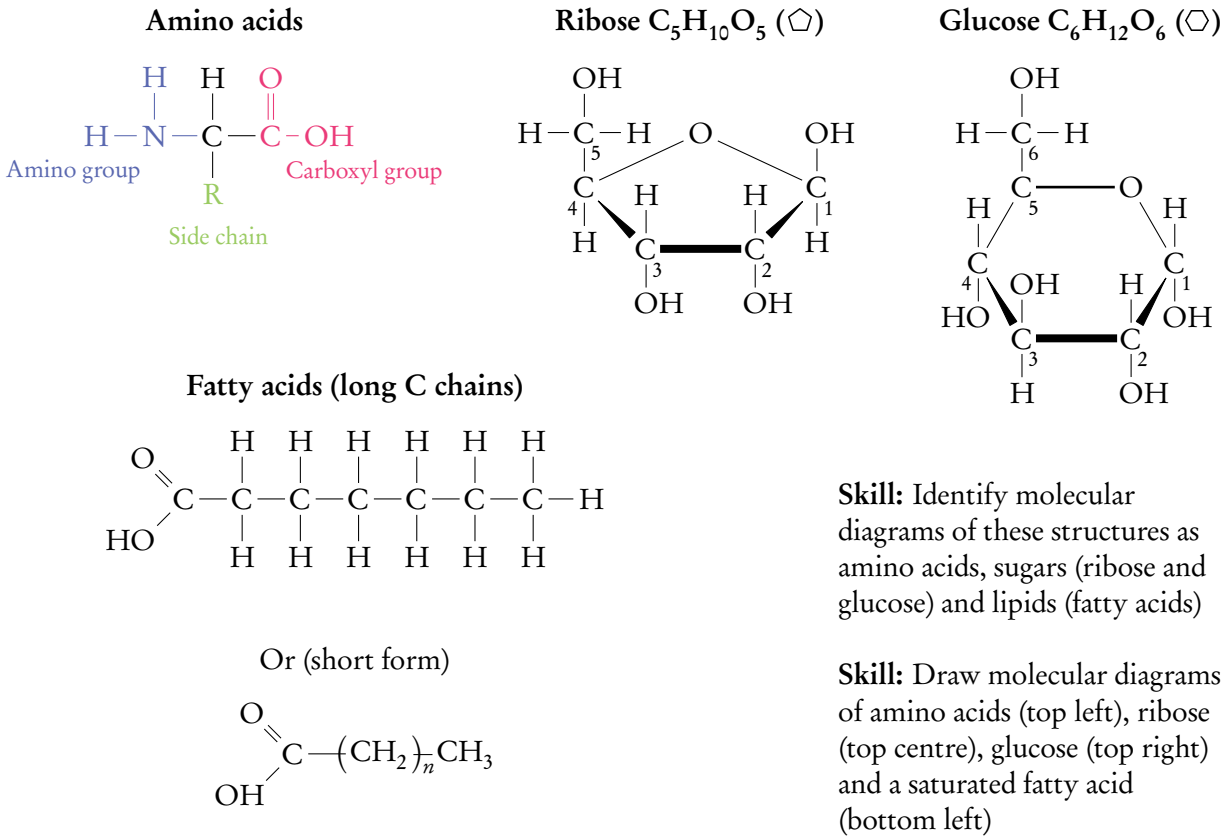
2.1 Molecules to metabolism

2.1.1 The carbon atom: the core of organic compounds

The field of molecular biology aims to explain living processes in terms of the chemical substances involved. The most frequently occurring chemical elements in living things are carbon, hydrogen, oxygen and nitrogen. Carbon (C) in particular is a very important element in the study of living things, as:

- all organic compounds contain C (few exceptions like CO_2 and CO)
- C can form four covalent bonds, and thus allows for the formation of a wide variety of stable and complex compounds
- some of these organic compounds essential for life include carbohydrates, proteins, lipids and nucleic acids.

A diagram of these four types of molecules can be found in Figure 2.1.



Skill: Identify molecular diagrams of these structures as amino acids, sugars (ribose and glucose) and lipids (fatty acids)

Skill: Draw molecular diagrams of amino acids (top left), ribose (top centre), glucose (top right) and a saturated fatty acid (bottom left)

Figure 2.1: Molecular diagrams.

2.1.2 Metabolism

Metabolism is a web of all the enzyme-catalysed reactions in a system (e.g., cell or organism). Metabolic pathways can consist of chains or cycles, and can be anabolic or catabolic.

Anabolism

Synthesis of complex molecules from simpler ones, for example, the formation of macromolecules from monomers by condensation reactions.

Anabolism is associated with condensation reactions, which consist of the removal of a water molecule each time a monomer is added to a polymer chain or another monomer.

E.g., amino acids → polypeptide + water.

Catabolism

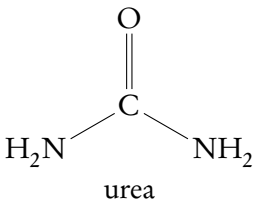
The breakdown of complex molecules into simpler ones, for example, the hydrolysis of macromolecules into monomers.

Catabolism is associated with hydrolysis, which consists of the addition of water molecules to break down a polymer.

E.g., dipeptide + water → 2 amino acids.

Example.

Urea: endogenous molecule or artificially produced toxic compound?



urea

In earlier days, organic molecules were believed to be solely synthesized in living organisms. Because urea is an organic compound synthesized in the kidneys as a waste product, it was believed to only be an endogenous molecule. In the early 1800s however, researchers first managed to synthesize artificial urea using silver isocyanate and ammonium chloride. Nowadays it is used as a nitrogen-releasing fertilizer, as well as in the automobile industry and for medical use.

2.2 Water

2.2.1 Water: molecular and chemical characteristics

Water is an essential molecule for life on Earth. It is a polar molecule that consists of 2 hydrogen atoms bound by covalent bonds to an oxygen atom. The principle of covalent bonding consists of sharing of electrons between atoms. It is this bonding gives water its most important characteristic for living organisms: being polar. This polarity arises as water has a slightly positively charged pole where the hydrogen atoms are located and a slightly negatively charged pole where the oxygen atom is located.

Polar molecule is a molecule that has an uneven distribution of charges across the molecule. For example, it is more negative at one end and more positive at another.

Non-polar molecule is a molecule that has an even distribution of charges across the molecule, so no positive or negative poles are formed

Due to the polarity of water molecules, the small negative charge on the oxygen atom has the ability to attract the slightly positively charged hydrogen atoms in nearby hydrogen atoms from other molecules. This attraction leads to the formation of hydrogen bonds between molecules and can explain a number of properties of this molecule, including thermal, cohesive, adhesive and solvent properties.

It is important to remember that in water, covalent bonds are formed between a hydrogen and an oxygen of the same molecule, while hydrogen bonds are found between a hydrogen from one molecule and an oxygen from another

2.2.2 Thermal, cohesive, adhesive, and solvent properties of water

Thermal properties

High specific heat capacity: large amounts of energy are needed to raise the water's temperature. Hydrogen bonds are said to be the strongest of the weak bonds as they restrict movement, meaning it takes a lot of energy to break them down

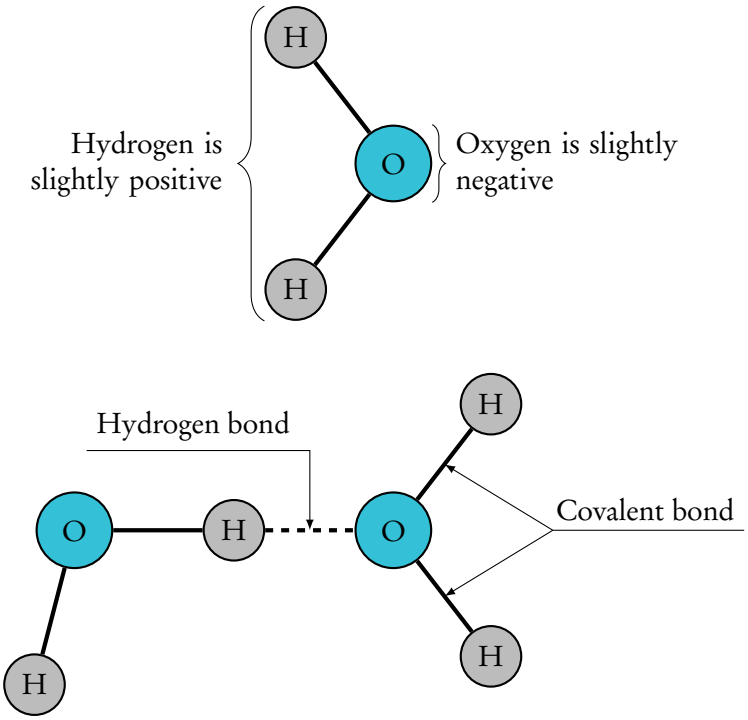


Figure 2.2: Diagrams showing the molecular structure of water (top) and the hydrogen bonds between two water molecules (bottom).

High latent heat of vaporization: hydrogen bonds between water molecules in a liquid form make it very hard for single molecules to escape as vapour. The energy necessary to break these hydrogen bonds and vaporize water is very high compared to other liquids (100 °C). When water vaporizes, a large release of energy occurs, causing a cooling effect on the surface upon which the water used to rest. The concept of sweating as a cooling effect demonstrates this: all the energy used to break hydrogen bonds is released, cooling the skin.

High latent heat of fusion: water at 0 °C must lose a lot of energy before forming ice crystals. Water expands as it freezes and therefore ice can float upon its surface.

Cohesive properties

Water molecules can stick to each other through the formation of hydrogen bonds between the hydrogen of one and the oxygen of another water molecule.

Can explain the formation of water droplets, why some organisms can “walk on water”, etc.

Adhesive properties

Water can adhere to charged surfaces through the formation of hydrogen bonds due to its polarity.

Solvent properties

Water is an excellent solvent for other polar molecules that attract the charged poles of water molecules (e.g., inorganic molecules with positive or negative charges, polar organic molecules, enzymes, etc.). Water can form bonds around other polar compounds, such as NaCl, separating them. Compounds and molecules that dissolve in water are referred to as hydrophilic. Water can also form hydrogen bonds around molecules whose elements are tightly bonded and thus acts as an ideal transport medium for polar molecules (like glucose in blood)

2.2.3 Hydrophilic vs. hydrophobic substances

Hydrophilic ("water-loving") are all molecules that can readily dissolve in water and can freely associate with it by forming intramolecular bonds. These include polar molecules and ionic compounds

Hydrophilic compounds can readily dissolve in water.

Hydrophobic ("water-hating") are all molecules that cannot associate with water molecules or easily dissolve in it. These include large and non-polar molecules.

These molecules tend to be insoluble in water.

The hydrophilic and hydrophobic nature of compounds, as well as the solvent property of water, are essential in the transport of molecules in blood for example (which has a high water content). Below is the mode of transport of various important molecules based on their solubility in water:

- Glucose and amino acids are polar, so they can be freely transported and dissolved in blood.
- Cholesterol and fats are non-polar so they are transported in small droplets called lipoproteins, where these non-polar molecules are coated by phospholipids and proteins, which are in turn, polar themselves.
- Oxygen is non-polar, and while some molecules can dissolve in water, they are not sufficient to supply the entire body, therefore, most oxygen is transported in the blood bound to haemoglobin.

A good molecule used to illustrate the importance of the polarity of water and hydrogen bonding for living organisms is methane.

Methane, as opposed to water, has four hydrogens bound to its central atom (in this case a carbon). This causes methane to have an even distribution of charges across the molecule, or a tetrahedral Lewis structure in comparison to water's bent Lewis structure, making it non-polar. This non-polarity gives methane very different properties than those previously discussed for water, and these can demonstrate the vital role of the polarity of water. The latter is shown in Figure 2.3.

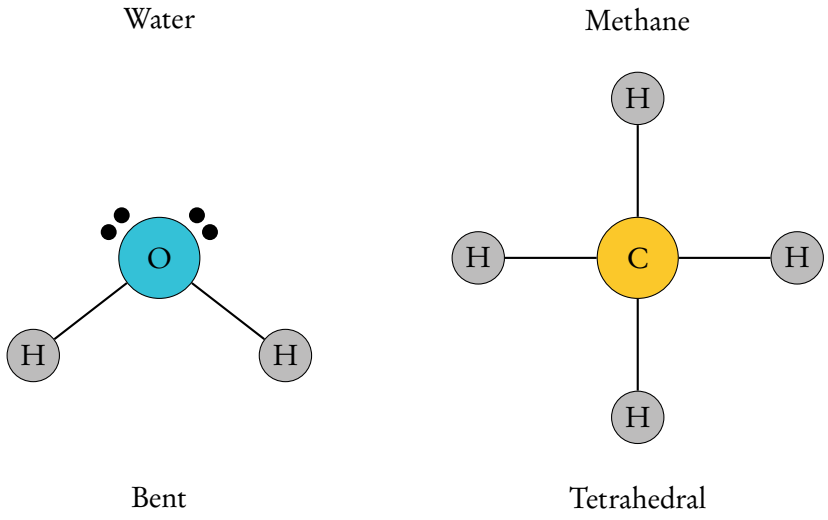


Figure 2.3: Water vs. Methane.

Example.

Comparing thermal properties of water and methane

Property	Methane	Water	Explanation
Melting point	−182 °C	0 °C	Ice melts at a much higher temperature: hydrogen bonds restrict the movement of water molecules and heat is needed to overcome this.
Specific heat capacity	2.2 J/(g °C)	4.2 J/(g °C)	Water's heat capacity is higher: hydrogen bonds restrict movement so more energy is stored by moving molecules of water than methane.
Latent heat of vaporization	760 J/g	2257 J/g	Water has much higher heat of vaporization: much heat energy is needed to break hydrogen bonds and allow a water molecule to evaporate.
Boiling point	−160 °C	100 °C	Water's boiling point is much higher: heat energy is needed to break hydrogen bonds and allow water to change from a liquid to a gas

2.3 Carbohydrates and lipids

2.3.1 Carbohydrates

Carbohydrates are organic molecules composed of hydrogen, oxygen, and carbon atoms. Monosaccharides are the monomers of carbohydrates, and are therefore the building blocks of more complex carbohydrates.

Monomer is the building block or basic unit of a class of compounds that can be polymerized to make larger compounds

Dimer is a compound made from the bonding of two monomers

Polymer is two or more repeated monomers from a class of compounds bound together, forming a more complex molecule

The most important carbohydrates from monomers to polymers are shown in the table bellow:

- monomer = monosaccharide
- dimer = disaccharide
- polymer = polysaccharide

Table 2.1

Monosaccharide	Glucose (G)	Fructose (F)	Galactose (Ga)
Disaccharides	Maltose (G+G)	Sucrose (G+F)	Lactose (G+Ga)
Polysaccharides (all polymers of G)	Cellulose	Glycogen	Starch/Amylose/Amylopectin

2.3.2 Lipids

Lipids are hydrophobic compounds that have important functions in:

- Long term energy storage.
- Heat insulation.
- Buoyancy.
- Shock absorption

The main monomers of lipids are fatty acids: long hydrocarbon chains with a carboxyl group at the end. Fatty acids may be:

Saturated: all the carbon atoms in the fatty acid chain are connected by single covalent bonds, so the number of hydrogen atoms connected to each carbon cannot be increased.
Monounsaturated: there is one double bond between two carbon atoms in the fatty acid chain.
Polyunsaturated: there is more than one double bond between the carbons in the fatty acid chain.

Unsaturated fatty acids can be:

Trans unsaturated: hydrogen atoms are bonded to carbon on the opposite sides of the double bond.
Cis unsaturated: hydrogen atoms are bonded to carbon on the same side of the double bond.

There are three main classes of lipids: phospholipids (important membrane components) steroids (cholesterol and hormones) and triglycerides (long-term energy storage). We will look at the formation of triglycerides, important in energy storage, by means of a condensation reaction.

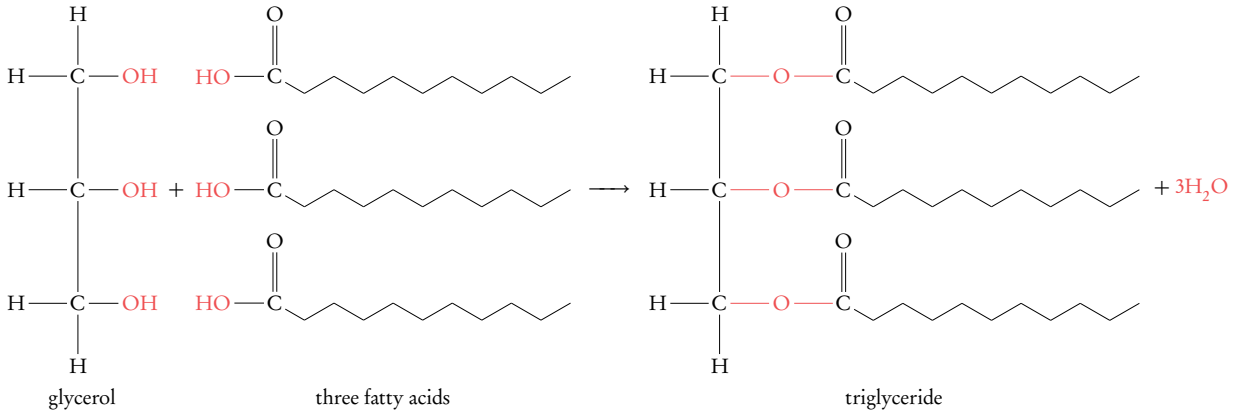


Figure 2.4: Triglyceride formation.

Both lipids and carbohydrates are suitable for energy storage. However, each is more suitable for a specific function:

Carbohydrates

- More easily digested than lipids, good for energy storage that needs to be more rapidly released.
- Soluble in water → easier to transport in blood.

Lipids

- Can store more energy per gram than carbohydrates → better for long term energy storage.
- Not soluble in water, also harder to break down and transport around the body (build-up of high energy content fats).

Example.

Health issues associated to trans- and saturated fatty acids

Trans fats have been banned in several countries in the world, as there is a positive correlation between a diet high in trans fats and coronary heart disease.

Saturated fats have also been shown to have a positive correlation (albeit, weaker than trans fats) with the incidence of coronary heart disease.

However, many of the tested populations do not fit these findings, so evidence must be carefully evaluated before banning products and establishing anti trans or saturated fat campaigns.

Example.

Determining the body mass index (BMI)

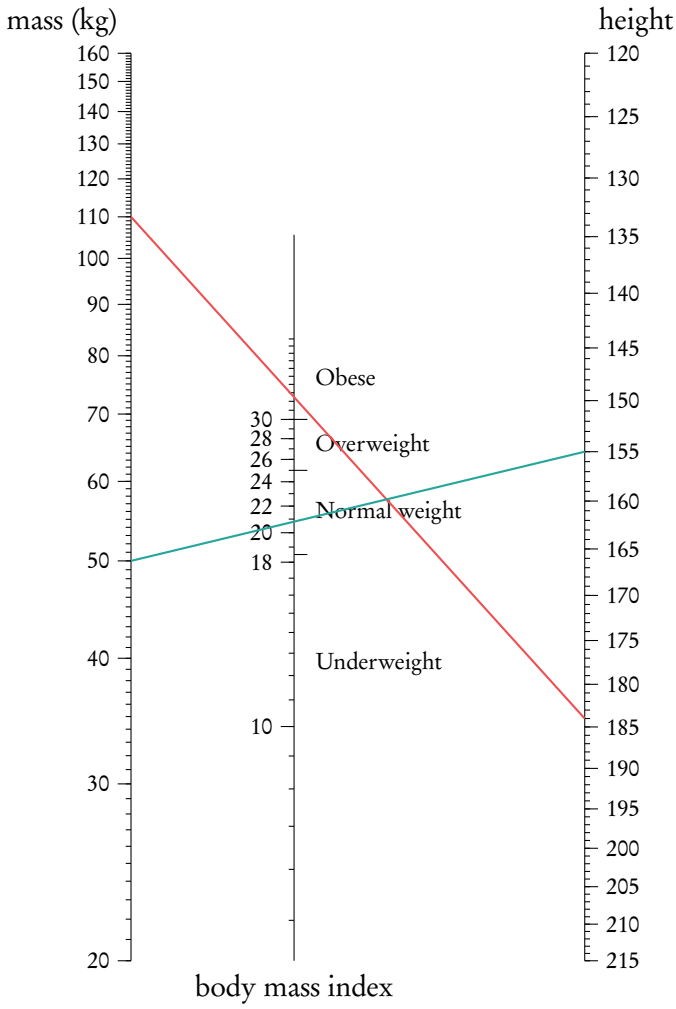
Because of the natural variation in size between adults, weighing someone does not provide a clear indicator of body mass. The body mass index is a screening tool to identify possible weight problems, and it can be calculated using the following formula:

$$\text{BMI} = \frac{\text{mass in kg}}{(\text{height in meters})^2}$$

where:

Body mass index	Conclusion
Below 18.5	Underweight
18.5 to 24.9	Normal weight
25.0 to 29.9	Overweight
30.0 or more	Obese

A nomogram can also be used to calculate BMI, by drawing a line that connects the height and weight lines, the BMI measure is indicated by the scale in the middle.



$$\text{BMI} = \frac{50\ (\text{kg})}{1.55^2\ (\text{m})} = 20.81$$

$$\text{BMI} = \frac{110\ (\text{kg})}{1.84^2\ (\text{m})} = 32.49$$

2.4 Proteins

2.4.1 Amino acids: the building blocks of proteins

Amino acids, containing a carboxyl, an ammine and an R group, are the monomers of proteins that when linked together by peptide bonds form complex proteins. Proteins are important organic molecules that carry out major functions in cells and in the extracellular space.

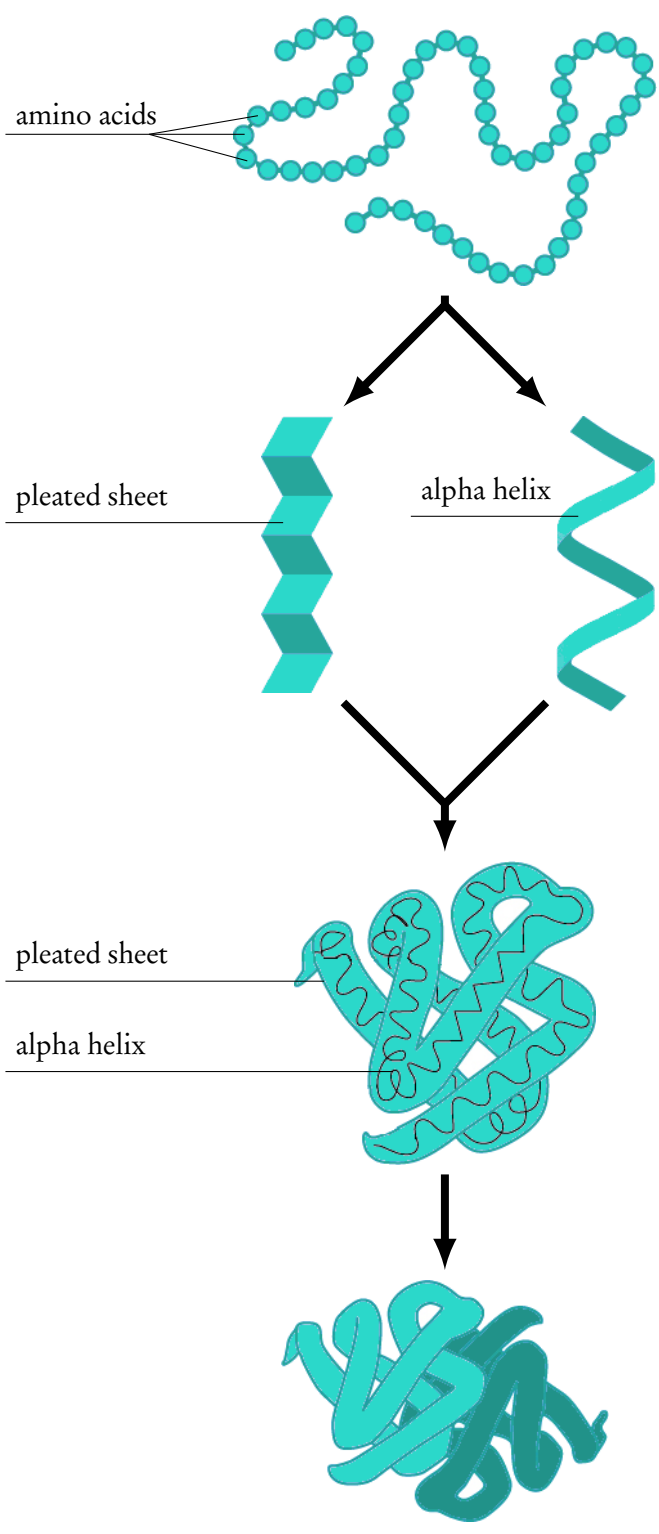
Although there are only 20 different amino acids, millions of proteins exist as these monomers can be linked in any given sequence

This means that if you have a protein made of n amino acids, there are 20^n different proteins that may be made.

The specific sequence of each protein is coded for in the genetic material of the organism. As we will see later in the chapter, DNA is transcribed into mRNA and later translated by ribosomes into polypeptide chains.

The Central Dogma of molecular biology states that there is a sequential transfer of information where DNA is transcribed into RNA, which in turn is translated into proteins.

From amino acids to polypeptides, there are 4 discrete levels of organization recognizable in proteins.



Primary structure

Consists of a string of amino acids (the amino acid sequence)

Secondary structure

Formation of alpha helices and beta pleated sheets. This organization is stabilized by the formation of hydrogen bonds.

Tertiary structure

Formation of the 3D structure of the polypeptide. This occurs due to interactions between the R groups of the amino acids. These include: disulphide bridges, hydrogen bonds, van der waal interactions, and ionic bonds.

Quaternary structure

Multiple polypeptide chains combined to form a single protein.

Figure 2.5: Protein organisation.

2.4.2 The peptide bond: from amino acids to polypeptides

Figure 2.6 is a diagram showing the formation of a dipeptide (a 2-amino acid molecule) via a condensation reaction, and the breakdown of a dipeptide into two amino acids. The condensation reaction creates a covalent, peptide bond between the carboxyl group of one amino acid and the amino group of the other, and results in the release of a water molecule. In the hydrolysis reaction (Figure 2.7), water is added in order to break the peptide bond.

You need to be able to identify the peptide bond!

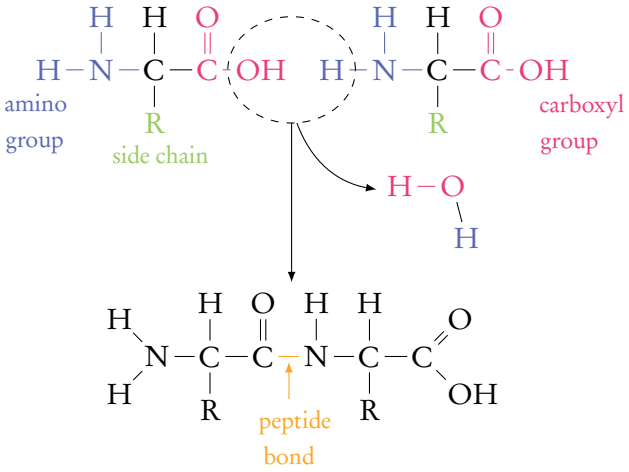


Figure 2.6: Condensation.

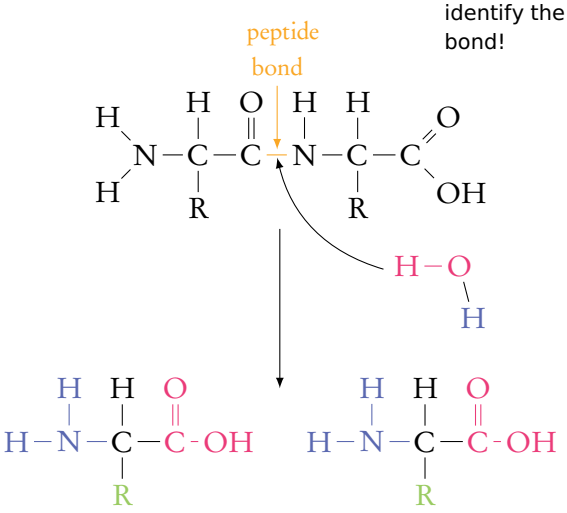


Figure 2.7: Hydrolysis.

2.4.3 Functions of proteins

Table 2.2 depicts some of the major functions proteins carry out in an organism, as well as specific examples for each function.

Table 2.2: Protein functions.

Function	Example	Details	Shape
Structural	Collagen	Strenghen bone, tendon and skin	Fibrous
Transport	Hemoglobin	Bind oxygen in the lungs and transports to other tissues	Globular
Movement	Actin	Involved in the contraction of muscles	Fibrous
Defence	Immunoglobulins	Acts as antibody	Globular

2.4.4 Proteomes: the fingerprints of cells

Proteome is the entire set of proteins expressed by a genome, cell, tissue, or organism at a given time. While the genetic make up of an organism is the same in all cells, each tissue or individual cell shows variable gene expression and thus different proteins are created. The proteome of individuals within the same species is quite similar (as the genetic make up is also similar), however, each individual has a unique proteome (like a fingerprint, which can be similar but never identical to other individuals).

2.5 Enzymes

2.5.1 Concepts and definitions

Enzymes are globular proteins that function as biological catalysts that speed up chemical reactions in biological processes.

- Substrates are substances acted upon by enzymes.
- Active site is the region on the enzyme to which substrates bind and where catalysis occurs.
- The activity of enzymes relies on the concepts of molecular motion and collision, in other words, substrates and enzymes must "collide" with one another due to their individual motion (kinetic energy). The more collisions between enzyme and substrate, the faster the reaction occurs.
- Enzymes speed up reactions without getting consumed by the process, meaning they can speed up many reactions.

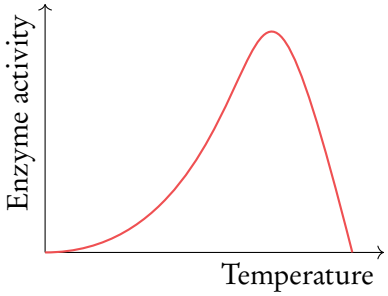
There are two main models that aim to explain the mechanism of action of enzymes:

The Lock-and-key model: the substrate and enzyme have shapes that make them fit perfectly with each other. Thus, each enzyme catalyses a specific reaction

The Induced-fit model: as substrate and enzyme approach each other, their interactions make them shift physical conformation so that they fit perfectly with one another.

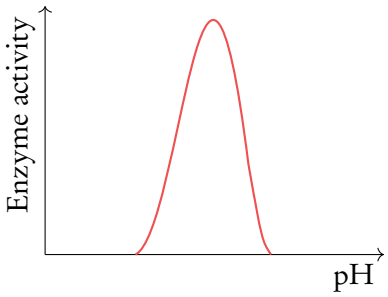
2.5.2 Influencing enzyme activity: temperature, pH and substrate concentration

Temperature



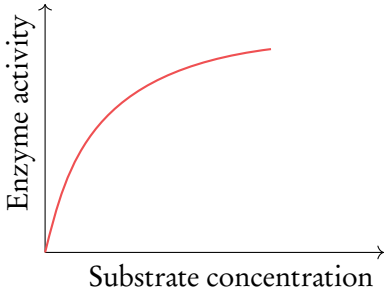
Enzyme activity increases as temperature increases, often doubling with every 10 °C rise. This is because collisions between substrate and active site happen more frequently at higher temperatures due to faster molecular motion.
Enzymes are proteins, therefore at high temperatures they are denatured and stop working. This is because heat causes vibrations inside enzymes which break bonds needed to maintain the structure of the enzyme.

pH



Enzyme activity is reduced as pH increases above the optimum because the conformation of the enzyme is altered more and more. Above a certain pH the alkalinity denatures the enzyme and it does not catalyze the reaction at all.
Enzyme activity is reduced as pH increases above the optimum because the conformation of the enzyme is altered more and more. Above a certain pH the alkalinity denatures the enzyme and it does not catalyze the reaction at all.

Substrate concentration



At low substrate concentrations, enzyme activity increases steeply as substrate concentration increases. This is because random collisions between substrate and active site happen more frequently with higher substrate concentrations.
At high substrate concentrations most of the active sites are occupied, so raising the substrate concentration has little effect on enzyme activity. A plateau is reached when enzymes are working at full capacity at their maximum rate

Example.

The use of lactase in the production of lactose-free milk

Many enzymes are used in industrial processes (for instance, in the food industry). Enzymes are often immobilized on a surface and employed in large concentrations to catalyse a wide range of biochemical reactions. A common example is the use of enzyme lactase in the production of lactose-free milk.

Lactose is the disaccharide in milk that many people are intolerant to as they do not produce the enzyme lactase to break it down. Often times milk and other milk products are treated with immobilized lactase, and lactose is broken down prior to consumption. The resulting monosaccharides are easier to digest by lactose-intolerant people, and result in a sweeter flavour (less artificial additives needed). The use of the enzyme also speeds up the production of fermented products like yogurt and cheese.

Immobilized lactase can be used in much larger concentrations and can resist larger changes in pH and temperature compared to endogenous lactase.

The immobilized enzymes can also be reused, and the products are not contaminated with enzymes (easier to introduce and remove from the sites of reaction.

2.6 Structure of DNA and RNA

2.6.1 Nucleotide structure

Nucleic acids are the biomolecules responsible for information storage, essential to all forms of life. The two major types of nucleic acids DNA (deoxyribonucleic acid) and RNA (ribonucleic acid) are essential compounds involved in gene expression in cells. RNA and DNA polymers consist of repeated units of nucleotides, which are in turn made of a 5 carbon sugar linked to a phosphate group at carbon 5, and to one of five nitrogenous bases (adenine, guanine, thymine, uracil and cytosine) at carbon 1. The overall nucleotide structure is shown in Figure 2.8.

Skill: Draw a simple diagram of the structure of single nucleotides (you may use simple circles for the phosphate, pentagons for the sugar [deoxyribose or ribose] and rectangles for the base).

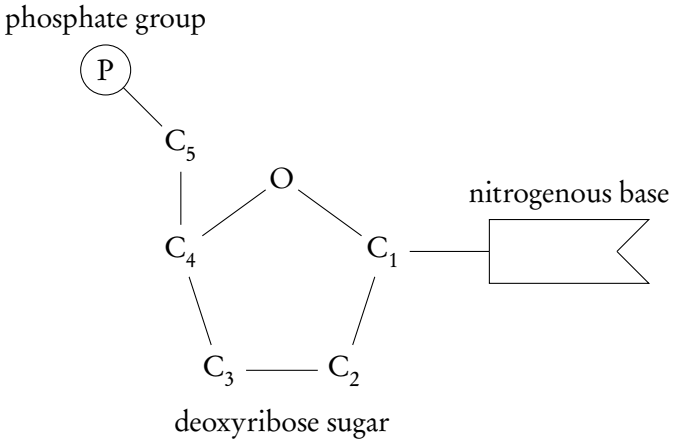


Figure 2.8: Nucleotide structure.

The nucleotide can have either a ribose (RNA) or a deoxyribose (DNA) pentose sugar. These differ in the presence or absence of an oxygen molecule. This oxygen molecule makes ribose a less stable molecule than deoxyribose, due to the fact that oxygen has high electronegativity, meaning that it really wants to more electrons. This instability causes RNA to be single stranded while DNA can be double stranded.

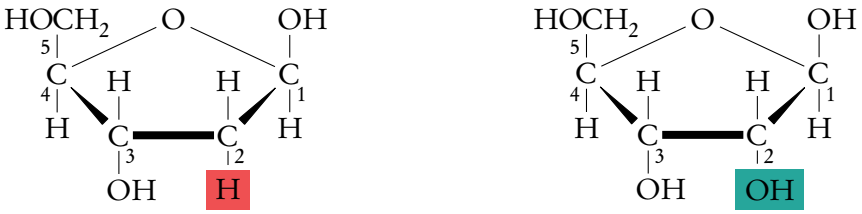


Figure 2.9: Deoxyribose and ribose.

2.6.2 DNA vs. RNA

Both types of nucleic acids share structural similarities, but also significant differences:

RNA

- Contains a 5-carbon sugar
- Sugar is called ribose
- Single-stranded molecule
- Contains bases adenine (A), uracil (U), cytosine (C), and guanine (G)

DNA

- Contains a 5-carbon sugar
- Sugar is called deoxyribose
- Double-stranded molecule
- Contains bases adenine (A), thymine (T), cytosine (C), and guanine (G)

2.6.3 The formation of the DNA double helix

DNA is composed of a double stranded helix of DNA nucleotides. Each strand of DNA is held together by covalent bonds that form between the phosphate group of one nucleotide to carbon 3 of the neighbouring nucleotide. This forms a single-stranded backbone. The DNA double strand is then achieved by the formation of hydrogen bonds between the nitrogenous bases of two nucleotide strands. Base pairing in DNA is complementary, meaning that one base can only bind to a specific complementary base:

- Adenine (A) binds to thymine (T) → 2 hydrogen bonds.
- Cytosine (C) binds to guanine (G) → 3 hydrogen bonds.

The two DNA strands are antiparallel, in other words, they run in opposite directions (where one strand has a 5′ end, the complementary strand has a 3′ end).

The diagram shows the structure of the DNA double helix, showing two joined antiparallel DNA strands bound together by complementary base pairing of adenine with thymine (2 H-bonds); and cytosine and guanine (3 H-bonds).

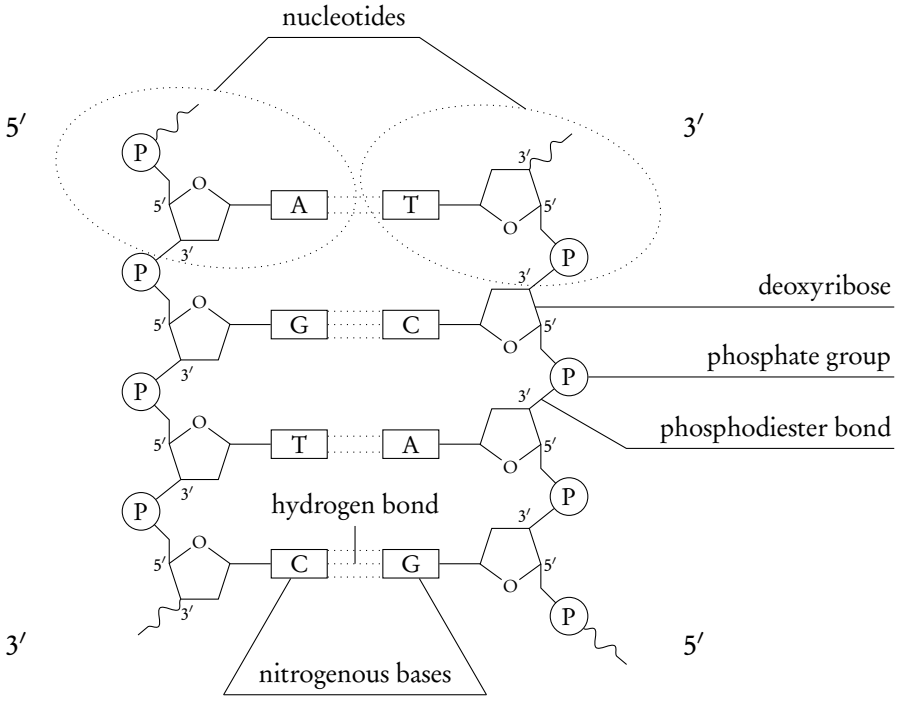


Figure 2.10: DNA structure.

2.7 DNA replication, transcription and translation

2.7.1 DNA replication

During the DNA replication process, one double stranded DNA molecule gives rise two daughter DNA molecules. This process is said to be semi-conservative, meaning that each new DNA double helix contains one newly synthesized daughter strand and one strand from the original parent DNA strand, which serves as a template to ensure that both new strands are identical. Essentially, part of the original DNA is conserved at each replication step.

Below is a brief description of the process of DNA replication:

- Takes place during the synthesis (S) phase of the cell cycle.
- Helicase unwinds the double helix and separates the two DNA strands by breaking hydrogen bonds.
- The two parent strands that emerge from this process serve as templates for the new daughter strands to be synthesized.
- Enzyme DNA polymerase can then link free nucleotides to the template strands by complementary base pairing. Note that DNA polymerase can only add nucleotides at the 3′ end of a growing strand.
- Two identical daughter DNA strands are created, resulting in two semi-conservative double stranded DNA helices.

Example.

Taq DNA polymerase: production of multiple copies of DNA by polymerase chain reaction (PCR)

This technique has been one of the greatest biotechnological developments in DNA research. It allows scientists to amplify desired regions of DNA in very little time. PCR consists of the following steps:

1. Isolate the desired region of DNA (using restriction enzymes).
2. Introduce it in a mixture containing free nucleotides, primers and Taq DNA polymerase.
3. The mixture is heated up to 90 °C to separate the DNA strands of the original template.
4. Temperature is then reduced to 55 °C to allow for primer annealing to the now separated strands.
5. Taq polymerase (isolated from thermophiles, organisms that can survive at very high temperatures) works optimally at 72 °C, so the mix is heated to this temperature to enhance the formation of new double-stranded copies of the original DNA.
6. Process is repeated several times until the DNA is amplified.

2.7.2 Transcription: from gene to messenger RNA (mRNA)

Transcription is the synthesis of mRNA copied from the DNA base sequences present in an organism's chromosomes. The sections of DNA that code for polypeptides are called genes, but in order for these polypeptides to be expressed, machinery located outside the nucleus is needed. Thus, a messenger RNA (mRNA) molecule carries the "message" from the DNA to the cytoplasm. Below is the explanation of the process of transcription:

- RNA polymerase unwinds the area of the DNA to be transcribed.
- RNA polymerase catalyses the addition of free RNA nucleotides using one of the newly separated DNA strands as a template for complementary base pairing (this creates a copy of the complementary DNA strand containing the gene of interest).
- In this process, thymine is replaced by nitrogenous base uracil (only present in RNA nucleotides).
- Translation occurs in a 5′ to 3′ direction.
- Once the whole gene has been transcribed, the resulting single-stranded mRNA molecule peels off and moves out of the nucleus to be translated into a polypeptide.

Skill: While you must be able to determine the mRNA sequence that will result from a given DNA sequence, it is essential that you can also go backwards, and deduce the original DNA sequence from a given mRNA sequence. Try it with the following mRNA sequence!

Tip: first deduce the complementary base sequence to the given mRNA to get one of the DNA strands, the second DNA strand, as you will realize, is identical to the mRNA sequence, with thymine replacing the uracil bases in the sequence.

A U C G A A C G U U G G G C C C G A

2.7.3 Translation: making functional proteins from mRNA sequences

Once the DNA "message" has entered the cytoplasm in the form of mRNA, translation takes place, where polypeptides are synthesized by ribosomes. When studying this process, researchers found that the genetic code is written in a language of codons: which consist of three consecutive bases (triplet), where each codon codes for a specific amino acid (see the table below to see which codons code for what amino acids). Codons are located on the mRNA sequence, while anticodons (complementary to codons) are found on tRNA molecules, another type of RNA that carries the appropriate amino acid to the ribosome where translation occurs. Below is a description of this process:

- The mRNA strand created during the process of transcription binds to a ribosome.
- The ribosome begins to slide over the mRNA until it reaches a starting codon, where a tRNA with a complementary anticodon can bind, bringing the first amino acid of the polypeptide to be made.
- A second tRNA molecule with the appropriate anticodon binds to the second codon.
- The ribosome catalyses the formation of a peptide bond between the two amino acids, creating a dipeptide carried by the second tRNA.
- The ribosome slides over the mRNA molecule, leading to the release of the first tRNAs (the one that is no longer carrying an amino acid) and the binding of a new tRNA to the following codon.

- The amino acid chain keeps growing as this process is repeated until a stop codon is reached, at which point the polypeptide breaks away from the tRNA and can fold and be modified to become a functional protein.

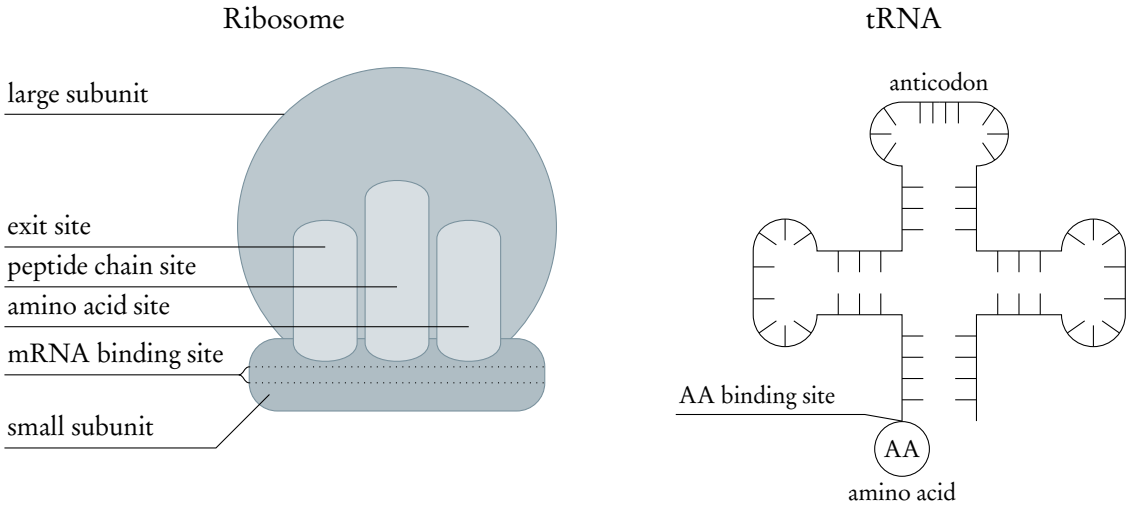


Figure 2.11: Ribosome structure and tRNA.

Example.

Universality of the genetic code: producing human insulin in bacteria

The genetic code has been shown to be universal. That is, in all organisms, the codon code is the same (one codon codes for the same amino acid in any organism). This is very advantageous, as researchers have been able to synthesize important proteins at higher rates by introducing a human DNA sequence for instance in a smaller organism like E. coli, resulting in faster synthesis of the desired protein.

Below is a table showing this universal codon code:
Insulin is a great example of this. Researchers isolated the insulin gene from humans and introduced it into E. coli (a bacterium that rapidly replicates and can yield large amounts of protein in very short time periods). E. coli can then transcribe and translate the insulin gene using its innate machinery. Researchers can then isolate and purify this very important enzyme and use it in for example, the treatment of diabetic patients.

A C T A C G T A C C T G G G A C T A G A C T

Skill: Use a table of the genetic code to deduce which codon(s) corresponds to which amino acid. For example, try coding the following DNA sequence (only one strand is given) into its transcripted mRNA sequence and this sequence into separate amino acids (remember to first find the start codon, and to correctly identify the stop codon, if present).

2.8 Cell respiration

2.8.1 Cell respiration: substrates and products

Cellular respiration is the controlled release of energy, in the form of ATP, from organic compounds in cells

Cellular respiration follows the equation below:

Glucose	+	Oxygen	⟶	Carbon Dioxide	+	Water	+	ATP
$C_6H_{12}O_6$	+	$6O_2$	⟶	$6CO_2$	+	$6H_2O$	+	36 ~ 38 ATP

Cell respiration can follow an aerobic (in the presence of oxygen) and an anaerobic pathway (no oxygen). The latter creates a much smaller yield of ATP.

2.8.2 Anaerobic cell respiration

When no oxygen is available to the cells, the following process occurs:

- Glycolysis occurs in the cell's cytoplasm, where a glucose molecule is broken down into two smaller 3-carbon molecules called pyruvate.
- This process leads to a small yield of ATP (2 molecules per reaction) and other products that can later be used in aerobic cell respiration.
- In yeast cells, pyruvate is converted into ethanol and carbon dioxide (there is no further yield of ATP and the products are released as waste). This process is known as fermentation.
- In mammalian cells, pyruvate molecules are converted into lactate molecules (also known as lactic acid), with no further yield of ATP. Lactate accumulates and can lead to changes in pH (lactic acidosis), which can be dangerous in the long term

2.8.3 Aerobic cell respiration

When oxygen is present, pyruvate can be further broken down in the cytoplasm and enter the mitochondria in the form of acetyl-CoA (a 2-carbon molecule).

- Acetyl-CoA enters the Krebs cycle, where a series of redox reactions lead to the release of carbon dioxide and the formation of intermediate molecules.
- These molecules are used in the electron transport chain (at the mitochondrial membrane), resulting in a large yield of ATP (34-36 ATPs) and the release of water as a by-product

2.9 Photosynthesis

2.9.1 Photosynthesis

Photosynthesis is the process in which plants produce their own organic substances to be used as nutrients.

The process uses energy from the Sun and simple organic compounds (water and carbon dioxide) to create complex carbohydrates to be used as fuel (mainly glucose) and oxygen:

$$\underset{6CO_2}{\text{Carbon Dioxide}} + \underset{6H_2O}{\text{Water}} \longrightarrow \underset{C_6H_{12}O_6}{\text{Glucose}} + \underset{6O_2}{\text{Oxygen}}$$

2.9.2 Light spectrum and chlorophyll

Sunlight is made up of a range of wavelengths including colours red, green and blue within the visible light spectrum. The smaller the wavelength the more energy is reflected (blue wavelength), and the larger the wavelength the less energy reflected (red). Green colour is reflected from medium wavelengths. To absorb and reflect these light waves, specific pigments in plants are needed. The main photosynthetic pigment is chlorophyll; it absorbs red and blue light very well, and reflects mostly green light (thus giving plants their green colour). Chlorophyll is located in clusters inside chloroplasts. Figure 2.12 shows the absorption spectrum of chlorophyll, showing peaks at the wavelengths easily absorbed by the pigment (blue and red) and a trough on green, the least absorbed wavelength. By looking at the action spectrum (Figure 2.9.2, wavelengths of light most used during the photosynthesis reactions) it is clear why chlorophyll is the main pigment in this process: the wavelengths readily absorbed by chlorophyll are majorly used in photosynthesis.

Skill: Draw the absorption spectrum of chlorophyll and the action spectrum for photosynthesis.

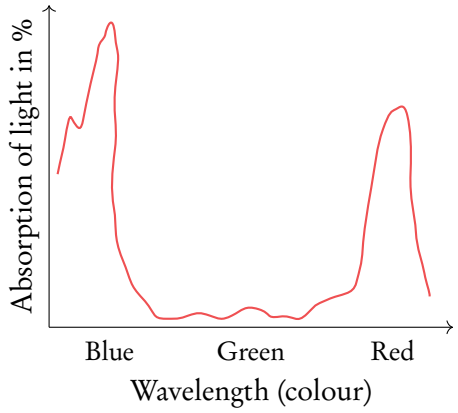


Figure 2.12: Absorption.

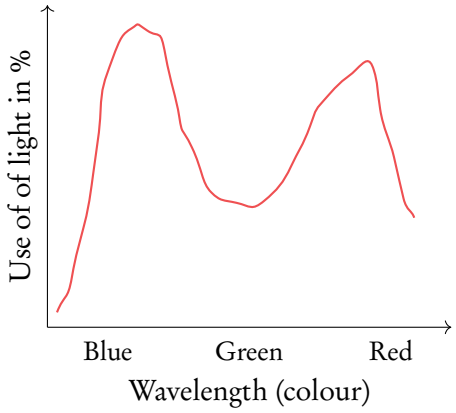


Figure 2.13: Action.

2.9.3 Production of oxygen by photolysis

Photosynthesis consists of light-dependent and light-independent reactions. The light dependent reactions result in the yield of ATP, oxygen and hydrogen.

Hydrogen and electrons are then involved in the electron transport chain which results in a yield of ATP and intermediate molecules for the light-independent reactions

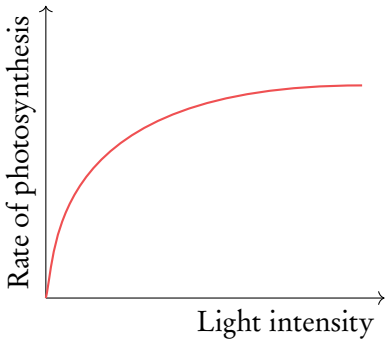
2.9.4 The Calvin cycle: using energy to form carbohydrates and other carbon compounds

The light-independent reactions lead to the formation of complex carbohydrates.

Also known as the Calvin cycle, where ATP and carbon dioxide are used to convert inorganic compounds into organic compounds. This is achieved by carbon fixation, which requires energy from ATP.

2.9.5 Rate-limiting factors of photosynthesis

Light intensity



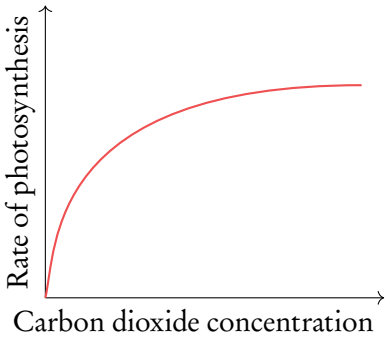
At low light intensities, rate of photosynthesis is limited.

Photolysis, which requires the absorption of light waves slows down, and thus, so does oxygen and ATP production.

Indirectly limits the light-independent reactions, as ATP is necessary for carbon fixation to occur.

The graph levels off once all the enzymes and reactions are occurring at the highest speed possible.

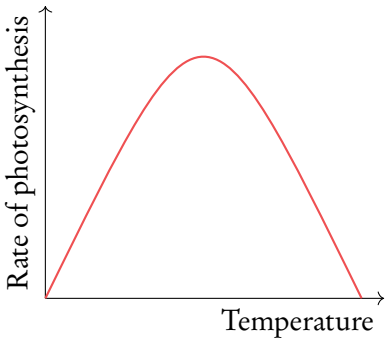
Carbon dioxide concentration



Rate-limiting step in the Calvin cycle → carbon cannot be fixed to inorganic compounds and thus glucose production slows down.

Increasing CO_2 concentration increases the rate of photosynthesis, until the photosynthetic enzymes involved in the cycle (e.g., rubisco) reach their saturation point and can no longer increase reaction rates.

Temperature



At low temperatures, the enzymes involved in photosynthetic reactions work very slowly.

Rate of reaction increases steadily as temperature increases, until reaching an optimum point when all enzymes are working at a high rate.

When the temperature surpasses this optimal point, enzymes can be denatured, once again decreasing the photosynthetic rate.

Skill: Design experiments to investigate the effect of these factors on photosynthetic rates.

GENETICS

3

3.1 Genes and chromosomes

3.1.1 Genes

Gene a DNA sequence that defines a certain heritable characteristic.

One DNA molecule contains many genes, but not all of these genes are "switched on", meaning expressed.

Chromosome a DNA molecule that carries genes.

Within a species, all chromosomes are made of the same DNA molecule, with certain variations of alleles.

The expression of genes on this DNA molecule is what differs one chromosome from another.

The number of chromosomes is defined per species. In eukaryotic organisms, chromosomes come in pairs with two chromosomes of the same pair carrying the same genes: a human, for example, has 46 chromosomes, meaning 23 pairs.

Allele a variation of a certain gene, differing from the other allele of the same gene by a few bases. Different alleles code for different variations of the trait coded for by that gene.

Alleles are a result of mutations of the gene sequence. Most genes come in two or more allelic forms. Since chromosomes come in pairs, an organism can have two or more possible alleles of a gene.

If an organism has two of the same alleles, it is called *homozygous* for the trait.

If an organism has two different alleles, it is said to be *heterozygous* for the trait.

Alleles can be dominant and recessive, where **dominant alleles** are always expressed if present, while **recessive alleles** are only expressed if present homozygously.

3.1.2 Sickle cell anaemia as an example of a gene mutation

Sickle cell anaemia is a heritable disease caused by a mutation of a gene coding for the haemoglobin molecule.

A mutation is a change in the base sequence of a DNA molecule.

In sickle cell anaemia, a base substitution mutation causes a an adenine base in the GAG triplet to be substituted by thymine (GTG).

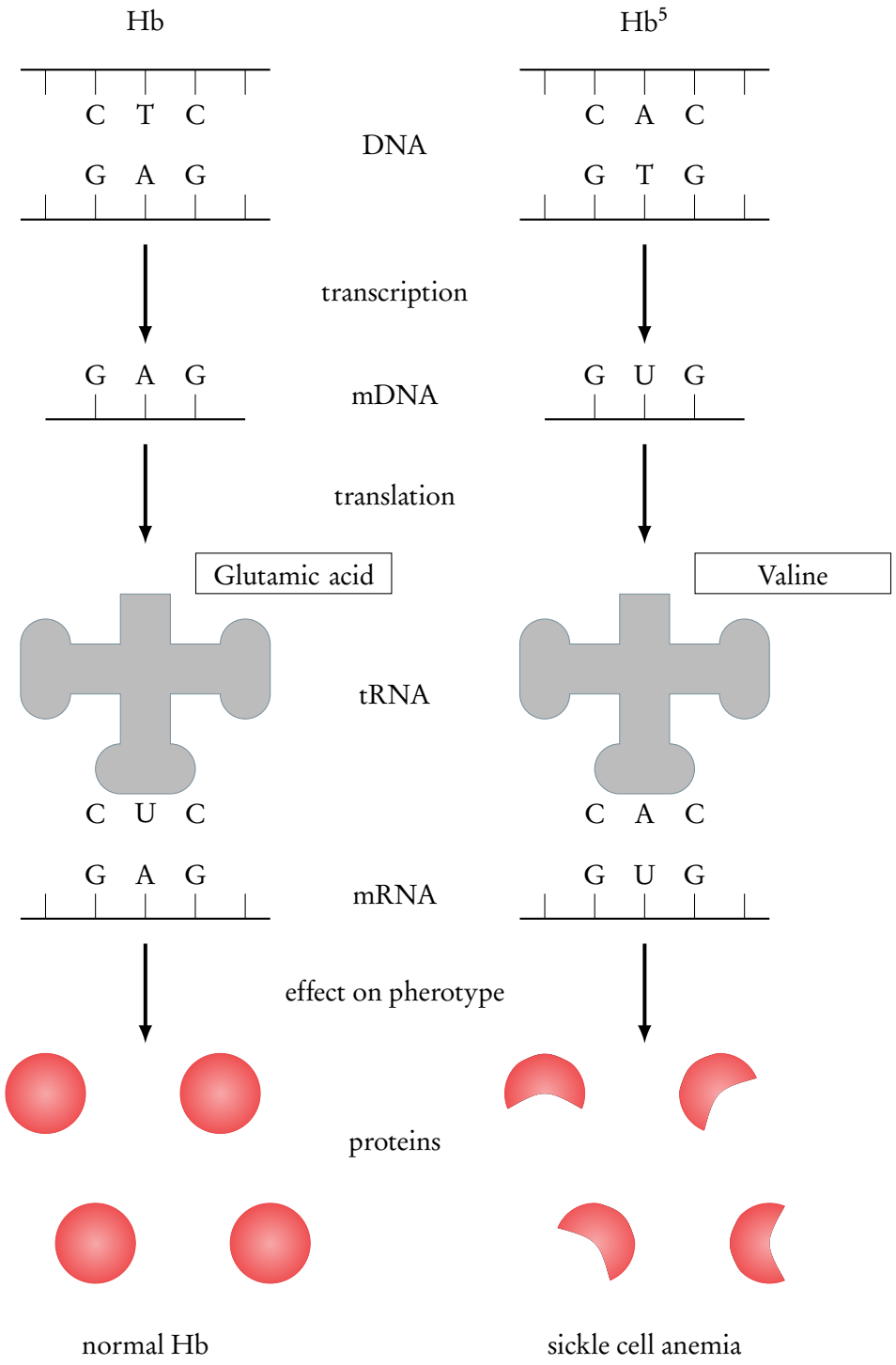
Recall that a triplet of nucleotides codes for a specific amino acid within a protein.

In this case, GAG codes for glutamic acid which becomes substituted by valine (GTG) in sickle cell anaemia.

Recall that protein folding ultimately depends on the amino acid sequence. The difference in this amino acid (from glutamic acid to valine) changes the shape of the haemoglobin protein, leading to a less functional molecule.

Individuals with sickle cell anaemia have moon shaped red blood cells with lower oxygen-carrying capacity compared to normal red blood cells.

On the other hand, malaria parasite is less likely to infect the sickle cells compared to the healthy ones, so the people with this condition are resistant to malaria.


Hb
Hb5
C T C
G A G
C A C
G T G
DNA
transcription
G A G
G U G
mDNA
translation
Glutamic acid
Valine
C U C
C A C
tRNA
G A G
G U G
mRNA
effect on pherotype
proteins
normal Hb
sickle cell anemia

3.1.3 Genome and Human Genome Project

Genome refers to the entire genetic information of an organism.

The genome not only includes genes, but all the genetic information found in the cells of an organism: introns and exons

Animal cell genome includes chromosomal DNA as well as DNA in the mitochondria, just as a plant genome includes all chromosomes and chloroplast DNA.

Bacterial cell genome includes their chromosomal DNA and their plasmid DNA

Human Genome Project refers to the sequencing of the entire human genome.

The HGP resulted in the mapping of the location, size, and number of genes in humans (19 to 20 thousand of them). The project also concluded that humans share most of their genetic sequence, with the exception of short nucleotide polymorphisms (SNPs).

The rest of the DNA sequence is the non-coding region which can control expression of the coding regions: the introns.

3.1.4 Complexity of organisms and their genomes

The size of the genome of a species does not relate to the complexity of the organism.

Similarly, the number of genes in an organism does not correlate with the complexity of that organism

3.1.5 Prokaryotic and eukaryotic chromosomes

Cairn's method of measuring DNA length

Cairn's method involves adding a radioactively labelled nucleotide (thymidine) to cells undergoing replication.

Table 3.1

Organism	Genome size (number of bases)	Number of genes	Number of chromosomes
E. coli	4.6 million	2,300	…
Maize (corn)	2.3 billion	32,000	10
Mouse	2.8 billion	23,000	40
Human	3.0 billion	20,000	46

Recall that during replication, each parent strand gains a new daughter strand which assembles from the available nucleotides through complementary base pairing.

In this way, the two new daughter strands incorporate the radioactive nucleotides (thymidine, which also discriminates between DNA and RNA replication) and can be visualized after light exposure.

This method was used to show the nature of replication in bacterial, and subsequently in animal cells.

Table 3.2: Comparison of prokaryotic and eukaryotic DNA.

	DNA	Chromosomes	Plasmid
Prokaryotic	Circular “Naked”	1 circular	Present
Eukaryotic	Linear Associated with proteins	Many linear	Not present

Prokaryotic DNA

- Bacteria have one circular DNA molecule that is not associated with proteins.
- Extra genetic information is stored on plasmids, and can easily be shared between bacteria.
- Antibiotic resistance genes are often found on plasmid DNA

Eukaryotic DNA

- DNA is associated with proteins called histones.
- Histones are used to wrap DNA around them in order to protect it against damage as well as to control expression of certain genes.
- Recall that eukaryotic chromosomes come in pairs.
- A pair of identical chromosomes is called a homologous pair and these chromosomes carry the same genes (with possibly different alleles).
- A complete set of chromosomes (in a human 46) is called a diploid number of chromosomes.
- Sex cells contain half the number of chromosomes (one from each pair), which is said to be haploid, in order to conserve the species' number of chromosomes after fertilization (joining of two sex cells).

3.1.6 Karyograms and karyotypes

Karyogram is an image of all the chromosomes of an organism's cell, shown in decreasing size of the homologous pairs.

Karyograms can help determine the sex of the organism as well as the possible chromosomal irregularities that might be disease-causing.

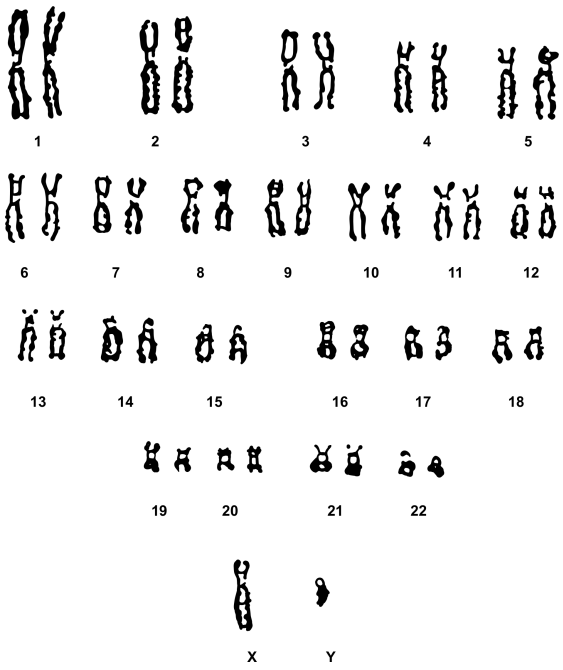


Figure 3.1: Karyogram.

One such irregularity in humans is trisomy 21 (an extra chromosome in the 21st pair) that is a cause of the Down syndrome.
23rd pair of human chromosomes determine the sex of a baby.
These chromosomes are called sex chromosomes (as opposed to all other ones that are called autologous).
These chromosomes do not have to be identical; a male individual will have one X and one Y chromosome which are of different sizes, while a female individual will have two X chromosomes of the same size (and banding pattern).

Karyotype is the characteristic pattern of chromosomes of an organism, referring to their size, shape and the banding pattern.

Karyogram is obtained in two possible ways: amniotic fluid sampling and chorionic villus sampling.

Amniotic fluid sampling

A hypodermic needle is inserted through the abdomen of the mother into the amniotic sack.

The embryo swims in the amniotic fluid which contains the cells that the embryo has shed off.

The karyogram is obtained by collecting the DNA from these cells.

Chorionic villus sampling

Similarly, the chorionic villi make up the embryonic side of the placenta.

These villi are of the embryonic tissue origin which means that they contain the same cells as the child.

By sampling the chorionic villi (again using a needle), the child's cells can be obtained and karyogram constructed.

3.2 Meiosis

Meiosis is a type of cell division in which one cell with a diploid nucleus divides into 4 genetically distinct cells with haploid nuclei. This is the process whereby gametes (sex cells) are made.

Diploid cells have two variations of each chromosome (one maternal- and one paternally derived)

Haploid cells have one variation of each chromosome (either a maternal- or paternally derived one)

The AIM of meiosis is to create cells with half the number of chromosomes, so that during fertilization, each parent could contribute their own set of genes to the offspring and thereby conserve the number of chromosomes of a species and promote variation.

Meiosis consists of two divisions: meiosis I (or reduction division); and meiosis II, which can be referred to as mitotic division.

In meiosis I, the number of chromosomes is halved between the two newly formed cells (therefore the name "reduction") while in meiosis II, the number of chromosome between the parent and daughter cells stays the same, but the chromatids separate (therefore the name mitotic).

The stages of each meiotic division have the same name as in the mitotic division, but the events of each stage differ slightly.

Meiosis also requires duplication of DNA, which occurs prior to first meiotic division.

Homologous pairs are a set of one maternal and one parental chromosome that have the same genes in the same loci along the chromosome. Remember that diploid organisms have two variations of each chromosome number (for example, you have two chromosome 21s)

Sister chromatids are identical copies formed by the replication of a chromosome. These are joined at the centromere in a replicated chromosome. Once sister chromatids separate, they are referred to as **individual chromosomes**

3.2.1 Meiosis I

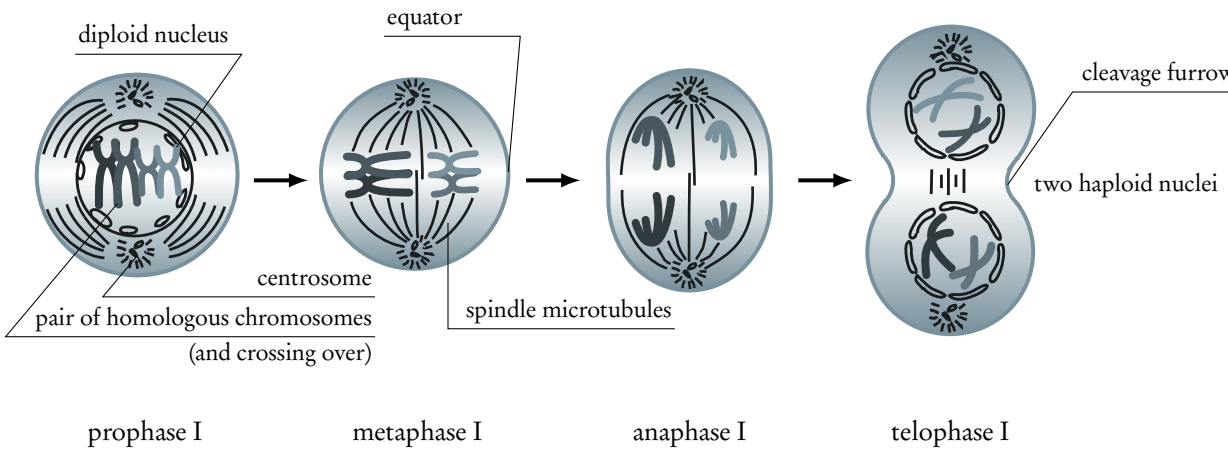


Figure 3.2: Meiosis I.

Prophase I

- Prior to this phase, the DNA has already duplicated (S phase) and the cell contains double the number of chromosomes (depicted as two chromatids of each chromosome).
- DNA supercoils and chromosomes shorten.
- Nuclear envelope breaks down
- Centrioles move to the poles.

Metaphase I

- **Homologous chromosomes pair up** at the cell equator (this means that the pairs of each chromosomes line up on top of each other).
- **Each pole's spindle microtubule attaches to one chromosome from each homologous pair** (recall that in mitosis, one chromosome would have one of each pole's spindle microtubules)

Anaphase I

- **Each spindle microtubule pulls one whole chromosome of the homologous pair towards it's pole, causing a division of the chromosome pairs across the cell** (recall that in mitosis, at this step, only the chromatids would separate so that a full set of chromosomes would be present at each pole).
- The movement of the **chromosomes** is achieved through shortening of the spindle microtubules.

Telophase I

- Nuclear envelope forms around each set of chromosomes.
- The cell divides into two cells with **haploid number of nuclei** (only one chromosome from each homologous pair).
- Chromosomes partly uncoil.
- **The cell will proceed with meiosis II**

3.2.2 Meiosis II

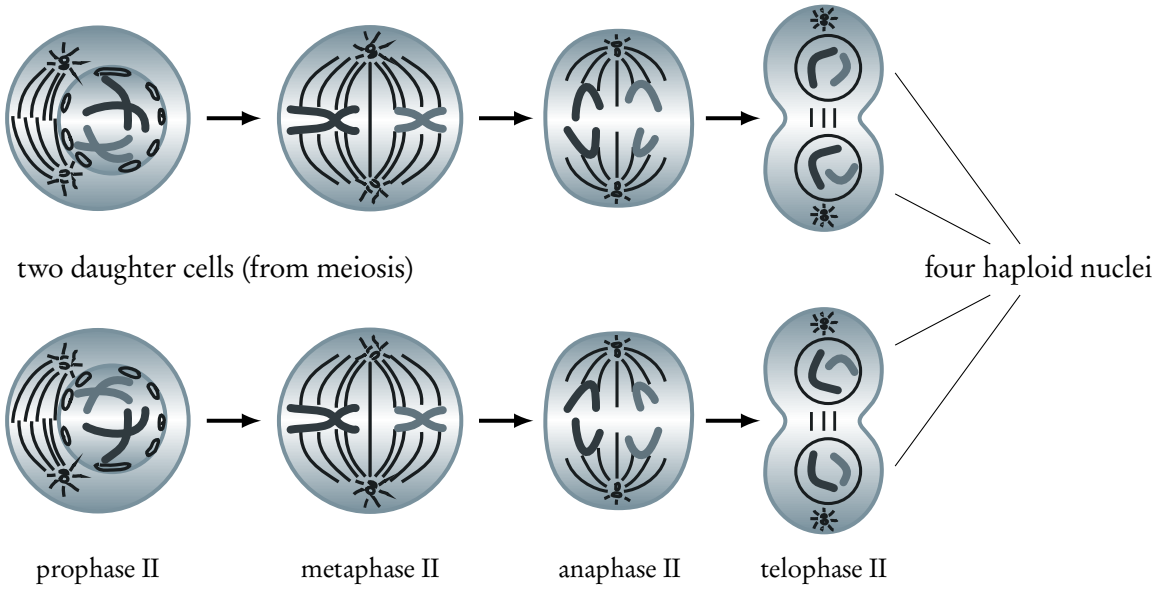


Figure 3.3: Meiosis II.

Note that the events of this phase are identical to mitosis, but the starting number of chromosomes is halved!

Before meiosis II, there is no duplication of DNA, so the cell proceeds straight from the telophase into the new division.

Recall that each cell now possesses one chromosome of each homologous pair, but with two chromatids (meaning that each chromosome is made up of two sister chromatids with identical DNA!)

Prophase II

- Chromosomes supercoil again and become shorter.
- Centrioles again move to the poles of the cell.
- Nuclear envelopes break down.

Metaphase II

- Chromosomes line up at the metaphase plate, one next to each other across the equator.
- Spindle microtubules (one from each pole) attach to the centromeres of the chromosomes (centromeres).

Anaphase II

- Spindle microtubules pull the sister chromatids apart, so that one chromatid of each chromosomes travels to the opposite pole.
- Therefore, each pole of the cell will receive one DNA copy of each chromosome.

Telophase II

- At this last stage, each pole of the cell contains half the number of chromosomes compared to beginning of meiosis I, but the same number of chromosomes (just half the chromatids) compared to meiosis II.
- The nuclear envelope forms and the cell divides into two cells.
- Recall that in the first meiotic division, two cells were formed, meaning that now, each of those two cells divided into two, yielding a total of 4 cells, each with half the number of chromosomes

3.2.3 Meiosis and variation

When we talk about variation and meiosis, it is important to understand the following terms:

Crossing over process through which the non-sister chromatids within a homologous pair, exchange genetic material during prophase I.

Through exchange of genetic material between non-sister chromosomes of a homologous pair, gametes end up with chromosomes with new gene combinations that were not present before. These are called recombinants.

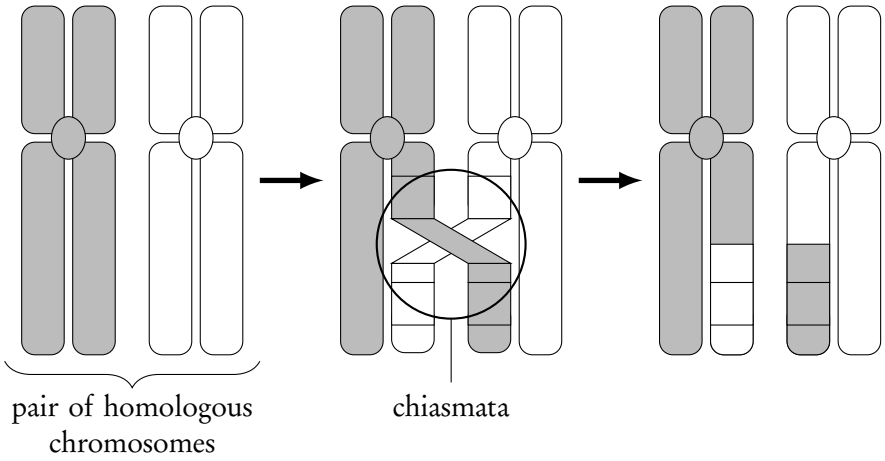


Figure 3.4

Random orientation refers to the fact that the positioning of each homologous chromosome at the metaphase plate during metaphase I is random (not pre-determined).

Recall that, after prophase I, each chromosome in a homologous pair possesses different allele combinations.

Depending on which chromosome orients towards which pole in metaphase 1, each cell will end up with a different set of chromosomal alleles.

If these definitions are clear, then it is obvious how within one individual, there is an infinite variation between the gametes. Now, adding the process of fertilization, where two random gametes from two different individuals of a species fuse, there is truly an infinite number of possible combinations and therefore infinite genetic variation.

3.2.4 Failures of meiosis

Recall that failures of checkpoint mechanisms during mitosis often result in tumour formation. The failures of meiosis, on the other hand, are usually lethal for the embryo, or result in genetic disorders.

Example.

Down Syndrome

Down syndrome is a chromosomal abnormality in which the individual possesses 1 extra chromosome in their 21st chromosomal pair.

This is a result of improper separation of homologous chromosomes during anaphase I, or improper disjunction of sister chromatids during anaphase II.

The cell that ends up with an extra chromosome in the 21st pair will be able to continue its life cycle through fertilization.

The cell that ends up with one less chromosome will not be able to continue its life cycle and will not survive past fertilization.

Disjunctions are believed to be common, but most of them are lethal to the embryo and present themselves as spontaneous abortions.

3.3 Inheritance

Allele a variation of a gene that differs from another allele by a few bases only. This results in variations of a characteristic in an organism. A gene can have none as well as several alleles.

Genotype combination of alleles of one or more genes (literally capital and lower case letters in Punnett grids). Remember that diploid organisms have two copies of each chromosome, which allows two to have two alleles per gene.

Phenotype the physical trait that is expressed by a certain genotype (what you can see with your eyes, like eye colour etc.)

Homozygous two of the same alleles.

Heterozygous two different copies (of an allele).

Dominant allele allele that is expressed both in homozygous and heterozygous combinations.

Recessive allele allele that is only expressed in homozygous combinations.

Co-dominant dominant alleles that are both expressed when present, since neither of them overpowers the other ones.

Locus is a fixed, physical location on a chromosome where genes can be found.

3.3.1 Mendel's law of inheritance

Mendel discovered some basic laws of inheritance by cross-fertilizing pea plants with different traits (flower colour, pea shape). He observed "hidden" traits that tend to surface after several generations. These were in fact what we now call recessive alleles.

Since gametes possess only one set of chromosomes (haploid) compared to somatic cells, they also possess only one allele that they can pass onto the offspring. The other parent will give the other allele of the gene.

Since alleles are variations of traits (e.g., a gene codes for hair colour in general, but the alleles code for the specific hair colours), the combination of alleles will determine the final trait of the individual.

A Punnett grid is a useful tool to predict all the possible offspring combinations of a particular trait.

3.3.2 Punnett grids

Represent the maternal alleles on one side, and paternal alleles on the other side of the grid.
In the first step, based on the parent's full set of chromosomes, one can determine what possible alleles the parents' gametes can have.
In the second step, by combining all the possible parents' alleles in the grid, one can determine the possible offspring combinations.

		maternal alleles: A	maternal alleles: B
paternal alleles	C	AC	BC
paternal alleles	D	AD	BD

Example.

Rules of Punnett grids

Parental generation is called P1, first offspring generation F0 and all other offspring generations are numbered F1, F2 etc.

Dominant alleles determine the letter used to describe the trait (if brown eyes are dominant to green eyes, than the trait will be defined by letter B and not G).

Dominant alleles are written in the capital letter, and recessive alleles in the lower case letter (therefore, brown eyes will be B, and green eyes will be b, not g!).

Example.

Pea flower colour (purple allele dominates the white allele)

	Parent 1	Parent 2
Genotype	PP (homozygous dominant)	pp (homozygous recessive)
Possible gametes	P and P	p and p
Phenotype	Purple flowers	White flowers

The Punnett grid is constructed by placing the alleles of one parent on the vertical side of a 2 × 2 square, and the other parent on the horizontal side.

	Parent 1: P	Parent 1: P
Parent 2: p	Pp	Pp
Parent 2: p	Pp	Pp

P1:	PP	pp
F0 Genotype	Heterozygous (dominant) Pp	
F0 Phenotype	Purple (since one dominant allele is always present)	

Let's see now what happens if you cross-pollinate the offspring.

	Parent 1: P	Parent 1: p
Parent 2: P	PP	Pp
Parent 2: p	Pp	pp

P1:	Pp	Pp
F1 Genotype	25% PP, 25% pp, 50% Pp (25% HomD, 25% HomR, 50% HetD)	
F1 Phenotype	75% purple, 25% white	

3.3.3 Co-dominant alleles

Recall that co-dominant alleles are those where neither of the alleles over-rules the others. All the present alleles are expressed.

For example: Each individual has one of the four possible blood groups, namely A, B, AB or O. These are in fact the surface molecules carried on the red blood cells (RBCs) that help the body distinguish between self and non-self. An individual may have "A molecules", "B molecules", "A and B molecules", or no molecules (O) on the surface.

Depending on what molecules are expressed in the RBCs of an individual, he/she will have antibodies or an immune reaction to the molecules he/she does not have.

Therefore, for example, a person with A expressed on their RBCs cannot receive blood from someone with B expressed on their RBCs. Additionally everyone can receive from O-type donors as their RBCs express no molecules on the surface. Meanwhile they cannot receive from any donors that are not O, as they recognize anything on the surface as foreign. Overall, it is very dangerous to receive blood from a mismatched donor, as it can lead to one's immune system attacking their own blood.

Alleles that determine the blood groups are either allele for A, for B, or for 0. Alleles A and B are co-dominant, and allele for 0 is recessive to both A and B. Therefore, if an individual has both the allele for A and B, her blood group will be AB, but if she has allele A and allele 0, her blood group will be A.

Rules of Punnett grids

- For co-dominant alleles, the letter used to represent all alleles is capital I.
- For the specific alleles, for example in the ABO blood group example, blood group A is labelled as capital I with a superscript A, so I^A and blood group B as I^B.
- If there is another allele that is recessive to both the co-dominant alleles, that one is labelled as a lower case letter i with no superscript.

Example.

ABO blood groups

	Parent 1	Parent 2
Phenotype	Blood group A	Blood group B
Genotype	I^Ai (heterozygous A)	I^Bi (heterozygous B)
Possible gametes	I^A and i	I^B and i

Parent 2 \ Parent 1	I^A	i
I^B	I^AI^B	iI^B
i	I^Ai	ii

P1:	I^Ai	I^Bi
F1 Genotype	25% I^Ai, 25% I^Bi, 25% I^AI^B, 25% ii	
F1 Phenotype	25% A, 25% B, 25% AB and 25% 0	

Example.

Another example

	Parent 1	Parent 2
Phenotype	Blood group AB	Blood group 0
Genotype	I^AI^B (co-dominant)	ii (homozygous recessive)
Possible gametes	I^A and I^B	i and i

Parent 2 \ Parent 1	I^A	I^B
i	I^Ai	I^Bi
i	I^Ai	I^Bi

P1:	I^Ai	I^Bi
F1 Genotype	50% I^Ai, 50% I^Bi	
F1 Phenotype	50% A and 50% B	

3.3.4 Sex linkage

Recall that the chromosomes can be divided into somatic and sex chromosomes. The sex chromosomes are the ones that determine the sex characteristics of an organism, amongst others.

Sex chromosomes are labelled as X and Y. Y chromosome is much smaller: for that reason, X chromosome carries more genes that the Y chromosome does.

The presence of Y chromosome determines that gender of the child will be male: females normally carry two X chromosomes, while males carry one X and one Y chromosome.

This means that the female will pass on only X chromosomes to her offspring, while the male can pass on either an X or a Y chromosome.

In order for a female offspring to be born, gametes carrying an X in both male and female cell must meet, and for a male to be born, a female gamete with X and a male gamete with Y have to fertilize.

Sex linkage refers to the inheritance of genes that are located on the sex chromosomes.

Since the X chromosome carries more genes than the Y chromosomes, males will often lack one copy (and therefore one allele) of the sex linked genes. For this reason, many of the sex linked diseases affect males to a higher degree than females.

Rules of Punnett grids

- For sex linked genes, the letters assigned to the traits are either X or a Y, depending on the gender of the individual.
- The trait is labelled as a superscript on the X or Y.
- Dominant allele is written in the capital letter, while the recessive is written in the lower case letter.

Example.

Red-green colour-blindness

Red-green colour-blindness is a sex linked disorder carried on the X chromosome where the affected individuals cannot distinguish between red and green colours. It is a recessive disorder, meaning that only individuals with no dominant (healthy) alleles are affected by it. However, since it is a sex linked trait, carried on the X chromosome, males already have a disadvantage since they have only one chromosome that can either carry the healthy or the affected gene.

Females carry two X chromosomes, and therefore two alleles for colour vision. Males carry one X chromosome with the gene for colour vision, and a Y that doesn't contain the gene at all. If a female has one healthy and one affected gene, she will be called a carrier but she will be healthy. She might pass on her affected X chromosome to her son, who will not inherit another X chromosome, but a Y chromosome from his father and therefore be affected by the disease. Note that females can be affected as well, but in that case they would have to have a carrier mother and an affected father (and still there is only 50% chance that they will have the disease).

Let's look at what happens in the Punnett grid.

Parent	Mother	Father
Phenotype	Healthy (carrier)	Healthy
Genotype	X^HX^h	X^HY
Possible gametes	X^H and X^h	X^H and Y

		Parent 1	
		X^H	X^h
Parent 2	X^H	X^HX^H	X^hX^H
	Y	X^HY	X^hY

P1:	I^Ai I^Bi
F1 Genotype	25% X^HX^H, 25% X^HX^h, 25% X^HY, 25% X^hY
F1 Phenotype	75% healthy child, 25% affected child (but 50% that the son will be affected, and 0% chance that the daughter will be affected)

3.3.5 Dominant and recessive genetic disorders

So far, the traits we have shown have all been recessive. This means that only the individuals with two affected alleles get the disorder. If the disease is of dominant inheritance, one affected allele is enough for the individual to carry the disease. This will result in a much higher percentage of affected individuals in a family tree (compared to the recessive disorders).

Example.

Huntington's disease

	Parent 1	Parent 2
Phenotype	Healthy	Huntington's
Genotype	Hh (homozygous recessive)	Hh (heterozygous dominant)
Possible gametes	h and h	H and h

		Parent 1	
		h	h
Parent 2	H	hH	hH
	h	hh	hh

P1:	I^Ai	I^Bi
F1 Genotype	50% Hh and 50% hh	
F1 Phenotype	50% affected offspring, 50% healthy offspring	

3.3.6 Pedigree charts

Pedigree charts are a way to represent the inheritance of certain traits in a form of a family tree, where the oldest individuals are set at the top, and their offspring follow downwards.

There are some rules you should keep in mind:

- The female is always labelled as a circle ○ and the male as a square □.
- Most pedigree charts show affected individuals as coloured figures ● ■ and healthy and carrier individuals as transparent figures ○ □.
- Such a chart helps determine the possible genotypes of individuals and chances for affected offspring in the future.

Note that in the exam, you could be asked to also determine whether the disease is sex linked, recessive or dominant.

Here are again some tips that might help you out with that

- Charts where mostly males are affected usually represent a sex-linked trait (this means that more than 90% of the affected individuals are males).

- Two healthy individuals cannot have a child with a dominant disorder.
- In recessive disorders, two healthy parents can have an affected child, but two affected parents cannot have a healthy offspring.
- Try to annotate the diagrams as much as possible to help you keep track of what you figure out.

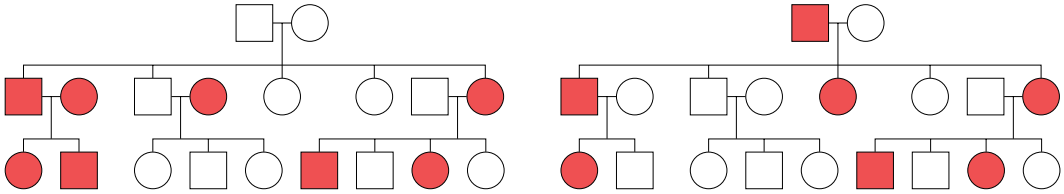


Figure 3.5: Recessive vs. dominant chart.

3.4 Genetic modifications and biotechnology

3.4.1 PCR and gel electrophoresis

A single cell contains a miniature amount of DNA. A DNA sample, obtained from a piece of tissue or bodily fluid is often not enough on its own to give conclusive results. For that reason, the DNA needs to be multiplied to make sure there is enough for proper analysis:

Polymerase chain reaction (PCR)

PCR is a method through which a molecule of DNA is copied many times, yielding a high number of identical DNA molecules. The system is based on the cellular replication process but employs the use of the polymerase enzyme from *Thermus aquaticus*, which works best at high temperatures. At high temperatures, the two strands of DNA molecules naturally separate, and the polymerase enzyme is able to replicate both chains. When this process finishes, the temperature is lowered, so that the chains join again. This is repeated through several cycles, until the DNA is sufficiently quantified. You can imagine this goes quite fast, since from one DNA molecule, you get two, which can then be amplified to another four, then 16 an so on.

In synthesis, the steps of PCR are:

- Denaturation: ($\sim 95\,^{\circ}C$) the DNA sample is heated to separate the double stranded molecule into two single strands.
- Annealing: ($\sim 55\,^{\circ}C$) the DNA primers attach to the 3′ ends of the target sequence.

- Elongation: (~ 72 °C) the heat-tolerant DNA polymerase (Taq) binds to the primers and copies the DNA strands (e.g., from 2 to 4 strands).

These steps are repeated over and over until a large number of copies from the original molecule is obtained.

Gel electrophoresis

This method was developed to visualize the DNA fragments, or proteins isolated from cells. The principle of this method is to separate DNA fragments or proteins from a mixture, based on their size and charge. The electrophoresis chamber consists of an agarose gel submerged into a liquid, and two electrodes (a positive and negative) at each side. The voltage across the chamber makes the molecules of different sizes and charges move across the gel at different speed. Large and less charged molecules stick behind, while the small and highly charged molecules travel faster.

The result is a pattern of bands visualized under UV light which can be compared between cells, or individuals (in case of paternity tests).

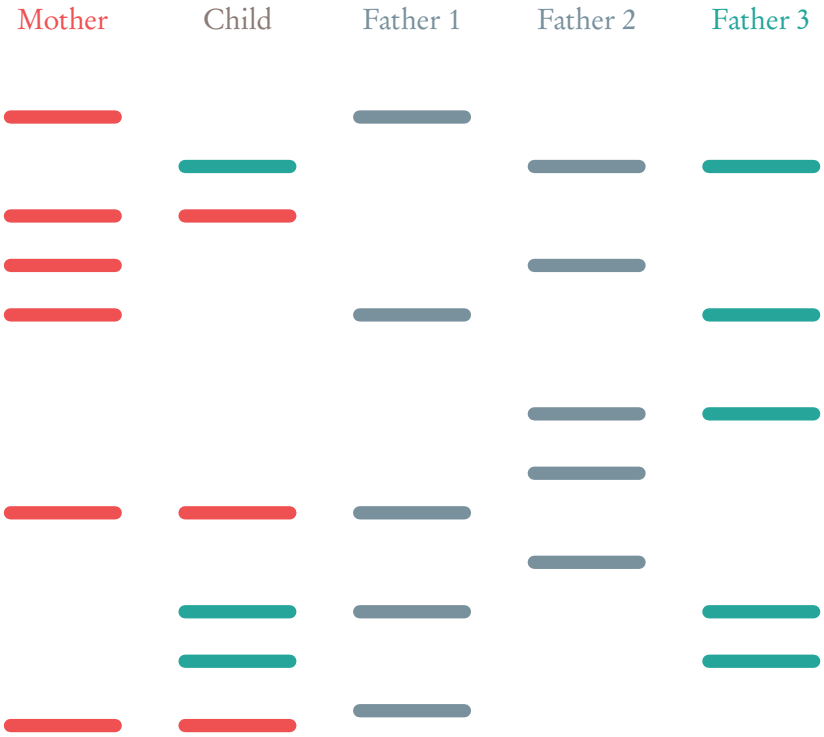
Gel electrophoresis can be used to determine the paternity of a child by comparing DNA fragments of the mother, the child and the suspected fathers.

Since the child's DNA is a combination of his father's and mother's DNA, the child's patter will contain some of his mother's and some of his father's bands

ample.

Paternity determination

Example.



3.4.2 Genetic modifications

Recall that the genetic code is universal, meaning that all the organisms translate the same triplets of bases into the same amino acids. With that in mind, you can see why a gene in one organism's coding for a specific protein, could be transferred to another organism's where it would again code for the same protein.

Example.

E. coli and the production of insulin

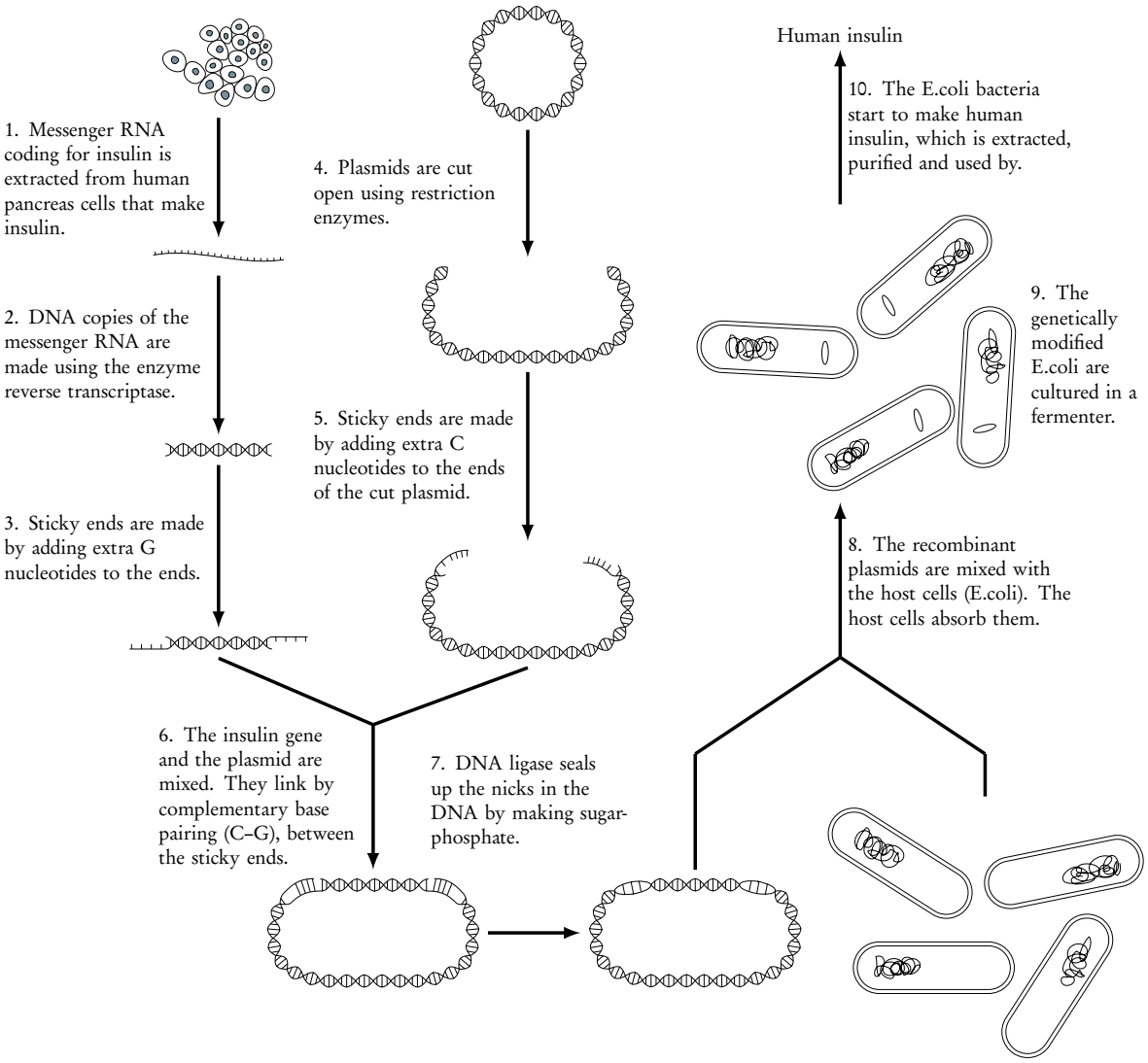
Bacteria can be genetically modified to produce a human protein of interest. An example of this is the production of insulin through E. coli. This is achieved by extracting the messenger RNA from human cells producing insulin (pancreatic cells) and converting that mRNA back into DNA using reverse transcriptase enzyme.

This piece of DNA could now be ligated into a plasmid using restriction enzymes, enzymes that are able to cut DNA at a specific point with a specific patter, leaving sticky ends through which the gene of interest (from previous step) could be ligated into the plasmid (which has also been cut with the same restriction enzymes).

Once the plasmid with the gene of interest is made, it can incubated with the bacteria which will then take it up and start transcribing and translating the newly acquired gene. These bacteria are now called recombinant bacteria.

The result will be the production of the protein, which can then be collected as a part of the bacterial secretions.

Example.


1. Messenger RNA coding for insulin is extracted from human pancreas cells that make insulin.
2. DNA copies of the messenger RNA are made using the enzyme reverse transcriptase.
3. Sticky ends are made by adding extra G nucleotides to the ends.
4. Plasmids are cut open using restriction enzymes.
5. Sticky ends are made by adding extra C nucleotides to the ends of the cut plasmid.
6. The insulin gene and the plasmid are mixed. They link by complementary base pairing (C–G), between the sticky ends.
7. DNA ligase seals up the nicks in the DNA by making sugar-phosphate.
8. The recombinant plasmids are mixed with the host cells (E.coli). The host cells absorb them.
9. The genetically modified E.coli are cultured in a fermenter.
10. The E.coli bacteria start to make human insulin, which is extracted, purified and used by.
Human insulin

3.4.3 Benefits and risks of genetic modifications

Benefits

- With less pest damage, there are higher crop yields, so less food shortages.
- With better yield, less land is needed for the same amount of crop production, and the unused land can be conserved for wildlife.
- There is no need to use pesticides that damage other organisms living in the vicinity.

Risks

- Long term effects of genetically modified foods have not yet been determined.
- The pollen of the modified crops might be blown away to the wildlife where it might kill the organisms that do not normally infect the plant.
- The genetically modified plants have an evolutionary advantage to the non-modified plants, so the random cross-pollination might create an imbalance in the ecosystem.

Example.

Bt maize

Bt maize can be genetically modified to express a bacterial gene for Bt toxin that is toxic to the pests that usually attack it. In that way, the crops are "resistant" to the pest infestations.

3.4.4 Clones and cloning

Clone an organism that is genetically identical to its parent organism.

Cloning is a technique of producing genetically identical cells, tissue or organisms. This is usually done to obtain a higher number of cells or individuals with a desirable set of characteristics. Cloning of plants can be relatively easy by taking a piece of root or stem that contains plant stem cells that will grow into a new, genetically identical plant. Animal cloning is more difficult since animals cannot develop from a group of stem cells found in the body.

Example.

Dolly the sheep

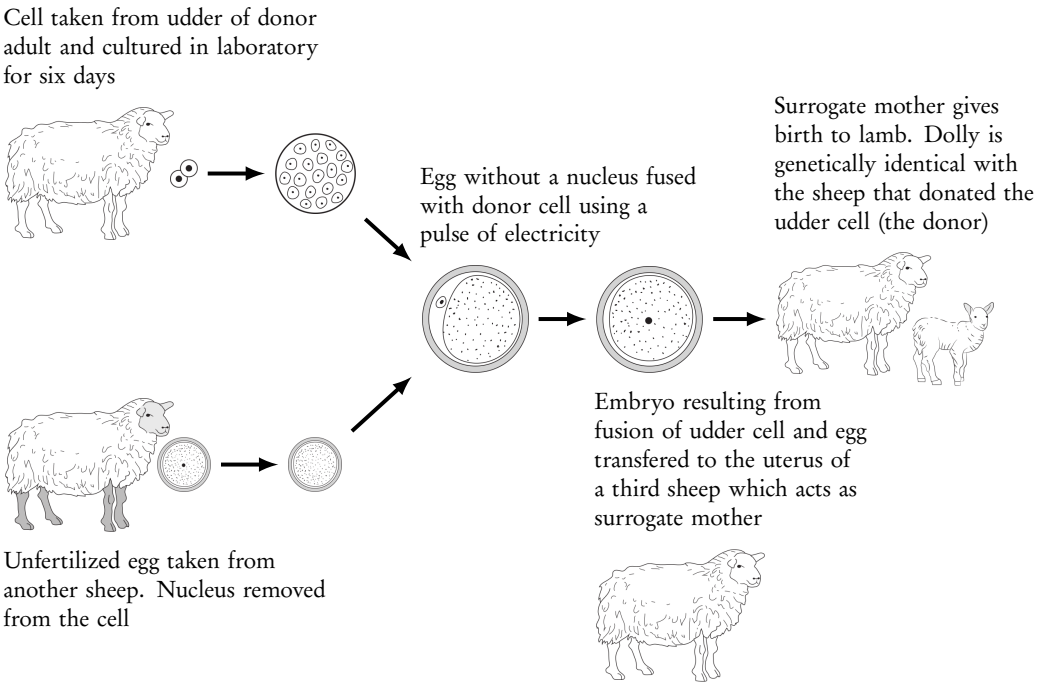
Dolly the sheep was the first cloned animal. Three sheep were used to give rise to Dolly, namely one that donated the egg cell (without the nucleus), one sheep that donated its genetic material (nucleus of a somatic cell) and one sheep into which the embryo was implanted. Therefore, Dolly was genetically identical only to the sheep donating the nucleus.

Process

An egg cell was obtained from a sheep, and the nucleus of that cell was removed. The egg cell contains only half the genetic information, so its nucleus cannot be used in cloning. However, the egg cell contains the vital enzymes and organelles for development.

Udder cells (somatic cells) from another sheep were taken and grown in deprived environment which cause them to switch off all their genes. A nucleus of such a cell was isolated (it contained all the chromosomes), and then fused with the egg cell without the nucleus.

The fused cells were inserted into the third sheep (the surrogate) and they developed as a newly formed embryo. The sheep that was born was named Dolly and was genetically identical to the mother providing the nucleus of its cell.



ECOLOGY

4

4.1 Species, communities and ecosystems

4.1.1 Key terms and definitions

Species a group of organisms that can interbreed and produce fertile offspring. Its members can be reproductively isolated (live in a different habitat) but as long as they hold the ability to potentially interbreed with other members from different habitats, they are part of the same species.

Habitat the environment in which a species normally lives, or the location of a living organism.

Population a group of organisms of the same species who live in the same area at the same time.

Community a group of populations living and interacting with each other in the same geographical area.

Ecosystem community and its abiotic environment.

Ecology the study of the relationship between living organisms and between organisms and their environment.

4.1.2 Autotrophs vs. heterotrophs

One way organisms can be classified into different groups is based on their method of nutrition, in other words, by the ways in which they obtain organic compounds necessary to provide essential nutrients to each organism. In this way, organisms can be classified as autotrophs and heterotrophs.

Autotrophs can synthesize their own organic compounds from simple inorganic compounds found in the abiotic environment, to do this, they absorb carbon dioxide, water and other inorganic nutrients from the environment for synthesis (e.g., plants, algae, cyanobacteria (all of these are photosynthetic organisms)). Autotrophs are commonly referred to as producers.

Heterotrophs obtain organic compounds from other living organisms (e.g., humans, insects, fish, etc.). Heterotrophs are commonly referred to as consumers.

Some species can obtain nutrients through both methods (e.g., some bacteria) but this is a rare occurrence.

4.1.3 Heterotrophs: consumers vs. detritivores vs. saprotrophs

Heterotrophs can be divided into three subcategories:

Consumers: organisms that obtain organic matter from other living or recently killed organisms

- Primary consumer: eats autotrophic organisms → herbivore
- Secondary consumer: eats herbivores → carnivore
- Tertiary consumer: eats secondary consumer → top carnivore
  (top carnivore can also be a quaternary consumer, depending on the size of the food chain)

Detritivores: decomposers that internally digest dead organic matter like leaves and carcasses (e.g., earthworms and woodlice)

Saprotrophs: decomposers that live in or on dead organic matter and externally digest it, by secreting digestive enzymes and absorbing the products of digestion (e.g., fungus and bacteria)

4.1.4 Nutrient cycling

Since autotrophs sustain themselves by absorbing nutrients and other inorganic compounds from the abiotic environment, there has to be a way in which this inorganic compound supply is maintained. This is achieved through a process known as nutrient cycling. When an organism dies, decomposers are in charge of breaking it down and absorbing as many nutrients and as much energy as possible via digestion. The remains of the organism are then mostly inorganic compounds that return to the abiotic environment after the process of decomposition. Gas balance (oxygen-carbon dioxide) is usually replenished by the processes of cell respiration and photosynthesis in plants and consumers. This returns balance to the ecosystem, once again providing available inorganic matter for autotrophs to make use of. This results in ecosystems having the potential to be sustainable for long periods of time, as long as a source of energy and the necessary fuel sources are available.

Example.

Mesocosms: proving that ecosystems are self-sustainable

The picture below shows one possible design of a mesocosm; an experimental set-up that tries to emulate a real-life ecosystem in an isolated space to determine if the ecosystem is indeed self-sustainable:

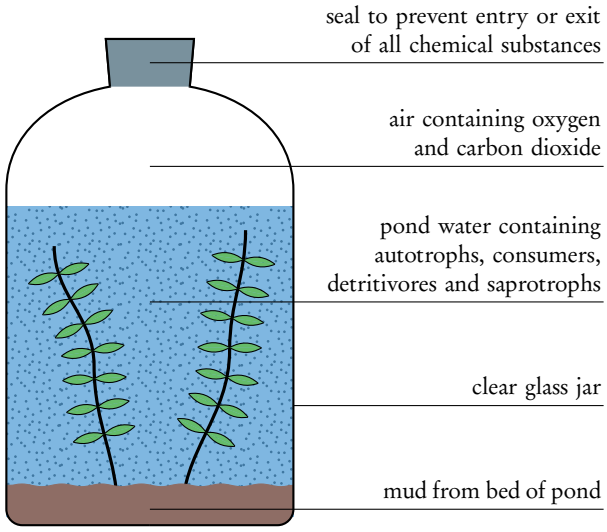


Figure 4.1: Mesocosms proving that ecosystems are self sustainable.

The set-up contains the main elements found in ecosystems: a variety of autotrophs and different types of heterotrophs (including decomposers that enable nutrient cycling), an abiotic environment (mud as a source of inorganic compounds and nutrients, water, air containing oxygen and carbon dioxide. With a source of energy (light), this sealed mini-ecosystem should be able to self-maintain for a long time.

4.2 Energy flow

4.2.1 Sunlight: main source of energy in ecosystems

In any given food chain, the first and most abundant level of organisms comprises autotrophs (e.g., plants and algae), also known as producers. Since autotrophs are mainly photosynthetic organisms, they require sunlight as a main source of energy in order to convert it into organic compounds and obtain the necessary nutrients for survival. Without this essential energy source, producers would not survive and primary consumers would not be able to feed, severely disrupting the food chain.

4.2.2 Food chains and energy pyramids: analysing energy flow in ecosystems

A food chain is a sequence showing the feeding relationships and energy flow between species sharing a habitat. The arrow shows the direction of the energy flow (energy is taken up upon ingestion by the next organism in the food chain).

Example.

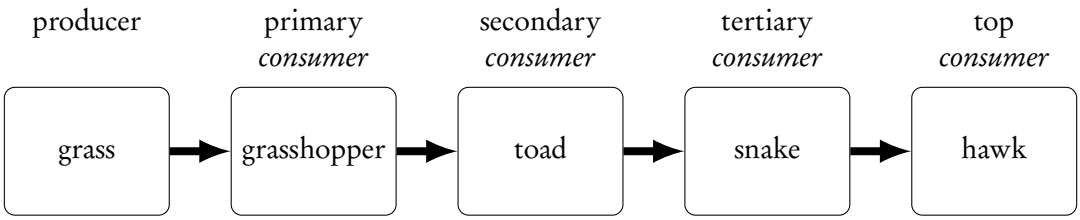


Figure 4.2: Food chains.

A series of interconnected food chains creates a food web, these are much more complicated to draw and interpret (some organisms can be different types of consumers for example). An organism's position in a food chain or web is also known as tropic level, and it is an easy way to classify organisms, the names of each trophic level are shown in grey above the food chain boxes. Energy in the form of carbon compounds flows from one organism to the next when the organism in the higher trophic level feeds on another. However, this energy flow is not 100% effective. We will see why in the next section.

4.2.3 Energy loss: limiting food chain length

Energy enters the ecosystem as sunlight, and is absorbed with about 20% efficacy by autotrophic producers and transformed into chemical energy

Chemical energy obtained from photosynthesis is transferred from one trophic level to the next by means of feeding. The chemical energy stored in bonds is released and made available to an organism when carbohydrates, lipids, proteins and nucleic acids are digested

At each step, only about 10% of the energy is successfully transferred to the feeding organism. This is because energy is lost in several ways:

- Energy released from carbon compounds is used in cell respiration and lost as heat
- When feeding, not the entire organism is eaten (bone, cartilage, etc. is often left to decompose)
- Loss of carbon dioxide, water and other waste products throughout the organism's life
- Some organisms die and decay before being eaten
- Warm-blooded and moving organisms lose more energy as heat

While nutrients can be recycled by decomposers, once energy leaves a food chain it cannot be taken up again

Energy losses of this kind restrict length of food chains and the biomass of the higher trophic levels

A pyramid of energy (example shown in Figure 4.3) shows the flow of energy from one trophic level to another in a community

- The first step is always the largest (producers)
- At each increasing trophic level, the bar becomes 10 times smaller (scaling is important here), as only 10% of energy is transferred
- Energy flow is expressed in units: kJ/m^2/year (kilojoules per square meter per year)

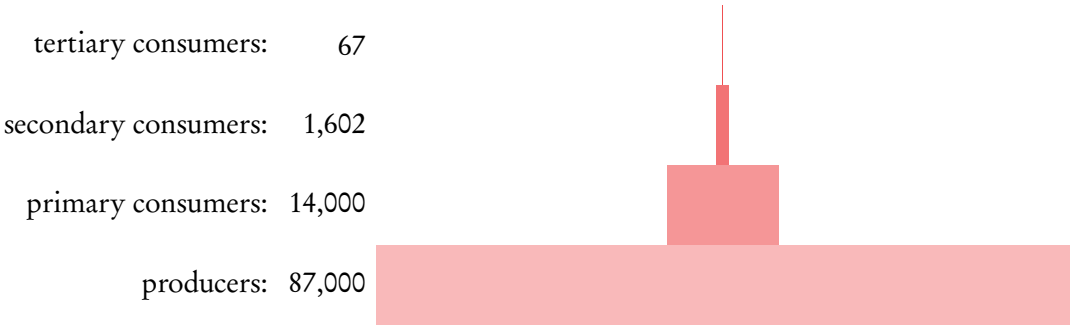


Figure 4.3: Food chains.

4.3 Carbon cycling

4.3.1 Carbon: how does it enter ecosystems?

Carbon often enters an ecosystem in the form of carbon dioxide, an inorganic molecule that is diffuses into autotrophic producers.

Autotrophs then have the ability to convert carbon dioxide into complex carbohydrates (organic molecules) and other carbon-containing molecules (e.g., proteins and lipids) through the process of photosynthesis.

Carbon dioxide is present in air; so terrestrial autotrophs can directly absorb it through specialized porous cuticles.

In aquatic ecosystems however, carbon can be found as dissolved CO_2 or in the form of HCO_3^- (hydrogen carbonate ions), which result from the chemical reaction when water and carbon dioxide combine to form carbonic acid (H_2CO_3).

These molecules can then be used in photosynthesis to produce organic compounds. These organic compounds are then used in the process of cell respiration, leading to the regeneration of carbon dioxide, which is released into the water or the atmosphere as a by-product.

4.3.2 The carbon cycle

As stated earlier, carbon dioxide enters ecosystems by diffusing into autotrophs, and is transformed into organic compounds through photosynthesis. Some carbon dioxide returns to the atmosphere as a by-product of cell respiration that takes place in producers. Primary consumers feed from producers, taking up some carbon-containing compounds (and secondary consumers feed on primary, etc.).

Cell respiration by all living organisms leads to further generation of carbon dioxide that is released into the atmosphere.

When consumers die, the leftover carbon molecules in their bodies are acquired by decomposers who eat them.

- As organic matter gets buried into the ground, it can end up in areas with no, or little, oxygen. Here, archaeans called methanogens produce methane from the metabolic by-products of anaerobic respiration.
- The methane will either diffuse into the atmosphere or accumulate under ground, forming natural gas deposits.

- Methane that diffuses into the atmosphere affects carbon dioxide concentrations as it then gets oxidized into water vapour and carbon dioxide,. However, methane persists for about 12 years in the atmosphere before being naturally oxidized.
- The rising number of cattle nowadays has also dramatically increased the methane concentrations released into the atmosphere.

Partial decomposition of dead organisms and fossilization lead to the formation of fossil fuels (more details in the next section)

Combustion of fossil fuels in industrial factories produces carbon dioxide that is released into the atmosphere in great quantities

All of the aforementioned interactions create a cycle of movement of carbon dioxide between the spheres of the earth. These include: the atmosphere (air), lithosphere (ground), hydrosphere (water), and biosphere (living organisms).

Skill: Construct a diagram of the carbon cycle.

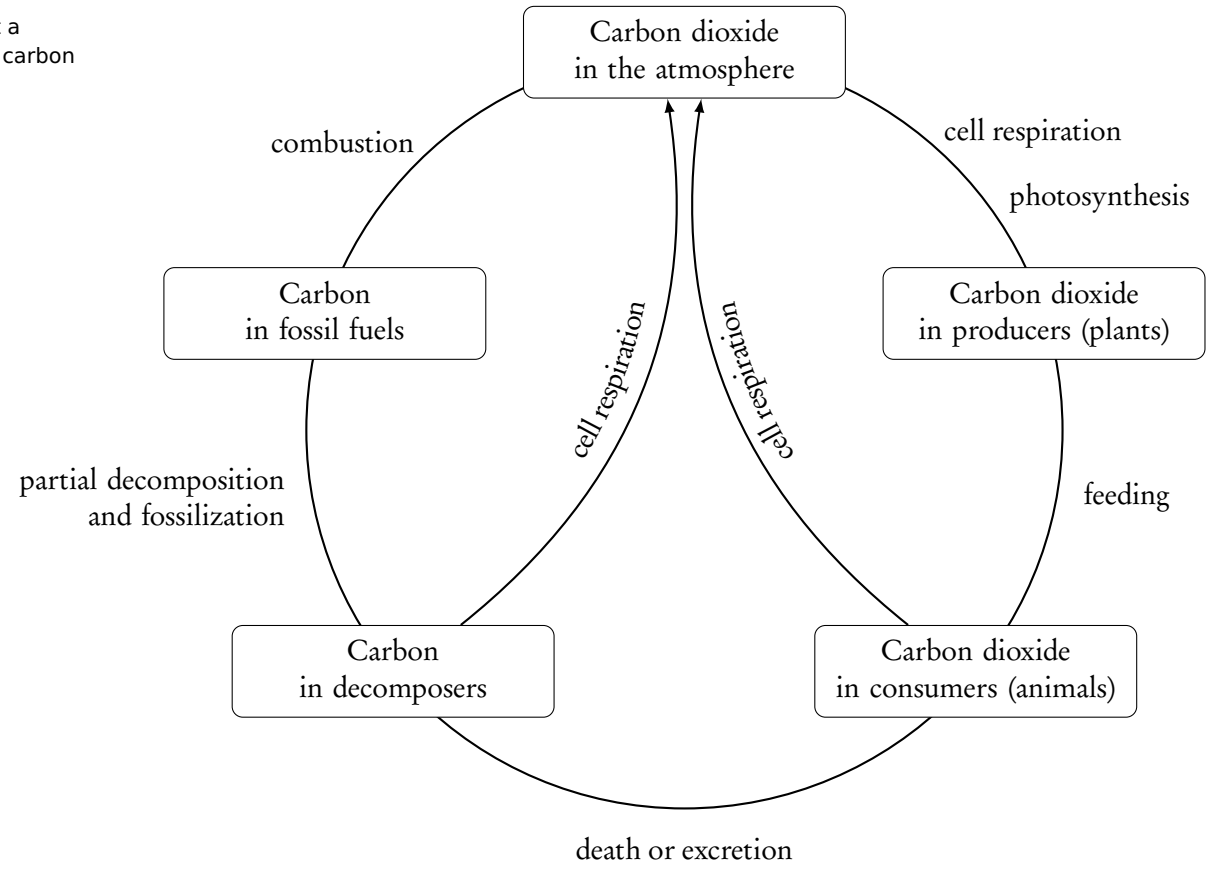


Figure 4.4: Carbon cycle.

4.3.3 Decomposition of organic compounds

Formation of peat and coal

In acidic and anaerobic conditions (e.g., swamps and bogs), saprotrophs cannot fully break down dead organic matter as they require oxygen to function properly.

Partially decomposed organic matter accumulates to form thick deposits called peat.

Peat deposits get compressed under sediments, and with increased heat underground, it forms into a highly concentrated material that undergoes chemical reactions and becomes coal.

Formation of oil and gas

Silt and the remains of dead organic organisms can sometimes accumulate in shallow seas.

Due to the anaerobic conditions, these organisms are only partially decomposed.

Like in peat formation, the slit accumulates and is buried under layers of sediment over time. Through this compaction and heating, hydrocarbons are formed, which make oil and gas, a process that takes millions of years.

The oil and gas formed is forced out of the source and it accumulates in porous rocks. It is then forced out of there when humans drill into such rocks.

4.4 Climate change

4.4.1 The greenhouse effects and greenhouse gases

The greenhouse effect, despite the negative connotations associated to the concept, is a naturally occurring phenomenon that has enabled life on Earth for millennia.

Sunlight enters the atmosphere in the form of waves. Short-wavelength radiation is partly absorbed by the ozone layer (mostly ultraviolet → about 25%). The remaining 75% of larger wavelengths radiation reaches the Earth's surface, where it is absorbed and produces heat.

The Earth's surface re-emits radiation (like a reflection) at much longer wavelengths (infrared → heat).

A high percentage (75–80%) of this radiation is absorbed by greenhouse gases in the atmosphere.

These gases re-emit radiation, and some of it reaches the surface of the Earth again, causing warming (atmospheric temperature is significantly warmer that outer space.

Greenhouse gases are special in that they have the ability to absorb this long-wavelength radiation that is emitted from the Earth's surface.

The main greenhouse gases are carbon dioxide and water vapour both found in low concentrations in the atmosphere.

Oxides of nitrogen and methane are also greenhouse gases present in the atmosphere.

It is important to realize that ozone is greenhouse gas, so ozone depletion does not increase the greenhouse effect.

4.4.2 The enhanced greenhouse effect and its effect on global temperatures

Currently, increased levels of greenhouse gases in the atmosphere caused by industrialization cause the atmosphere to retain more and more heat. This is known as the enhanced greenhouse effect, a phenomenon that has affected average global temperatures and climate patterns on Earth.

Human activity has considerably increased the production of greenhouse gases (predominantly carbon dioxide) in the last 200 years, starting after the onset of the industrial revolution, where the combustion of fossil fuels became a major source of fuels and energy for human development.

Some human activity that has led to the increase in greenhouse gas production:

- Burning of fossil fuels
- Use of ammonia-based fertilizers
- Industrial processes (e.g., production of nitric acid)
- Waste disposal in landfills
- Production and distribution of natural gas

These processes have led to a considerable increase in carbon dioxide and methane in the atmosphere. This in turn has caused a major increase in global temperatures in the last two centuries, causing rises in sea level, destruction of Arctic habitats, coral reefs, and much more.

4.4.3 Changes in atmospheric CO_2 concentrations and average global temperature

Over the last 150 years, carbon dioxide emissions have increased significantly, mostly as a result of fossil fuel combustion in industry. While there is a clear correlation between an increase in carbon dioxide emissions and an increase in global temperatures, other variable factors influence this process (e.g., atmospheric concentration of other greenhouse gases).

EVOLUTION AND BIODIVERSITY

5

5.1 Evidence of evolution and natural selection

Evolution is the accumulation of changes in heritable characteristics of a species over time.

This means that over times, certain characteristics of a species change, and if these characteristics are inheritable, then this change is transferred to all the subsequent generations.

Speciation is a process through which one species spits into two separate species.

Adaptation is the process of change by which an organism or species becomes better suited to its environment.

If the members of one species become separated for a long period of time, their characteristics (due to adaptations to the new environment) will start changing as well.

Sometimes it happens that these two populations change so much that, even if they got reunited, they would not be able to interbreed anymore.

5.1.1 Evidence of evolution

Pentadactyl limb

Mammals, birds, reptiles and amphibians all have limbs which they use to different purposes.

Some limbs are used for running, walking, swimming or jumping, but eventually, all possess the same pentadactyl structure (5 digits).

The explanation for this is that all these animals have the same ancestor that had a pentadactyl limb, but as the organisms adapted to different environments (water, forest, desert, etc.), the exact structure started differing.

As the limb structure changed as a response to different environments, this type of evolution is called adaptive radiation.

Selective breeding

Domesticated animals are an example of a “fast forwarded” evolution.

Wild animals with favourable characteristics for humans were bred with other such animals of the same species to get offspring with similar characteristics.

This process is called selective breeding.

An example of this would be a dog, which is a domesticated wolf.

Wolves that were less aggressive were domesticated and bred until more such offspring were produced.

Then, for example, only the smaller individuals were bred which resulted in a smaller dog species (etc.)

Fossil records

Fossils are remaining of organisms found in stones that can help us determine their age and compare them to the currently living species.

It is possible to determine the age of stones where fossils were found and this has shown that bacteria are found in the oldest fossils, followed by algae, fungi and more complex organisms later.

Acanthostega is a fossil of a vertebrae that doesn’t match any of the current living species, but shows similarities with them.

It has both 4 limbs that matches amphibians, but also a fish-like tail and gills which suggests it was probably a transition species between the fish and amphibians.

Melanism

Melanism refers to the phenomenon where a lightly coloured species has a darker variant.

Lightly coloured moths are well adapted to avoid predators by blending with the lightly coloured tree branches.

The melanistic form cannot blend in with the trees so are frequently eaten.

During industrial revolution, the smog caused the trees to darken so the lightly coloured moths suddenly became very visible on the tree branches and got eaten more often.

In these areas, the melanistic form was less noticeable so it had higher rate of survival, and became more prevalent.

The switch from the light population to the dark population is an example of evolution as it shows how the species changes as a result of a changing environment by passing on its favourable genes.

5.1.2 Natural selection

Charles Darwin was the first scientist to publish the theory of natural selection, although Alfred Wallace had the same idea at the same time (but was just too slow to publish).

Natural selection suggests that the better adapted species will have a higher chance of survival and will therefore be able to pass on their genes and the species will evolve towards the better adapted species.

Observations of natural selection

There are more organisms than the environment can support

Individuals must compete for natural resources to survive. Different individuals of the same population have slightly different traits which make them better or less well adapted to the environment. Individuals with better adapted traits are more likely to catch pray, survive and breed, so their genes are passed on to the next generation. In this way, the favourable characteristics are increased within the population, and the *population gradually evolves.*

* Note that only the genetically determined traits can be passed on this way. An athlete, whose muscles have grown through exercise will not pass her big muscles to her offspring.

Examples of natural selection

Example.

Beak size of finches

Galapagos finches feed on seeds that fall on the ground, and for that, they have specially adapted beaks.

Some finches have larger, and some finches have smaller beaks. The larger beaks are better for eating larger, harder seeds.

During drought season, smaller seeds are not common, and only the large seeds are produced. If the drought extends for a long period of time, as it did between 1974 and 1977, the finches with larger beaks tend to be better adapted to cracking bigger seeds and are more likely to survive.

The mean beak size during those drought years was found have increased due to the fact that the animals with smaller beaks couldn't open the larger seeds and would therefore die before passing on their genes.

However, during a rainy season in 1983, there were more smaller seeds, and the animals with smaller beaks were faster to pick those up, so they had an advantage compared to the ones with larger beaks.

The mean beak size again decreased, as now the better adapted individuals were those with the smaller beaks, and they could breed and create more offspring.

Example.

Antibiotic resistance in bacteria

Bacterial antibiotic resistance is a growing problem in the world.

Normally, the antibiotic resistance gene exists in organisms that naturally produce the antibiotic.

This gene can be transferred to bacteria through the means of a plasmid.

The bacteria that have the gene cannot be killed by the antibiotic, so when it is administered to the patient suffering from a bacterial infection, all the non-resistant bacteria will die, and the resistant ones will survive and multiply.

Since these bacteria can't be killed by this type of an antibiotic, another antibiotic can be administered, killing this population, but giving a selective advantage to the ones possessing resistance gene for the other antibiotic.

In the end, only the resistant bacteria survive, multiply and exchange genes, leading to a broad range of ineffective antibiotics.

This can be avoided by limiting the antibiotic use, and by always taking the full does that ensures that all the non-resistant bacteria are killed and that they can't acquire resistance genes from the resistant bacteria.

5.2 Classification of biodiversity

5.2.1 Binomial system and dichotomous key

Binomial system is a universal system used to name the newly discovered species.

The first name in the system is *genus* and is written in the capital letter. The second name is the name of the species, written in the lower-case letter. When printed, the name is written in italics, such as *Homo sapiens*.

Dichotomous key is a tool that helps biologists distinguish between different organisms and classify them correctly.

An example of dichotomous key will be made after you learn about the classifications of plants and animals.

The key makes use of a series of statements about the features of an organism. These statements are numbered. Some statements lead to other statements that help better classify the organism. Other statements immediately give the name of the organism in question

Classification is the term for grouping of species.

Taxonomists are biologists that specialize in the field of classification.

Artificial classification refers to classifying organisms based on one feature that they share, but disregarding all the other ways in which they differ.

An example of this would be classifying all animals with a tail together. A squirrel and a lizard would both be classified together, even though they share very little in common, besides that, and their tails have different structure and function.

Natural classification is an alternative way of grouping organisms, based on their ancestry.

If species are grouped based on their common ancestor, they will share many more features. This ways of classification also helps identification of species, and is useful for prediction of their characteristics.

5.2.2 Domains and phylogeny

All organisms are classified into three main domains, namely *archea*, *eubacteria* and *eukaryota*.

Previously, the organisms were divided either into prokaryotes or eukaryotes, but archea and bacteria are as different from each other as they are from the eukaryotes.

Based on their RNA sequences, it seems that eubacteria and archea diverged very early in the evolution.

Viruses are not living organisms so they do not fit into any of the domains.

Taxon is a group of organisms, grouped by the means of natural classification.

The 8 main taxa with the animal and plant exampls are:

Table 5.1: 8 main taxa.

Name	Human	Sequoia
Domain	Eukaryota	Eukaryota
Kingdom	Animalia	Plantae
Phylum	Chordata	Coniferophyta
Class	Mammalia	Pinopsida
Order	Primate	Pinales
Family	Hominidae	Cupressaceae
Genus	*Homo*	*Sequoia*
Species	*sapiens*	*sempervirens*

5.2.3 Classification of plants

Plants are classified into 4 main phyla, and you need to know how to distinguish between them, based on their structure.

Bryophytes – Mosses

- No real roots, but only rhizoids (root-like hairs)
- Simple leaves and stems
- No vascular tissues
- Reproduce using spores which are stored in capsules at the end of a stalk

Filicinophytes – Ferns

- Real roots and leaves, but short non-woody stems
- Leaves are often divided into pairs of leaflets
- Have vascular tissue
- Reproduce through spores which are made in sporangia, inside the leaves

Coniferophytes – Conifers

- Have real roots, leaves and woody stems
- Thick leaves with a waxy cuticle (imagine what a Christmas tree would look like)
- Have vascular tissue
- Reproduce using seeds which are made by female cones in structures called ovules
- Male cones will produce pollen used for fertilization

Angyospermophytes – Flowering plants

- Real roots leaves and stems
- Some plants, like trees and shrubs have a woody stem, others don't
- Have vascular tissue
- Reproduce using flowers - seeds are again made in ovules, but now in ovaries of flowers
- Fruits, which develop from these ovaries are used to disperse the seeds

5.2.4 Classification of animals

We will discuss 7 of the 30 possible animal phyla.

Porifera – Sponges

- No symmetry
- Attached to the surface
- No mouth or anus
- Contain pores

Cnidaria – Jellyfish

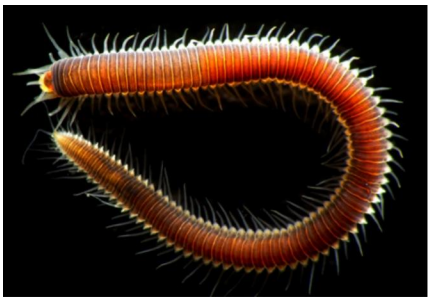
- Radial symmetry
- Tentacles and stinging cells
- Mouth, no anus

Platyhelminths – Flatworm

- Bilateral symmetry
- Flat body
- Unsegmented
- Mouth, no anus

Annelida – Centipedes

- Bilateral symmetry
- Segmented
- Mouth and anus



Arthropoda – Spiders and scorpios

- Bilateral symmetry
- Exoskeleton
- Segmented
- Appendages divided by joints

Mollusca – Snails

- Mostly bilaterally symmetrical
- Muscular foot and mantle
- Shell
- Mouth and anus

Chordata – Fish, mammals etc.

- Notochord and dorsal nerve chord (imagine a spine and nerves in it)
- Post-anal tail

5.2.5 Classifications of vertebrates

The phylum of chordata are very diverse, and we will now classify them further.

Bony ray-finned fish

Unlike in a dolphin with soft fins, these fish have fins supported by bones.

- Scales on skin
- Gills with one slit
- Fins supported by rays
- Swim bladder (so that they can change altitude in water)
- External fertilization

Amphibians (frogs)

- Soft, permeable skin
- Lungs with few folds
- External fertilization with gel that protects the eggs
- Larva live in water

Reptiles (crocodiles)

- Dry and scaly skin – impermeable
- Lungs with a lot of folds
- Internal fertilization with soft shelled eggs
- One type of teeth

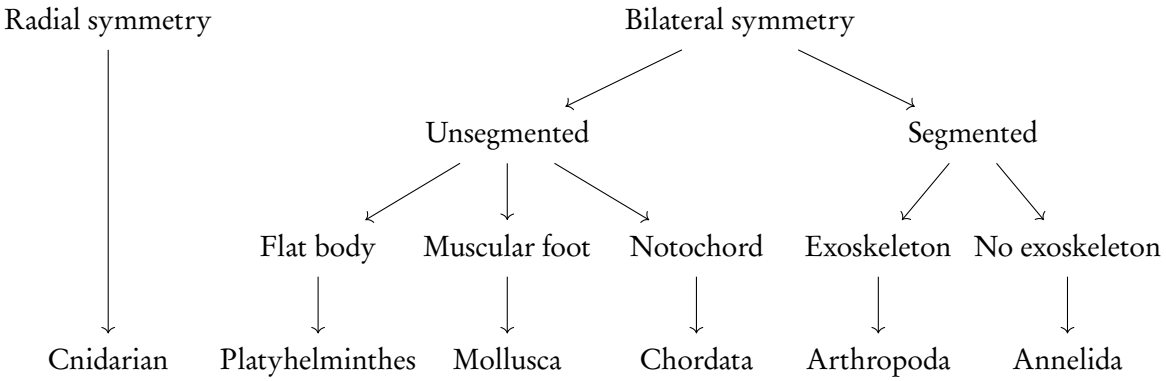
Birds

- Feathers on skin
- Lungs with parabronchi
- Wings, but no front legs
- Hard shells on eggs
- Beak, and no teeth

Mammals

- Hairs on skin
- Lungs with alveoli
- Give birth to live animals
- Mammary glands with milk
- Teeth of different kinds

Let's construct that dichotomous key, based on animal phyla!



5.3 Cladistics

Clade is a group of organisms that evolved from a common ancestor.

Cladogram is a tree diagram that shows how clades diverged one from another.

Cladistics is a method of classification that analyses base and amino acid sequence data to determine ancestry and construct cladograms.

Analogous traits are those traits that have a similar appearance and function, but have do not share the same origin.

Analogous traits arise from convergent evolution, meaning that species of different origins, developed similar features in response to their environment.

An example of this could be the wings of birds and bats, which have the same function even though the species developed these traits independently.

Homologous traits are traits that are structurally different, but have the same origin.

Homologous traits are a result of divergent evolution, where a particular trait, shared by many species, accumulates structural differences as a response to the environment.

An example of this is the previously mentioned pentadactyl limb (first section of this chapter).

In the past, the only way to compare ancestry of certain species was to look at their anatomical features, but at some point, as in the case of bats and birds, it might be difficult to determine whether these features share a common ancestor, or have arisen by convergent evolution.

Today, cladistics takes advantage of possibility of genome sequencing. There is a positive correlation between the number of amino acid sequences, and the time since they have split from a common ancestor.

5.3.1 Human classification through cladistics

Mitochondrial DNA was used to classify humans and several other primates, using a cladogram. Mitochondria contain their own DNA, which is passed on from a mother to her child, as it is the mother gamete's cytoplasm that is used for the first cell of the embryo development. The size of these DNA molecules is much smaller than that of nuclear DNA, and it resembles that of plasmids in prokaryotes (remember the symbiotic theory).

Still there are base pair differences that can help us determine the time points when certain primate species diverged from each other

- 5 million years ago: Human-Chimpanzee
- 140,000 years ago: African-European/Japanese
- 70,000 years ago: European-Japanese

5.3.2 Reclassification of figworts

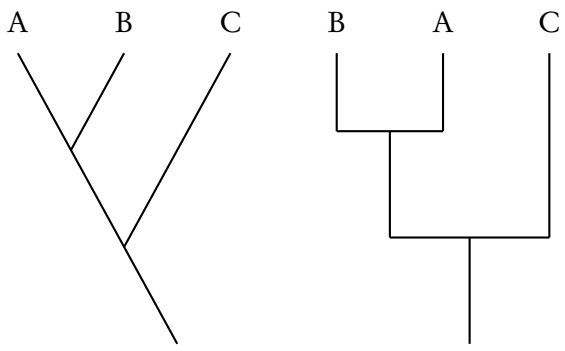
Figworts were originally classified based on their structural differences. Sequencing of their genome showed that species within that family did not share a common ancestor.

Some plants were moved to pre-existing families (like plantain and broomrape). Others were transferred to completely new families based on evidence of a split between species. Some pre-existing families were found to actually share the ancestor with figworts, so these families were all merged into one.

With the developments in computers' analytical power and sequencing methods, there will probably be more and more re-classifications.

5.3.3 Cladogram analysis

Cladograms are constructed by plotting lines with branching points which represent points of divergence between species. These lines are usually plotted against time and percentage difference in the analysed variable (amino acid sequence, base pair sequence etc.).



HUMAN PHYSIOLOGY

6

6.1 Digestion and absorption

6.1.1 Digestion: why is it essential?

The food we eat consists of large and complex organic molecules, eg. *starch*, which *cannot be absorbed* by cells in the intestines. Digestion is the biochemical *breakdown of large, insoluble molecules into smaller ones*. For example, starch broken down into glucose is a useful source of energy.

Skill: Production of an annotated diagram of the digestive system (TIP: annotated suggests that the elements shown on the diagram must be briefly described, use the information on this section to correctly annotate the diagram of Figure 6.1 with the basic function of each labelled structure)

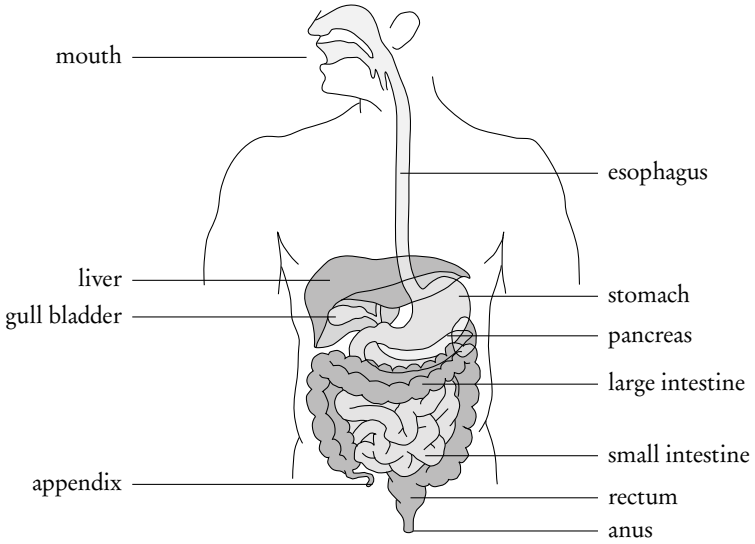


Figure 6.1: Digestive system.

Chemical Digestion is the breaking down of food with chemical agents. This includes enzymes, acids, and bile.

Mechanical Digestion is the act of physically digesting food through chewing, churning, and segmentation

6.1.2 Mixing and moving food along the gut: longitudinal and circular muscle contraction in the small intestine

Digestion begins in the mouth, where chewing breaks down the food into smaller pieces, as well as some enzymes begin to break down some carbohydrates. Then, the partially digested food arrives to the stomach, where churning occurs, which are movements of the stomach that mix and breakdown molecules more. Here, there are acids that also allow enzymes to get activated and break down molecules, as well as destroy possible pathogens with the low pH.Partially digested food from the stomach enters the small intestine and moves down this structure due to *peristaltic muscle contraction*.

The small intestine has an inner layer of *longitudinal muscle* and an outer layer of *circular muscle*. Circular muscles contract behind the food to prevent backflow, whereas the longitudinal muscles contract to move the food along the intestine. When both layers of muscle contract simultaneously, they allow for the food to be mixed with digestive juices from the gall bladder and pancreas.

To enhance the absorption process, the surface of intestinal cells contain small *finger-like projections* called *villi*, each of which contains a network of capillaries and a *lacteal* (a branch of the lymphatic system that enables lipid absorption) that connect to larger blood vessels and the lymphatic system. Moreover, each cell that lines the intestinal wall has *hair-like extension* called *micro-villi* that further increase surface area for absorption.

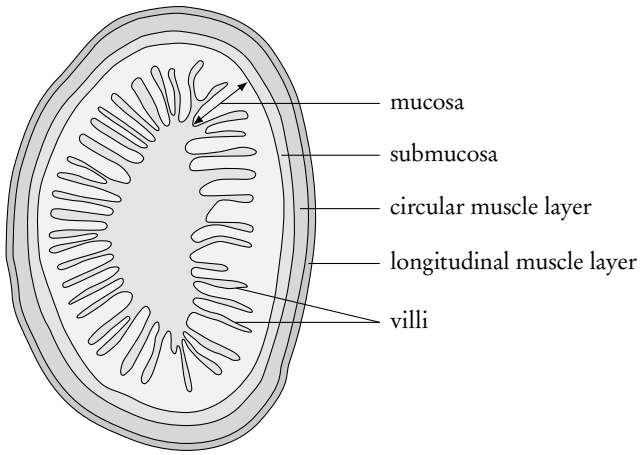


Figure 6.2: The structure of the small intestine.

6.1.3 Digestive enzymes

Skill: identification of tissue layers in transverse sections of the small intestine viewed with a micro-scope/micrograph

Physical breakdown of large food molecules is not enough for molecules to be small enough for absorption. Therefore, complementary chemical breakdown is necessary. Enzymes act as *biological catalysts* increasing the rate of digestion. This allows digestion to occur at *normal body temperature*. Several enzymes are needed as each is *substrate specific*. Note the source, substrate, products and optimal pH of each enzyme.

Enzyme type	Example	Source	Substrate	Products	Optimal pH
Amylase	Salivary amylase	Salivary glands	Starch	Maltose	7
Amylase	Alpha amylase	Pancreas	Starch	Maltose	7
Maltase	Intestinal maltase	Intestinal wall	Maltose	Glucose	7
Protease	Pepsin	Stomach wall	Proteins	Small polypeptides / amino acids	2–3
Endopeptidase	Trypsin	Pancreas	Proteins	Small polypeptides	7
Lipase	Pancreatic lipase	Pancreas	Triglycerides	Fatty acids + glycerol	7

6.1.4 Absorption: the structure and function of villi

The absorption phase is the process by which the products of digestion, mineral ions and vitamins are taken up through the villi that line the small intestine. To achieve maximal absorption the structure of the villus has a number of functional adaptations:

Villi have a large surface area to volume ration. They are one-cell thick structures, which is advantageous for the products of digestion to easily cross from the lumen of the intestine to the network of capillaries and lacteals for quick absorption.

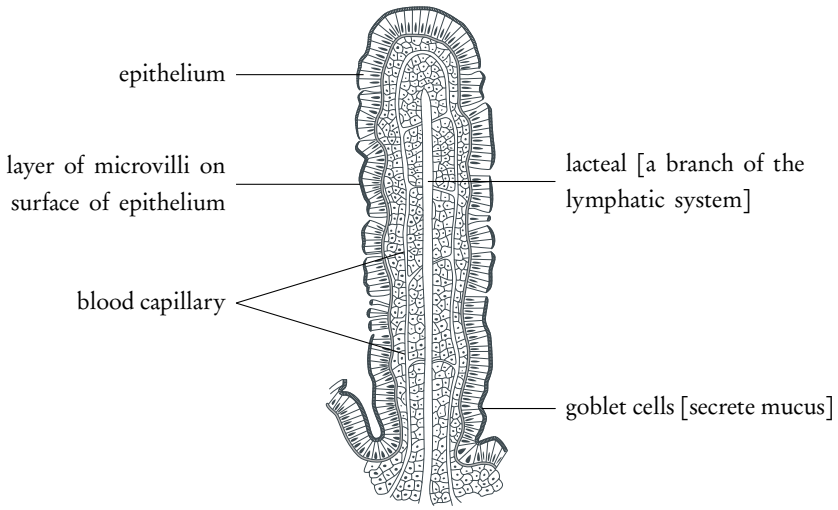


Figure 6.3: Structure of a villus.

Each cell in the mucosa contains smaller structures called microvilli that further increase surface area for absorption of nutrients. These structures contain specific protein pumps

and channels that facilitate the movement of molecules across membranes in the correct direction (from intestine to capillaries/lacteals).

Absorption occurs via different processes, all of which have been discussed in previous chapters, depending on the type of molecule to be absorbed:

Facilitated diffusion	(e.g., hydrophilic nutrients like fructose)
Simple diffusion	(e.g., hydrophobic nutrients like fatty acids)
Endocytosis	(e.g., larger molecules like cholesterol and triglycerides)
Active transport	(e.g., charged ions like calcium and sodium)

Example.

Digestion and absorption of starch derivatives

Starch consists of two different molecules: amylose and amylopectin, both linked by alpha-glucose 1,4 links. The only difference is that amylopectin also contains a few alpha-glucose 1,6 bonds. Amylase (salivary and pancreatic) can only break 1,4 bonds, digesting starch into maltose molecules and 1,6 bond-containing segments known as dextrins (which cannot be broken down by amylase). To further digest these molecules, maltase and dextrinase in the small intestine convert the remaining molecules into glucose, which can then be absorbed by the villus through protein pumps (active transport).

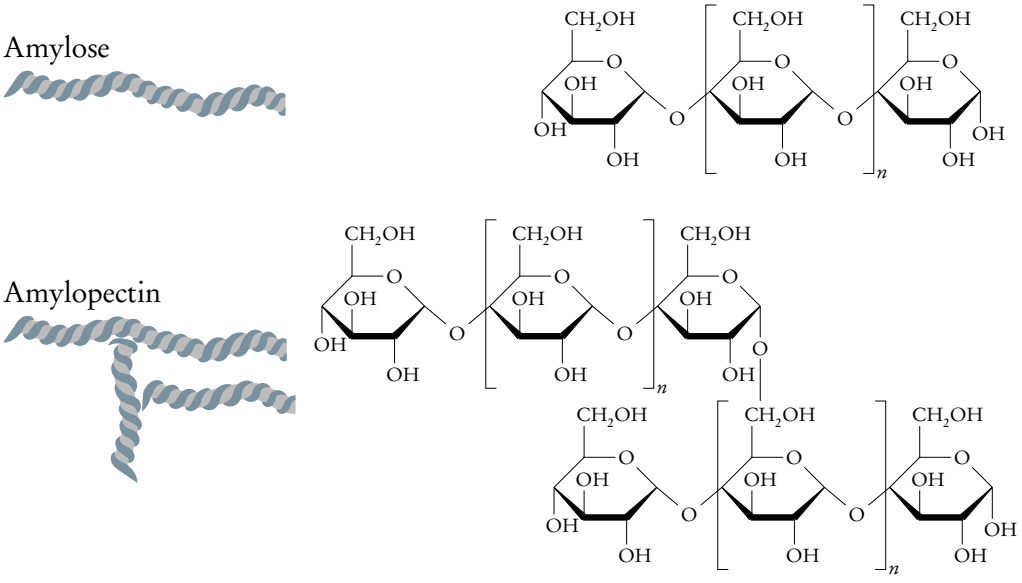


Figure 6.4: Amylose vs. amylopectin.

Diagram showing the difference between amylose and amylopectin (two components of starch molecules). Amylose consists only of 1,4 bonds that result in a straight chain of glucose molecules. Amylopectin on the other hand contains "kinks" that result from 1,6 bonds between certain glucose molecules. These kinks cannot be broken down by amylase, and must be digested by dextrinase in the small intestine.

6.2 The blood system

6.2.1 The cardiac cycle: blood circulation in the body

In the 17th century, William Harvey proposed the theory of blood circulation that continues to be applied today. He demonstrated that the 4-chambered heart was the central "pumping mechanism" that caused blood to circulate the body at high pressures in arteries, and returned to the heart through veins. He also found that these two types of blood vessels are connected by small, hardly visible vessels now known as capillaries. Further research led him to conclude that certain blood vessels contain valves that prevent the backflow of blood, as well as to distinguish between two separate circulations that take place in the body:

Pulmonary circulation that carries deoxygenated blood from the heart to the lungs, where it becomes oxygenated and returns to the heart.

Systemic circulation that carries newly oxygenated blood to the rest of the body, and returns deoxygenated blood back to the heart to enter pulmonary circulation.

Nowadays, the exact mechanism and structures involved in blood circulation have been clearly defined.

Figure 6.5 is a a diagram of the heart, our "central pump", labelled with the major blood vessels, valves, and chambers involved in circulation.

Skill: Recognition of the chambers and valves of the heart and the blood vessels connected to it in diagrams of the heart structure.

The atria collect blood from veins (vena cava/pulmonary) at low pressure. Blood leaves the atria into ventricles ensuring the ventricles are full.

On the other hand, ventricles pump blood into arteries out of the heart and into the 2 systems previously discussed. They can pump blood at high pressure because of their thicker, muscular walls. The heart valves work with the atria and ventricles to keep blood moving by preventing backflow. Note that the left ventricle supplies blood for the systemic circulation whereas the right ventricle supplies blood for pulmonary circulation.

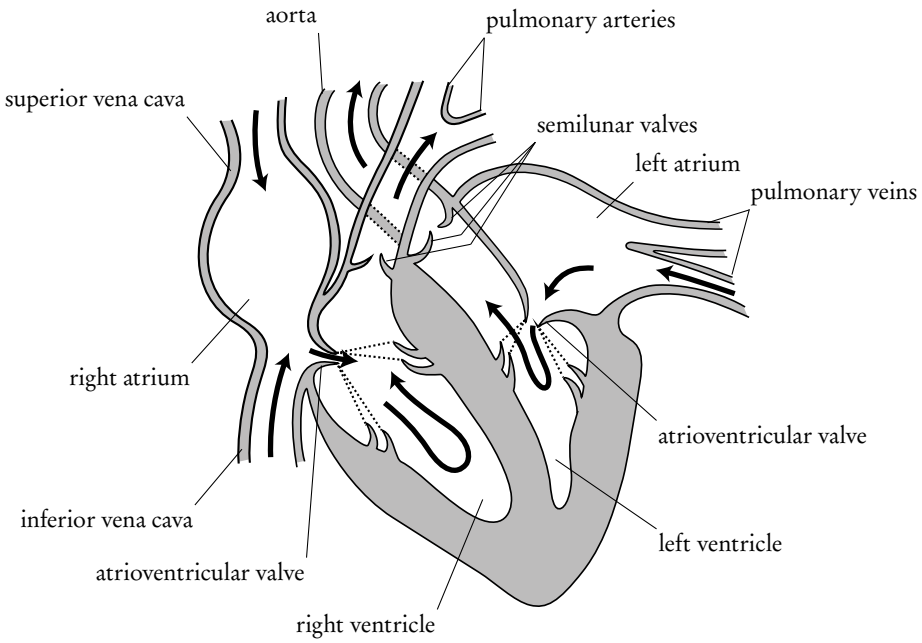


Figure 6.5: Heart structure (cross section).

TIP: Try going through each circulation process using the diagram of the human heart on Figure 6.5!

Pulmonary circulation

1. Deoxygenated blood from the superior and inferior vena cava collects within the right atrium.

2. The walls of the right atrium contract, pushing blood from the atrium into the right ventricle through the atrioventricular valve.

3. Once blood has accumulated in the right ventricle, it contracts powerfully causing:
   1. right atrioventricular valve to close to prevent backflow;
   2. increase of pressure in the right ventricle, leading to the opening of the right semilunar valve (also called pulmonary valve), pumping blood into the pulmonary artery. note that this is an artery that carries deoxygenated blood.

Systemic circulation

Blood from the pulmonary veins collects in the left atrium.

The walls of the left atrium contract, pushing blood from the atrium into the left ventricle through the left atrioventricular valve.

Once blood has accumulated in the left ventricle, it contracts powerfully causing:
1. left atrioventricular valve to close to prevent backflow;
2. increase of pressure in the left ventricle, leading to the opening of the left semilunar valve (also called aortic valve), pumping blood into the aorta.

The left ventricle has a much thicker musculature, as the aorta effectively distributes blood to the entire body, so an even more powerful contraction is necessary

4	Blood is carried by arteries, arterioles and capillaries toward the lung alveoli, where it is oxygenated.	The aorta branches towards the entire body, one of the first branches directs blood to the coronary arteries (which supply the heart muscle with oxygenated blood for efficient muscle contraction). The rest of the blood is carried by arteries, arterioles and capillaries to the whole body to provide nutrients and oxygen.
5	Pulmonary veins return oxygenated blood to the left atrium. Note that these are veins that carry oxygenated blood.	Venules, veins and the inferior and superior vena cava return deoxygenated blood to the right atrium.

Both circulations occur simultaneously, so atrial and ventricular contractions occur in unison. Figure 6.6 is a graph of the pressure changes at each of the processes described previously in the atria and ventricles:

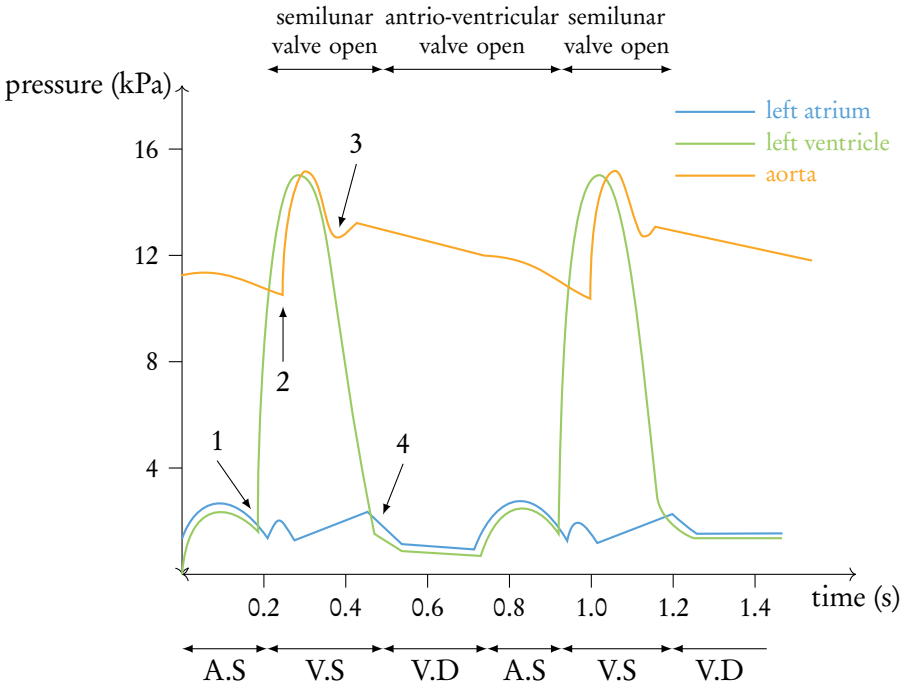


Figure 6.6: Pressure in the cardiac cycle.

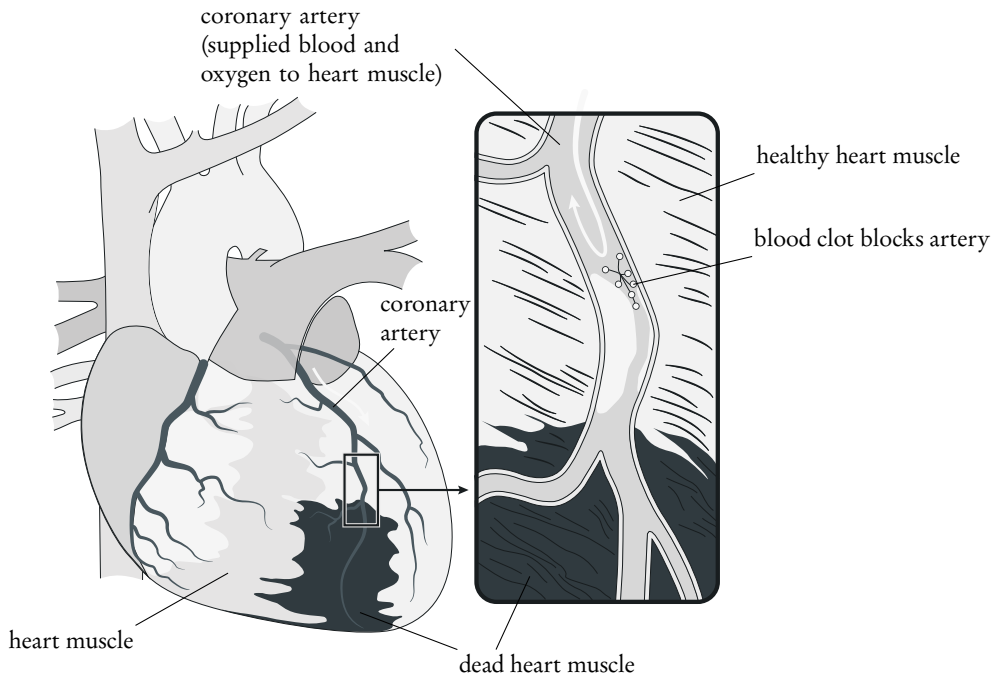
Example.

Coronary occlusion

Coronary artery occlusion, a common phenomenon caused by fatty plaques building up in the inner coronary arteries is a dangerous occurrence that restricts oxygen and nutrient supply to heart muscle, limiting contraction and thus blood circulation. This can cause chest pain and potential cardiac failure.

Some potential causes for this disease include:

- Hypertension
- Smoking
- High blood glucose (usually due to diabetes)
- High cholesterol levels
- Genetic factors



A comparison of the structure and functions of blood vessels

Artery	Capillary	Vein
Thick walls	Walls one-cell thick	Thin wall
No valves	No valves	Valves
High blood pressure	Low blood pressure	Low blood pressure
Carry blood from the heart	Link arterioles to venules	Carry blood to the heart
Narrow lumen	Narrow lumen	Wide lumen

Skill: Identification of blood vessels as arteries, capillaries or veins from the structure of their walls.

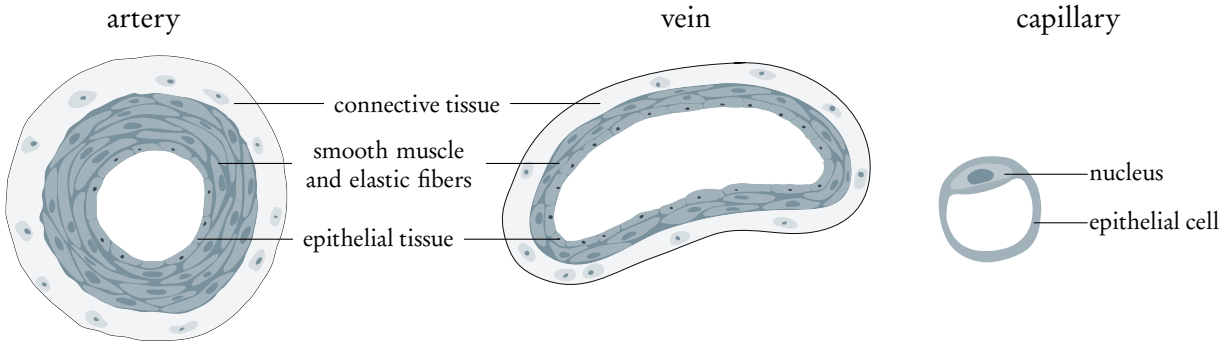


Figure 6.7: Comparison of the structure of an artery, a vein and a capillary.

6.2.2 Control of heartbeat: the role of the pacemaker cells, brain signals and adrenalin

Cardiac muscle is *myogenic*, meaning that it can contract and relax without stimulation from the nervous system. Heart contractions are initiated at an in-built *pacemaker* (which keeps the cardiac muscle working in a coordinated sequence), called the *sinoatrial (SA) node*.

The SA node is a region of pacemaker cells in the right atrium that sets the basic pace of the heart the SA node produces the initial impulse that *causes both atria to contract at the beginning of each heartbeat*.

This electrical current spreads between cells of the heart to create a coordinated contraction. It first spreads through the walls of the atrium for atrial contraction and gets delayed in between the atria and ventricles at a structure called “bundle of His” to have separate contraction phases. Finally it spreads down through the walls of the ventricles to cause coordinated ventricular contraction.

The *atrioventricular (AV) node* is located at the bottom of the right atrium. This structure also has pacemaker cells, with a rate of firing that is slower than that of the SA node. For this reason, the electrical impulse from the SA node reaches the AV node and

sets the pace of the heart beat. If there were to be any dysfunction of the SA node, the AV node could then take over and set a slow "survival" pace of the heart.

The natural rhythm of the pacemaker is modulated by the nervous system (signals from the medulla) and hormones (adrenalin).

Signals to speed up heart rate pass along the sympathetic nerve, and those to slow down heart rate pass through the parasympathetic to slow down heart rate.

Additionally, emotions such as stress and increase in activity level cause the adrenal glands to release the hormone adrenalin (which stimulates the pacemaker to increase heart rate).

6.3 Defence against infectious diseases

Blood clot is a semi-solid lump from liquid blood that is used to seal the cut in the blood vessels and prevent further entry of pathogens into the blood stream.

Platelets are cell fragments present in blood that help create a blood clot upon injury.

Clotting factors are molecules produced by damaged tissues and platelets which set off a cascade of events that lead to the formation of a blood clot.

6.3.1 Blood clotting

In case of a blood vessel injury, platelets and damaged cells release *clotting factors*.

These clotting factors cause the conversion of an inactive protein *prothrombin* into an active form called *thrombin*.

Thrombin further catalyses the conversion of soluble *fibrinogen* to insoluble *fibrin*, which is a long protein that forms a fibrous mesh that catches surrounding blood cells and forms a lump of blood called the blood clot.

If the clot is exposed to air, as is the case at the site of injury, it dries and protects the blood vessels from further entry of pathogens and blood loss.

Blood clotting in coronary arteries

In case of serious plaque deposits in coronary arteries (atherosclerosis), there is a high chance of the plaque rupturing and spilling into the blood stream.

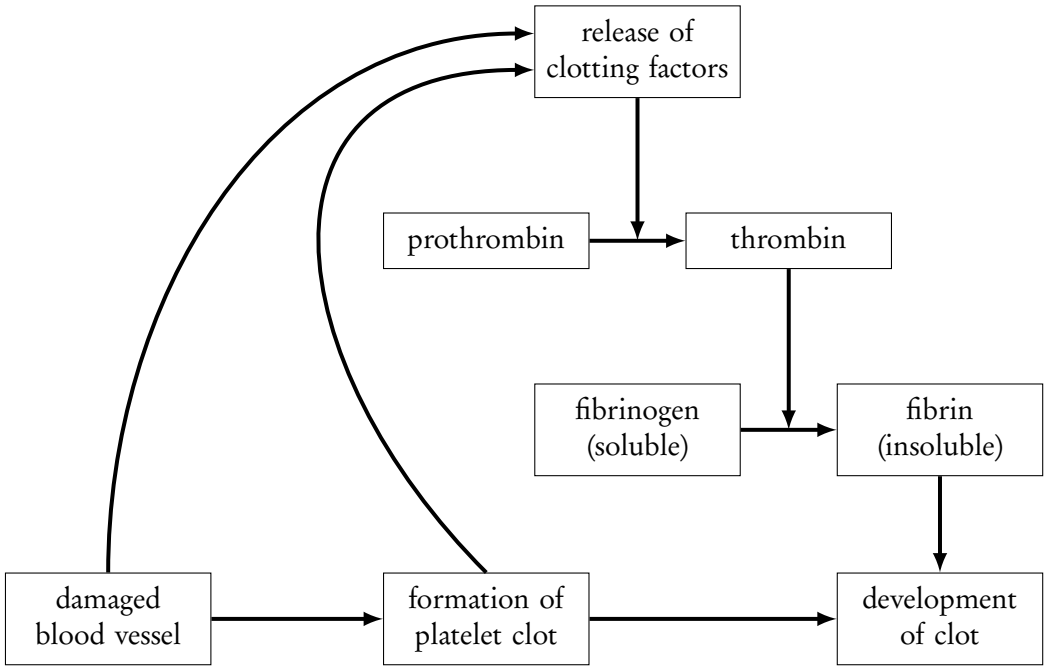
The rupture, as well as the contact of blood with the plaque contents causes a clotting cascade to begin, leading to the formation of a blood clot.

Since coronary arteries are rather narrow, the clot often blocks the blood supply through this artery, and therefore the heart tissue supplied by this vessel stops receiving oxygen and nutrients.

If a blood clot breaks off, it releases a thrombus that can move through the circulation until it gets stuck in smaller arterioles or near capillary beds, cutting off blood supply to the area.

If the supply is blocked for long periods of time the heart tissue gets damaged, which is termed heart attack, or to uncontrolled contractions of the heart called fibrillations.

Some heart attacks are less serious, and the heart can partially recover and start beating again, while more serious artery blocks lead to complete loss of heart function and death.



Pathogen is an organism that causes disease, for example a virus, bacterium or a fungus.

The human body is equipped with two "lines of defence" to protect itself from pathogens:

1st line of defence is the physical barrier, including the skin and mucous membranes.

Besides containing many tough layers as a physical barrier, the skin also provides a chemical barrier in the form of acidic secretions that prevent the growth of pathogens on its surface.

Mucous membranes are parts of the skin covered in a secretion called mucous, that keeps the skin moist and prevents growth of bacteria by killing them with lysozyme enzymes

Mucous membranes can be found in places where the skin has an opening into the body, such as the nose, throat, vagina and urethra.

2nd line of defence is formed by blood cells inside our body.

Phagocytes are white blood cells that ingest pathogens through a process called phagocytosis.

Once ingested, the pathogens are killed by the enzymes in cellular vesicles called lysosomes.

Phagocytes ingest pathogens in the blood and in other tissues, by leaving the capillaries and infiltrating the sites of infections.

Since phagocytes ingest any form of pathogens, they are said to form *non-specific immunity*.

Specific immunity is triggered by other types of white blood cells, called lymphocytes, which produce a response when in contact with a specific type of pathogen

6.3.2 Antibody production

Antigen is any sort of molecule that is recognised by our body as foreign.

Lymphocytes are white blood cells that are involved in specific immunity.

Upon encounter with antigens, lymphocytes can either activate other lymphocytes, or produce antibodies.

Antibody Is a protein produced by lymphocytes in response to the recognition of antigens.

Lymphocytes can only produce one type of antibody, so our body contains many different types of lymphocytes.

Lymphocytes express this type of antibody on their surface so that an antigen can bind it and be recognised by our immune system.

The process of specific immunity goes as follows:

1. When pathogens are encountered, phagocytic cells engulf and break down pathogens. These cells will engulf and break down anything encountered as "non-self".

2. After engulfment, these "antigen-presenting cells" will display fragments of the broken down pathogen on their surface, and migrate to the lymph nodes to alert the immune system of a threat.

3. Certain lymphocytes called "T-cells" will get activated by this warning and release cytokines to activate particular B lymphocytes.

4. The activated B lymphocytes are those capable of producing the specific antigens for the recognised antigen that was presented by the initial phagocyte.

5. These activated B lymphocytes will rapidly divide into high numbers of short-lived plasma cells that release large numbers of antibodies into the blood stream to target the pathogens for destruction.

6. A small proportion of the activated B and T cells will become memory cells, which provide long lasting immunity to the pathogen. Therefore, in the case of a subsequent infection, these cells will quickly react to produce large numbers of antibodies much faster.

6.3.3 HIV – Human Immunodeficiency Virus

HIV is a virus that reduces the effectiveness of the immune system by reducing the number of active lymphocytes.

HIV does so by penetrating the lymphocytes and integrating their RNA into the cell's DNA with the enzyme reverse transcriptase (which the virus carries)

This viral DNA not only allows the virus to replicate with the cells machinery, but it also leads to a impaired ability to produce antibodies, thus the infected person has a lowered immunity and is more susceptible to infections.

Once the body has lost the majority of this sort of lymphocytes, the condition is termed AIDS, *acquired immunodeficiency syndrome*, since the body lacks the immunity formed by antibody production.

AIDS can culminate in death, as the body cannot fight even the most common infections such as the common cold.

Since HIV is a virus, it cannot survive long outside the body, so it is transmitted through certain bodily fluids:

- Through blood in hypodermic needles (often in drug abusers).
- Through unprotected vaginal, oral or anal sexual intercourse.
- Through the placenta or breast milk.
- Through blood transfusions.

Antibiotics are chemicals produced by certain microorganisms to kill bacteria.

Penicillin is an antibiotic obtained from a *Penicillium* fungus which uses it to kill bacteria that might potentially invade it.

Antibiotics kill prokaryotic organisms (bacteria), and not eukaryotic (plant and animal), because they target metabolic processes specific for prokaryotes.

Therefore, antibiotics can kill bacteria in our body, without harming our own cells.

Viruses cannot be killed by antibiotics because they use the metabolism of the host cell, and therefore, to kill a virus, the cell containing it would also have to be killed.

With different types of antibiotics, most bacterial diseases can be contained, but due to the emergence of antibiotic resistance, some strains of bacteria cannot be so easily killed.

Example.

Florey and Chain

Florey and Chain tested penicillin on 8 mice that were infected with a pneumonia causing bacterium.

The treated mice recovered, while the untreated ones died.

Florey and Chain then treated the same antibiotic on patients dying from bacterial infections, and these patients recovered.

Today, drugs have to go through much more rigorous testing, before they can be given to humans.

First, the safety is thoroughly tested on animals.

Then, healthy humans are given the drug to assess if it is tolerated well.

If all of this goes well, a small number of very sick patients are given the drug, and if this is successful too, only then, a large scale study can be performed.

6.4 Gas exchange

6.4.1 Ventilation: why do we need it?

Ventilation is the exchange of air between the atmosphere and the lungs, achieved by breathing

Gas Exchange is the exchange of oxygen and CO_2 between the bloodstream and the alveoli. This exchange occurs via passive diffusion.

Ventilation is essential because, in order for gas exchange to occur, a concentration gradient must be established (gas with higher O_2 content must come into the lungs in order for it to diffuse into the alveoli, and CO_2 to diffuse out). Gas exchange is passive while ventilation is active to maintain the gradients needed for passive diffusion by continuously refreshing the air in the lungs.

Oxygen is essential for the processes like cell respiration.

Figure 6.8 is a diagram of the respiratory system, air flows through the trachea, bronchi and bronchioles until reaching the alveoli at the tips of the bronchioles, where gas exchange occurs between alveoli and adjacent capillaries.

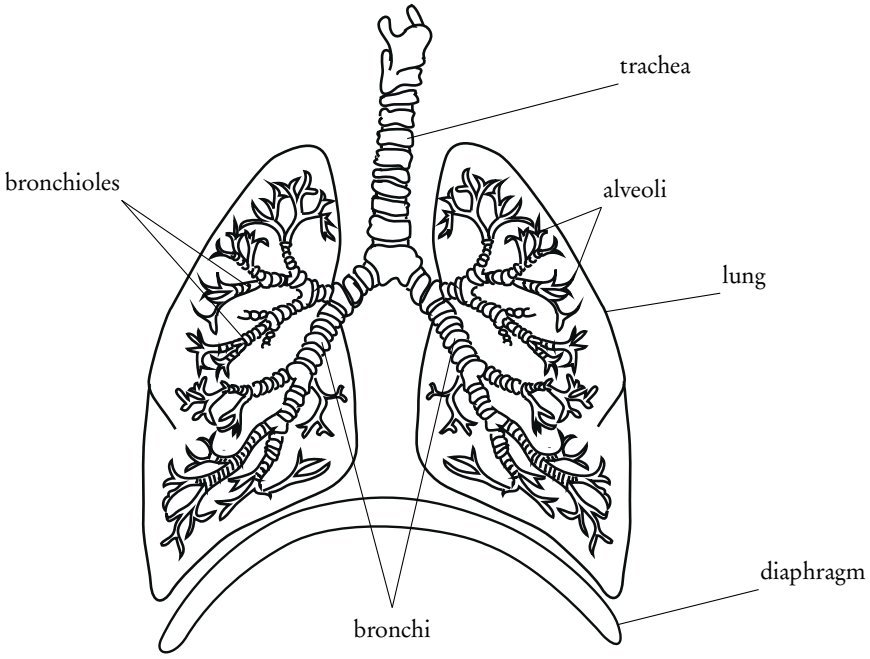


Figure 6.8: Ventilation system.

Example.

Lung cancer: causes and consequences

Causes:

- Smoking: tobacco smoke contains mutagens that can lead to tumour formation.
- Passive smoking: exhaled smoke from smokers passes carcinogens to others.
- Air pollution: e.g., nitrogen oxides from vehicles, diesel exhaust fuels.
- Radon gas.
- Asbestos and silica: dust from these materials causes cancer if deposited in the lungs.

Consequences:

- Difficulties with breathing.
- Chest pain.
- Persistent coughing.
- Loss of appetite.
- Weight loss.
- Coughing up blood.
- General fatigue.
- Can be fatal.

6.4.2 Alveoli: the site of gas exchange

Alveoli are the body's gas exchange surfaces, formed in clusters at the ends of the smallest bronchioles. They are essentially air sacs with a very small diameter. The presence of many alveoli creates a large total surface area for gas exchange. Each alveolus is surrounded by a network of blood capillaries allowing oxygen to diffuse through into the blood and carbon dioxide to diffuse out in the opposite direction. Here are some additional structural characteristics that enhance this process:

- Two types of cells:

  Pneumocytes type I extremely thin and adapted for gas exchange.

  Pneumocytes type II secrete a solution containing surfactant, which creates a moist surface inside the alveoli to prevent the sides of the alveolus adhering to each other by reducing surface tension.

- Cells in alveoli are one-cell thick and in close proximity to blood capillaries, which are also one-cell thick. This is essential as it creates a very short distance for diffusion of Oxygen and Carbon Dioxide.

Diagram showing type I and II pneumocytes, as well as the associated capillary. Direction of gas exchange is also shown.

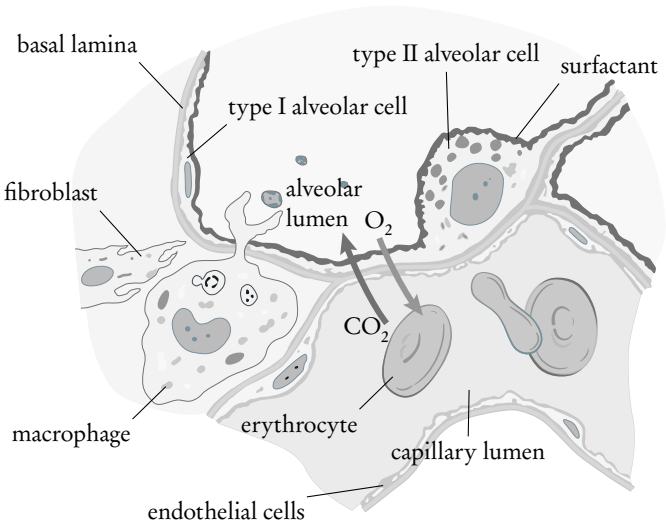


Figure 6.9: Type I and II pneumocytes and capillary.

Example.

Emphysema: causes and consequences

Emphysema is a chronic and progressive respiratory disease. Cilia that line the airways and expel mucus become damaged and cease to function appropriately, leading to a build-up of mucus that can lead to inflammatory response upon inhalation of smoke and air pollution. A protease is released from inflamed cells, causing the digestion of elastic fibres in the lung and eventually, alveolar walls collapse.

Causes:

- Smoking.
- Air pollution.

Consequences:

- Loss of elasticity of the lungs.
- Reduced surface area for gas exchange.
- Difficult to exhale air → difficulty carrying out intense pH.

6.4.3 Inhalation and exhalation: muscle contractions needed to regulate airflow

In order to understand gas exchange, you need to keep in mind that molecules will always flow from an area of high concentration to low concentration by diffusion

During inhalation

The external intercostal muscles contract while the internal intercostal muscles relax thus pulling the rib cage upwards.
The diaphragm contracts and flattens which increases the volume of thoracic cavity.
As a result, there is a reduction in pressure inside the thoracic cavity, leading to air entering the lungs.

During exhalation

In passive exhalation, external intercostal muscles and diaphragm relax, reducing the volume of the thoracic cavity, increasing the pressure of the cavity and therefore releasing air out of the lungs.
Forced exhalation also includes the contraction of internal intercostal muscles, further reducing the thoracic cavity volume.

Table 6.1

	Diaphragm	Internal intercostal	External intercostal	Volume	Pressure
Inhalation	Contracts	Relaxes	Contracts	High	Low
Exhalation	Relaxes	Contracts	Relaxes	Low	High

6.5 Neurons and synapses

6.5.1 Action potential: generating and transmitting electrical signals in the brain

Neurons are the essential messenger units in the body. They transmit electrical impulses from the brain to the rest of the body and vice versa, and transmit information within the brain. Figure 6.10 is a diagram of a myelinated motor neuron, which stimulates muscle fibres to contract.

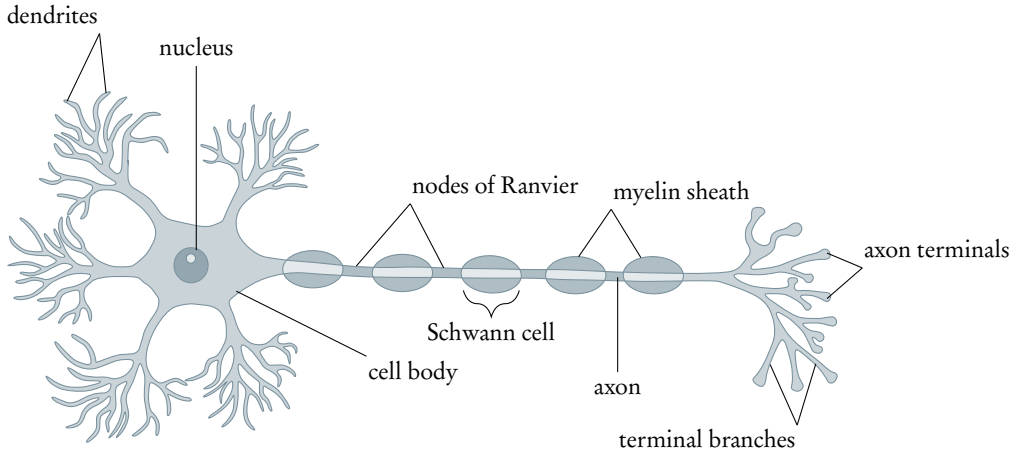


Figure 6.10: Motor neuron structure.

The generation and transmission of electrical impulses across a neuron is achieved by an action potential.

Resting potential The charge difference across the membrane when a neuron is not firing (−70 mV), as maintained by the sodium-potassium pump.

Action potential is an all or none event that consists of rapid changes in charge across the membrane that propagate along an axon when a neuron is firing.

Nerve Impulses are action potentials propagated along the axon of a neuron.

1. Before an action potential can be initiated, the neuron is at resting potential (−70).
2. Resting potential is established the active pumping of K^+ ions into the neuron and of Na^+ ions out of it, creating concentration gradients for both ions, and an overall

negative charge inside the neuron. This is because, as you may remember, the sodium-potassium pump pumps 2 potassium for every 3 sodium.

3. When input from a previous neuron is stimulating enough and the beginning of the axon reaches its threshold voltage (−55), an action potential is initiated.

4. Depolarization: Sodium voltage-dependent channels open and Na^+ diffuses into the neuron down its concentration gradient, reducing membrane potential and causing more sodium ions to open (membrane potential becomes more positive).

5. Repolarization: Potassium voltage-dependent channels open after a short delay due to the change in membrane potential, and K^+ ions diffuse out of the neuron down its concentration gradient. The inside of the neuron once again becomes more negative. In this stage, the electrical impulse has passed this section of the axon, and the sodium ions in the section adjacent open to transmit the impulse.

6. Concentration gradients of Na^+ and K^+ across the membrane are restored by the Na^+/K^+ pump, and the membrane in this section of the axon once again reaches resting potential (and is once again ready for another action potential).

In myelinated neurons (as seen in Figure 6.10), this ion exchange only occurs at the nodes of Ranvier, thus conduction of the action potential "jumps" down the axon far more quickly than in unmyelinated axons, where numerous adjacent sections of the axon must undergo the process outlined previously to carry the electrical impulse down the length of the axon. This is known as "saltatory conduction".

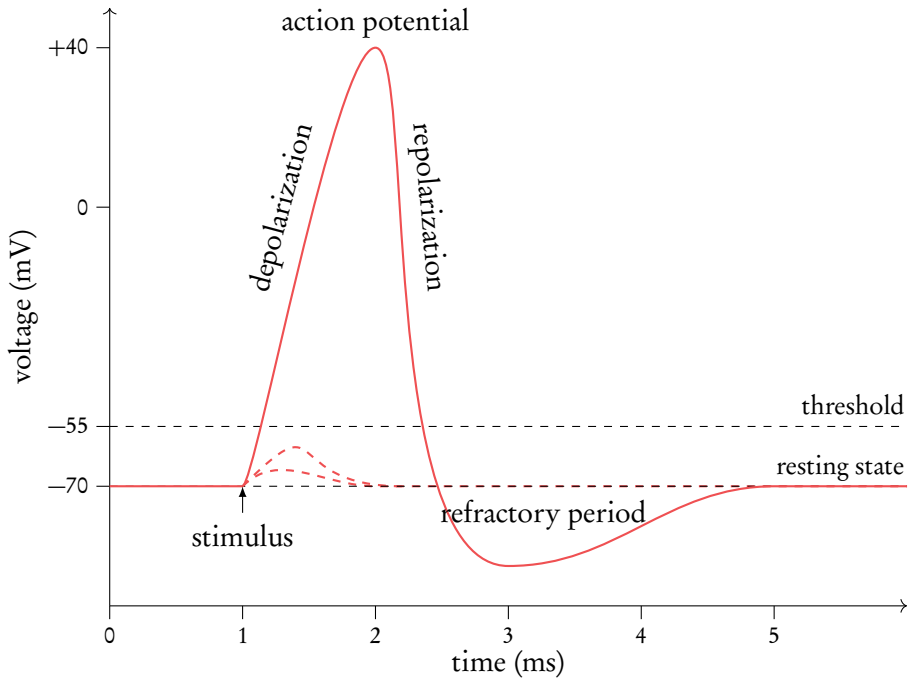


Figure 6.11: Action potential graph showing the processes of depolarization, repolarization and the re-establishing of membrane potential.

6.5.2 Neurotransmitters: chemical signalling across synapses

Once an action potential has reached the axon terminals, chemical signals are necessary to pass on information from the presynaptic neuron to the postsynaptic one or onto an effector cell (e.g., muscle fibre). Separating each neuron are small junctions known as synapses, through which specific chemical messengers called neurotransmitters (NTs) can diffuse. An overview of this process is:

1. A nerve impulse reaches the axon terminal of the presynaptic neuron, leading to depolarization at the terminal.
2. Depolarization leads to the opening of voltage-gated calcium channels and an influx of Ca^{2+} into the presynaptic neuron.
3. Influx of calcium causes neurotransmitter-filled vesicles to fuse with the presynaptic membrane and release NTs into the synaptic cleft by exocytosis.
4. NTs diffuse across the synaptic cleft and bind to specific NT receptors in the postsynaptic neuron.
5. This binding results in the opening of ligand-gated ion channels that allow either Na^+ or Cl^- to diffuse into the postsynaptic neuron.
   (a) Na^+ influx creates an excitatory signal at the postsynaptic membrane, and allows for the transmission initiation of the action potential if the threshold potential is reached.
   (b) Cl^- influx on the other hand, leads to hyperpolarization (inside of the neuron becomes more negative), resulting in an inhibitory signal that may prevent action potential initiation.
6. NTs in the synaptic cleft are rapidly degraded by enzymes or are taken up by the presynaptic neuron once more. Ca^{2+} is pumped out of the presynaptic neuron as well to re-establish a concentration gradient.

Example.

Cholinergic synapses

A common example of a synapse is the cholinergic synapse, which most commonly results in the opening of Na^+ ion channels in the postsynaptic membrane and thus transmits an excitatory signal. Acetylcholine is the NT that is released in cholinergic synapses, which then diffuses and binds to nicotinic receptors at the postsynaptic neuron. Enzyme cholinesterase rapidly degrades this NT where one of the residual components, choline, is reabsorbed into the presynaptic neuron.

Some chemicals found in neonicotinoid pesticides have a similar chemical structure as acetylcholine, and can bind to the acetylcholine receptors in cholinergic synapses. Cholinesterase is unable to degrade this chemical and thus, the cholinergic receptor remains blocked and nerve impulses cannot be mediated. This is a very dangerous phenomenon that is lethal for bees and insects that come into contact with these types of pesticides.

6.6 Hormones and homeostasis

6.6.1 Blood glucose

Glucose concentration in blood has to be tightly regulated in order to provide cells across the body with enough energy, but at the same time, to control water movement in and out of the cells.

The pancreas is the organ in charge of glucose regulation, and it does it with the production of two hormones:

Glucagon is produced by *alpha cells* and is secreted when the glucose levels are low:

- it leads to breakdown of glycogen in the liver
- this leads to the release of glucose in the blood

Insulin is produced by *beta cells* and is secreted in response to high blood glucose levels:

- it stimulates cells to take up the glucose from blood;
- it also stimulates liver and muscle cells to store glucose in the form of glycogen.

6.6.2 Diabetes

Diabetes mellitus is a disease of faulty glucose regulation. Two types of diabetes can be differentiated, based on the cause.

Type I diabetes

early-onset diabetes usually develops in those under 20 years old

inability to produce sufficient quantities of insulin

target cells remain sensitive to insulin

is linked with

- genetic predisposition
- virus
- autoimmune disorder
- destruction of (pancreatic) beta cells involved

- requires daily injections of insulin
- beta cell transplant

Type II diabetes

adult-onset diabetes usually occurs in those over 40 years old

inability to respond to insulin mainly due to insufficient receptors on target cells

target cells less sensitive to insulin

is linked with

- dietary
- lifestyle factors
- increased fatty acids in blood

- controlled by diet
- exercise
- weight loss
- medication but not insulin injections

6.6.3 Thyroxine and metabolism

Thyroxin is a hormone produced by the thyroid gland which is responsible for the metabolic activity of the cells.

Thyroxin is made out of 4 molecules of iodine. Low iodine intake can result in lack of thyroxin synthesis (which is why all the salt is additionally iodized).

When the body temperature drops, this is sensed by the hypothalamus in the brain which triggers the production of thyroxin by the thyroid.

Thyroxin increases the metabolic rate of the cells, causing higher heat productions, but also leads to vasoconstriction of skin blood vessels (to preserve heat) and shivering.

6.6.4 Leptin and melatonin

Leptin is a hormone secreted by adipose (fat tissue) cells, which controls appetite.

Leptin is produced by the adipose cells and travels to the hypothalamus in the brain, where it stimulates certain cells to signal for a decrease of appetite.

In this way, the body is able to regulate its body mass, by decreasing food intake as fat tissue increases.

Melatonin is a hormone produced by the pineal gland and it is responsible for controlling the sleep-wake cycles in humans.

In response to different amounts of light/dark, cells in the eye send impulses to the supra chiasmatic nuclei (SCN) in the hypothalamus.

The SCN controls melatonin production, by increasing it at night, and decreasing it at dawn.

Over the years, melatonin production in humans decreases so our sleep cycles become less regular.

When travelling long distances by plane, the SCN and pineal gland cannot adjust to the new light cycles at the new time zone rapidly enough, so during the first few days, the traveller's body continues to function at the old rhythm. This is termed *jet lag*. Taking oral doses of melatonin at the newly designated sleeping schedule can help the body adjust to the new time zone more rapidly.

6.7 Reproduction

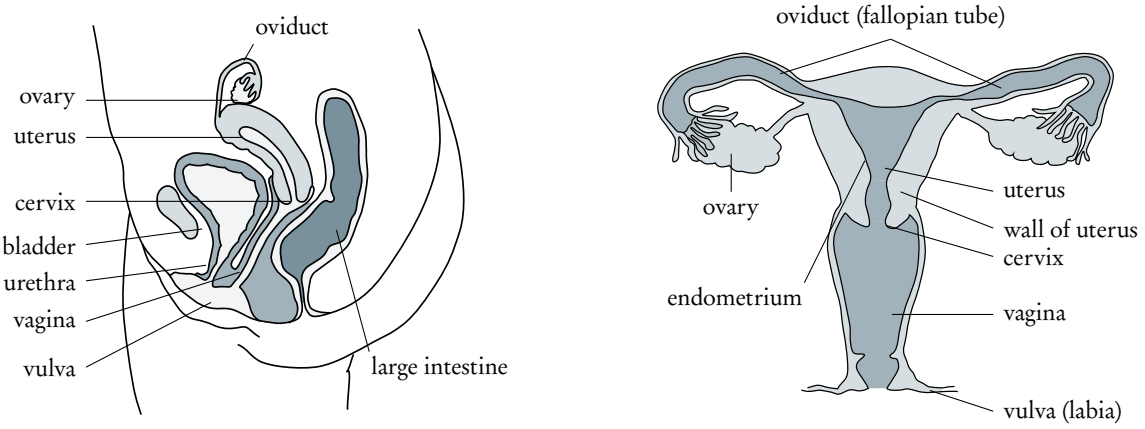


Figure 6.12: Female reproductive system.

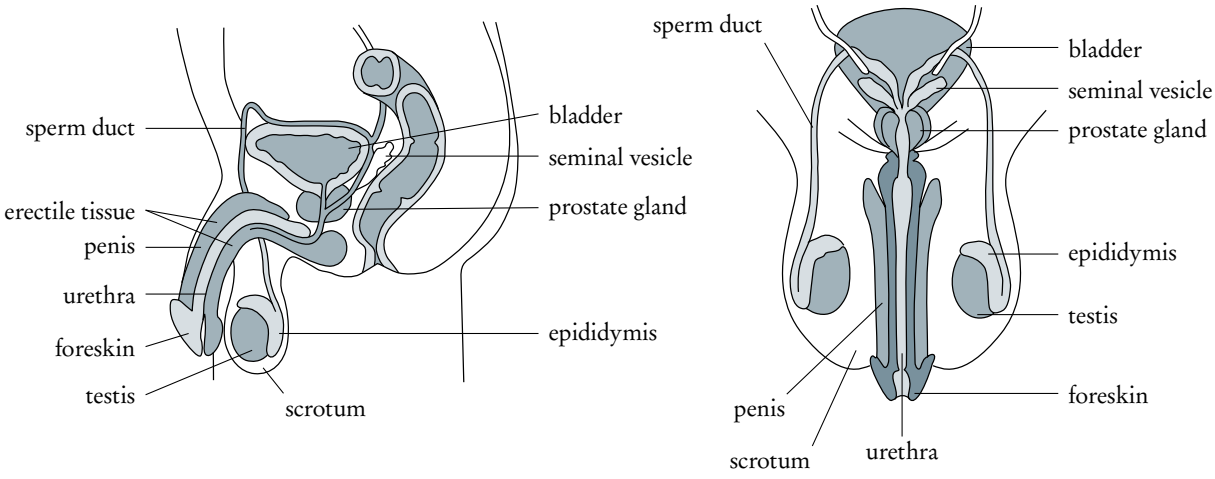


Figure 6.13: Male reproductive system.

6.7.1 Embryo development

The difference between a male and a female zygote is in the 23 pair of chromosomes.

A male has an XY combination, while the female has an XX combination.

A gene called SRY is present in male zygotes, but not in female ones.

If the SRY gene is present, it codes for a testis determining factor protein which causes development of testes.

6.7.2 Steroid hormones

Testosterone is produced by testes, both in a foetus and later in life. In a a foetus, testosterone leads to development of male genitalia. During puberty, it leads to development of secondary sex characteristics (growth of pubic hair, penis and testes). In later life, testosterone stimulates sperm production.

Oestrogen is produced in the ovaries. In foetus, it causes development of female genitalia (if there is no testosterone). In puberty, it leads to development of secondary sex characteristics.

Progesterone is also produced in the ovaries and its function is to thicken the uterus before embryo implantation.

Negative feedback means that the increase in a product of a process will lead to the decrease in the process itself.

Positive feedback means that the production of the final product will stimulate the process of production even further.

6.7.3 The menstrual cycle

In order to fully understand the processes during the menstrual cycle, the following terms should be clear.

Pituitary hormones are hormones produced in the pituitary gland (FSH and LH).

Follicle is a growing egg and surrounding fluid and cells

FSH (follicle stimulating hormone) stimulates follicle development and secretion of oestrogen by the follicle.

LH (luteal hormone) causes ovulation, the release of the egg from the ovary. A surge of LH occurs once during the menstrual cycle, and it happens due to a high concentration of estrogen.

Corpus Luteum is the structure left behind after the egg is released from the follicle. It produces progesterone and some estrogen and functions for a limited amount of time after ovulation if there is no fertilization.

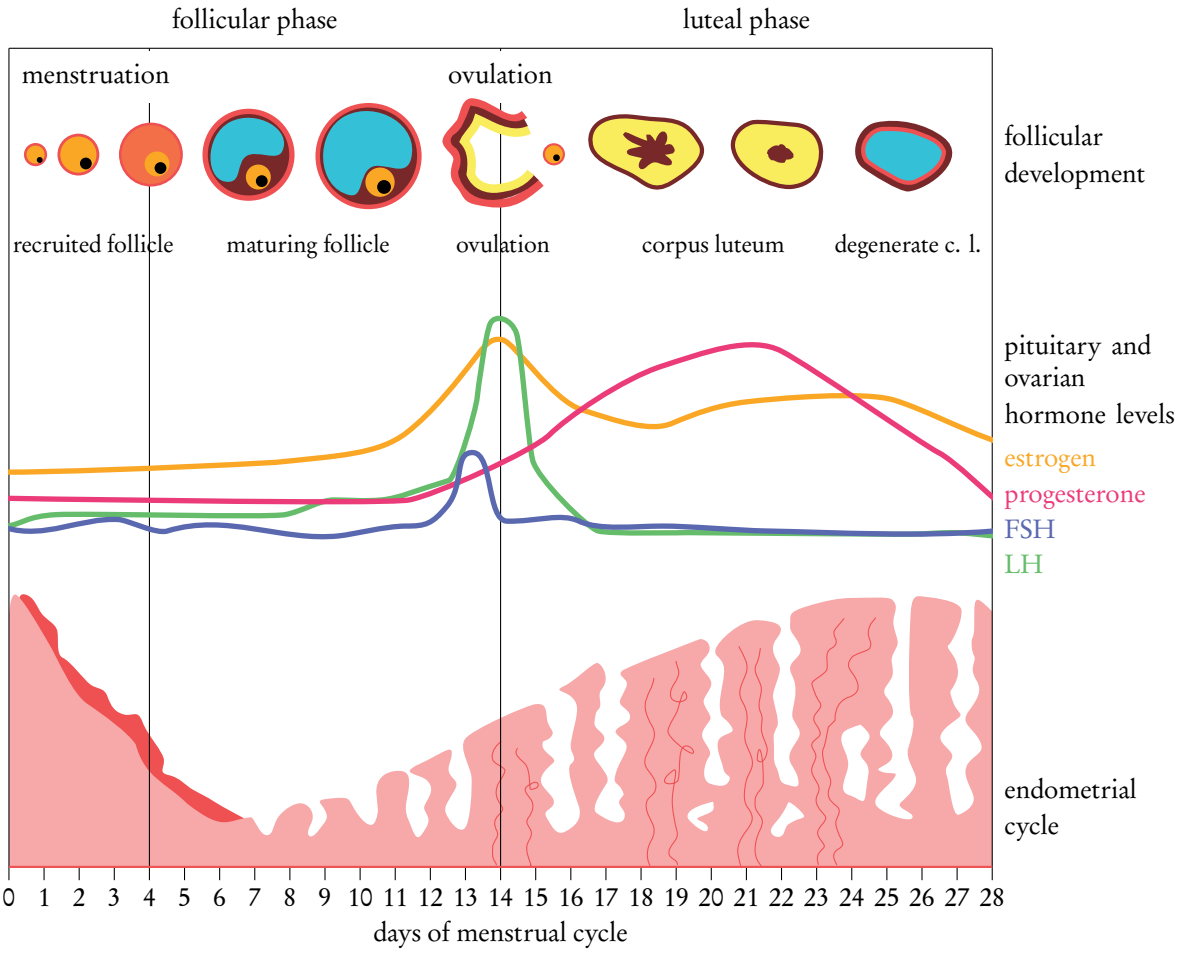
Ovarian hormones are hormones produced in the ovaries (oestrogen and progesterone).

Oestrogen is produced in a positive feedback loop with FSH by the follicle. It causes repairing and thickening of the uterus lining and causes LH secretion. At very high levels, it inhibits FSH, turning into a negative feedback mechanism.

Progesterone is produced by the corpus luteum and maintains the thick lining of the uterus. It inhibits LH and FSH hormones.

The aim of the menstrual cycle is to mature and release an egg, ready for fertilization, and to prepare the uterus for embedding the embryo in its wall.

1. The first, day 0 of the menstrual cycle, is the first day of bleeding. This corresponds to the beginning of the **follicular phase**.
    (a) FSH increases and stimulates the follicles with the egg to develop.
    (b) The development of follicles leads to oestrogen secretion.
    (c) Oestrogen and FSH are in positive feedback because oestrogen production makes follicle cells more sensitive to FSH, which in return results in more oestrogen production.
    (d) In this way, both oestrogen and FSH increase.
    (e) Oestrogen leads to repair and thickening of the uterus lining.
2. Around day 14, the uterus has gotten thicker, and the follicular phase of development is ending.
    (a) When oestrogen is high enough, it causes an LH surge by the pituitary gland. This corresponds to the **luteal phase**.
    (b) At the same time, the peak of oestrogen lead to FSH inhibition, which in turn leads to a decrease in oestrogen (negative feedback).
    (c) As LH reaches a peak, it causes completion of meiosis in the egg and release of the egg into the oviduct-ovulation (around day 14).
3. After ovulation, the broken follicle maintains the uterine lining, in case fertilization occurs.
    (a) LH stimulates the burst follicle to develop into corpus luteum.
    (b) Corpus luteum produces progesterone, and some oestrogen.
    (c) Progesterone will continue rising for a few days in order to maintain the thickening of the uterine lining.
    (d) The increase of progesterone and oestrogen levels inhibits the FSH and LH production by the pituitary (thereby preventing another ovulation).
4. If no fertilization occurs, the corpus luteum starts degenerating, and the menstruation will begin.
    (a) With degeneration of corpus luteum, progesterone and oestrogen levels start falling, thereby lifting the inhibition of FSH.
    (b) The drop in progesterone results in degeneration of the uterine lining and therefore, menstrual bleeding.
    (c) As FSH levels can begin to rise again, a new cycle of follicular development can start.



You should be able to understand the diagram of the menstrual cycle.

6.7.4 In vitro fertilization

In vitro fertilization (IVF) is a fertilization procedure outside of the body, where an egg and sperm cell are combined in a Petri dish to make a zygote. It is a method to overcome issues such as infertility and uterine problems.

The procedure of IVF can be described as the following:

1. Drugs are used to down-regulate the menstrual cycle.
2. FSH is injected to the female to stimulate many follicles to develop.
3. HCG is injected to the female to cause the follicles to mature.
4. The eggs are harvested from the ovaries and a semen sample is collected from the male.
5. The sperm cells are mixed with the mature follicles in a dish outside the body to allow for fertilization.
6. The dish is incubated at 37 °C allowing the embryos to develop sufficiently for implantation.
7. The dish examined to choose healthiest embryo.
8. A few healthy embryos are placed in the uterus of the mother using a catheter. Up to four embryos may be implanted, which is why some IVF mothers have more than one child from the procedure.
9. Finally a pregnancy test used to see if procedure has been successful.

Used in cases of

- blocked oviduct;
- low sperm count;
- need for genetic screening;
- infertility;
- cannot become pregnant;
- need for donor embryo.

6.7.5 Harvey's reproduction experiments

William Harvey was a scientist in the 17 century who wanted to explain how copulation resulted in offspring. He chose to study deer during their mating season. He would kill the deer after the mating, in order to observe the development of offspring in the uterus at different stages after mating.

The theory at the time suggested that the male produces an egg that is activated by menstrual blood, and then develops into a foetus in the human uterus.

Harvey showed that this theory was wrong, but he couldn't show that the foetus development was a result of copulation, since the developing embryo was too small to see without a strong microscope.

The story of William Harvey shows how science can only progress with a simultaneous progress in the apparatus and scientific techniques.