AQA AS Biology Unit 2

Contents

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Biology Unit 2 Specification

Physiology

Surface Area to Volume Ratio

The relationship between the size of an organism or structure and surface area to volume ratio. Explain the significance of the relationship between size and surface area to volume ratio for the exchange of substances and of heat.

Gas Exchange

Changes to body shape and the development of systems in larger organisms as adaptations that facilitate exchange as the ratio reduces. Use knowledge and understanding of the principles of diffusion to explain the adaptations of gas exchange surfaces. Gas exchange across the body surface of a single-celled organism; in the tracheal system of an insect (tracheae and spiracles); across the gills of a fish (gill lamellae and filaments including the countercurrent principle) and by leaves of dicotyledonous plants (mesophyll and stomata). Structural and functional compromises between the opposing needs for efficient gas exchange and the limitation of water loss shown by terrestrial insects.

The Circulatory system

Over large distances, efficient supply of materials is provided by mass transport. The general pattern of blood circulation in a mammal. Names are only required of the coronary arteries and of blood vessels entering and leaving the heart, liver and kidneys. The structure of arteries, arterioles and veins in relation to their function. The structure of capillaries and their importance in metabolic exchange. The formation of tissue fluid and its return to the circulatory system.

Haemoglobin and Oxygen Transport

Haemoglobin is a protein with a quaternary structure. The role of haemoglobin in the transport of oxygen. The loading, transport and unloading of oxygen in relation to the oxygen dissociation curve. The effects of carbon dioxide concentration.

The haemoglobins are a group of chemically similar molecules found in many different organisms. Different organisms possess different types of haemoglobin with different oxygen transporting properties. Relate these to the environment and way of life of the organism concerned.

Plant Cells

There are fundamental differences between plant cells and animal cells. The structure of a palisade cell from a leaf as seen with an optical microscope. The appearance, ultrastructure and function of cell wall and chloroplasts. Explain adaptations of other plant cells. Use an optical microscope to examine temporary mounts of plant cells, tissues or organs.

Polysaccharides

The structures of β-glucose and the linking of β-glucose by glycosidic bonds formed by condensation to form cellulose. The basic structure and functions of starch, glycogen and cellulose and the relationship of structure to function of these substances in animals and plants.

Water Transport in Plants

The structure of a dicotyledonous root in relation to the pathway of water from root hairs through the cortex and endodermis to the xylem. Apoplastic and symplastic pathways. The roles of root pressure and cohesion tension in moving water through the xylem. Transpiration and the effects of light, temperature, humidity and air movement.

Structural and functional compromises between the opposing needs for efficient gas exchange and the limitation of water loss shown by xerophytic plants. Measure the rate of water uptake by means of a simple potometer.

Biodiversity

Causes of Intraspecific Diversity

Variation exists between members of a species. Similarities and differences between individuals within a species may be the result of genetic factors, differences in environmental factors, or a combination of both. Collect and analyse data relating to intraspecific variation. Analyse and interpret data relating to interspecific and intraspecific variation. Appreciate the tentative nature of any conclusions that can be drawn relating to the causes of variation.

Loss of Genetic Diversity

Similarities and differences between organisms may be defined in terms of variation in DNA. Differences in DNA lead to genetic diversity. The influence of the following on genetic diversity: selection for high-yielding breeds of domesticated animals and strains of plants; the founder effect; genetic bottlenecks. Discuss ethical issues involved in the selection of domesticated animals.

Species Diversity

Diversity may relate to the number of species present in a community. An index of diversity describes the relationship between the number of species and the number of individuals in a community. Calculation of an index of diversity from the formula $d = N (N – 1) / \Sigma n (n – 1)$ where N = total number of organisms of all species and n = total number of organisms of each species. Calculate the index of diversity from suitable data.

Loss of Species Diversity

The influence of deforestation and the impact of agriculture on species diversity. Interpret data relating to the effects of human activity on species diversity and be able to evaluate associated benefits and risks. Discuss the ways in which society uses science to inform the making of decisions relating to biodiversity.

Sampling

The need for random sampling, and the importance of chance in contributing to differences between samples. The concept of normal distribution about a mean. Mean and standard deviation as measures of variation within a sample. Candidates will not be required to calculate standard deviation in questions on written papers.

Genetics

DNA Structure

The double-helix structure of DNA enabling it to act as a stable information-carrying molecule, in terms of the components of DNA nucleotides: deoxyribose, phosphate and the bases adenine, cytosine, guanine and thymine; two sugar-phosphate backbones held together by hydrogen bonds between base pairs; specific base pairing. DNA is the genetic material in bacteria as well as in most other organisms. Analyse, interpret and evaluate data concerning early experimental work relating to the role and importance of DNA.

DNA Replication

The semi-conservative replication of DNA in terms of: breaking of hydrogen bonds between polynucleotide strands; attraction of new DNA nucleotides to exposed bases and base pairing; role of DNA helicase and of DNA polymerase.

Gene Expression

Genes are sections of DNA that contain coded information as a specific sequence of bases. Genes code for polypeptides that determine the nature and development of organisms. The base sequence of a gene determines the amino acid sequence in a polypeptide. A sequence of three bases, called a triplet, codes for a specific amino acid.

In eukaryotes, much of the nuclear DNA does not code for polypeptides. There are, for example, introns within genes and multiple repeats between genes.

Mutations

Mutations are changes in DNA and result in different characteristics. Differences in base sequences of alleles of a single gene may result in non-functional proteins, including non-functional enzymes.

Chromosomes

A gene occupies a fixed position, called a locus, on a particular strand of DNA. In eukaryotes, DNA is linear and associated with proteins. In prokaryotes, DNA molecules are smaller, circular and are not associated with proteins.

Mitosis and the Cell Cycle

During mitosis, the parent cell divides to produce two daughter cells, each containing an exact copy of the DNA of the parent cell. DNA is replicated during interphase. Mitosis increases the cell number in this way in growth and tissue repair. Name and explain the events occurring during each stage of mitosis. Recognise the stages from drawings and photographs. Relate understanding of the cell cycle to cancer and its treatment.

Cell Differentiation

The cells of multicellular organisms may differentiate and become adapted for specific functions. Tissues as aggregations of similar cells, and organs as aggregations of tissues performing specific physiological functions. Organs are organised into systems.

Meiosis and Sexual Reproduction

The importance of meiosis in producing cells which are genetically different. Meiosis only in sufficient detail to show the formation of haploid cells; independent segregation of homologous chromosomes; and genetic recombination by crossing over. Gametes are genetically different as a result of different combinations of maternal and paternal chromosomes.

Antibiotics and Resistance

Antibiotics may be used to treat bacterial disease. One way in which antibiotics function is by preventing the formation of bacterial cell walls, resulting in osmotic lysis. Mutations in bacteria may result in resistance to antibiotics. Resistance to antibiotics may be passed to subsequent generations by vertical gene transmission. Resistance may also be passed from one species to another when DNA is transferred during conjugation. This is horizontal gene transmission.

Antibiotic resistance in terms of the difficulty of treating tuberculosis and MRSA. Apply the concepts of adaptation and selection to other examples of antibiotic resistance. Evaluate methodology, evidence and data relating to antibiotic resistance. Discuss ethical issues associated with the use of antibiotics. Discuss the ways in which society uses scientific knowledge relating to antibiotic resistance to inform decision-making.

Classification

A species may be defined in terms of observable similarities and the ability to produce fertile offspring. Candidates should appreciate the difficulties of defining species and the tentative nature of classifying organisms as distinct species.

The principles and importance of taxonomy. Classification systems consist of a hierarchy in which groups are contained within larger composite groups and there is no overlap. One hierarchy comprises Kingdom, Phylum, Class, Order, Family, Genus, Species. The phylogenetic groups are based on patterns of evolutionary history.

Originally classification systems were based on observable features but more recent approaches draw on a wider range of evidence to clarify relationships between organisms. Genetic comparisons can be made between different species by direct examination of their DNA or of the proteins encoded by this DNA.

- Comparison of DNA base sequences is used to elucidate relationships between organisms. These comparisons have led to new classification systems in plants. Similarities in DNA may be determined by DNA hybridisation.
- Comparisons of amino acid sequences in specific proteins can be used to elucidate relationships between organisms. Immunological comparisons may be used to compare variations in specific proteins.

Interpret data relating to similarities and differences in base sequences in DNA and in amino acid sequences in proteins to suggest relationships between different organisms.

The role of courtship in species recognition. Courtship behaviour as a necessary precursor to successful mating.

Gas Exchange in Organisms

All organisms need to exchange oxygen and carbon dioxide with their surroundings for respiration (or in plants for photosynthesis). These gases diffuse between the organism and the surroundings. From Fick's law we know that:

$$\text{Rate of Diffusion} \propto \frac{\text{surface area} \times \text{concentration difference}}{\text{distance}}$$

So the rate of exchange of gases therefore depends on the organism's surface area that is in contact with the surroundings. The requirements for respiration depends on the mass or volume of the organism, so the ability to meet the requirements depends on (surface area ÷ volume), which is known as the surface area : volume ratio. As organisms get bigger their volume and surface area both get bigger, but not by the same amount. This can be seen by performing some simple calculations concerning different-sized organisms. In these calculations each organism is assumed to be cube-shaped to make the calculations easier. The surface area of a cube with length of side L is $6L^2$, while the volume is L^3.

organism	length	SA (m^2)	vol (m^3)	SA:vol ratio (m^{-1})
bacterium	1 μm (10^{-6} m)	6×10^{-12}	10^{-18}	6,000,000:1
amoeba	100 μm (10^{-4} m)	6×10^{-8}	10^{-12}	60,000:1
bee	10 mm (10^{-2} m)	6×10^{-4}	10^{-6}	600:1
pig	1 m (10^{0} m)	6×10^{0}	10^{0}	6:1
whale	100 m (10^{2} m)	6×10^{4}	10^{6}	0.06:1

So as organisms get bigger their surface area : volume ratio gets smaller. A bacterium is all surface with not much inside, while a whale is all insides with not much surface. This means that as organisms become bigger it becomes more difficult for them to exchange materials with their surroundings. In fact this problem sets a limit on the maximum size for a single cell of about 100μm. In anything larger than this materials simply cannot diffuse fast enough to support the reactions needed for life. Very large single cells like birds' eggs are mostly inert food storage with a thin layer of living cytoplasm round the outside.

Organisms much larger than 100μm have to be multicellular, which means that their bodies are composed of many small cells, rather than one big cell. Each cell in a multicellular organism is no bigger than about 30μm, and so can exchange materials quickly and independently. Each human contains about 10^{14} cells.

Large organisms therefore need specialised exchange systems with a large surface area. These systems include lungs, gills, intestines, roots and leaves.

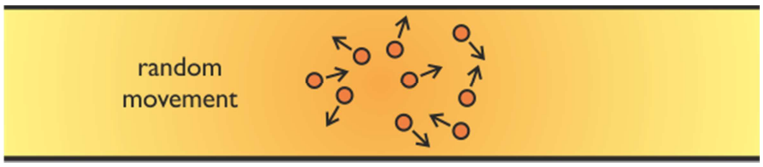
Heat Exchange

Organisms also need to exchange heat with their surroundings, and here large animals have an advantage in having a small surface area : volume ratio: they lose less heat than small animals. Large mammals keep warm quite easily and don't need much insulation or heat generation. Small mammals and birds lose their heat very readily, so need a high metabolic rate in order to keep generating heat, as well as thick insulation. So large mammals can feed once every few days, while small mammals must feed continuously. Human babies also lose heat more quickly than adults, which is why they need woolly hats.

Diffusion and Mass Flow

In unit 1 we saw how materials moved across cell membranes; and we saw that there were basically two methods: diffusion and active transport. In unit 2 we shall look at how materials move over larger distances inside living organisms. Again there are basically two methods: diffusion and mass flow.

1. In diffusion solutes move in a random direction due to their thermal energy. Diffusion does not require any energy (other than the thermal energy of the surroundings), so it is referred to as a passive process. If there is a concentration difference between two places then the random movement results in the substance diffusing down its concentration gradient from a high to a low concentration. Diffusion is very slow and is only useful over small distances (< 100 μm). It cannot be used to move substances over large distances in living organisms.



2. In mass flow a fluid (liquid or gas) moves in a particular direction due to a force. In living organisms this usually means the bulk movement of water (the solvent) together with all its dissolved solutes and suspended objects. So mass flow is like a river carrying everything with it. Mass flow always requires a source of energy to pump the fluid, but it has the advantage of being much faster than diffusion, especially over large distances. Mass flow is completely independent of concentration differences.

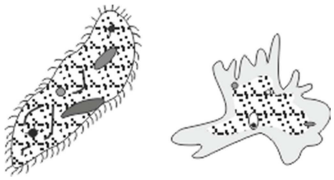
Examples of mass flow include: circulatory systems in animals, xylem and phloem systems in plants, filter feeder currents, and ventilation.

Gas Exchange in Small Organisms

Small organisms don't have specialised gas exchange systems like lungs or gills, but instead simply exchange gases through the surface of their bodies. To maximise their rate of gas exchange they have developed particular body shapes to increase their surface area : volume ratio. Compared to larger, more active vertebrates, most invertebrates also have relatively low metabolic rates, so don't need a fast rate of gas exchange.

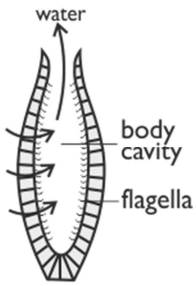
Single-celled Organisms

Microscopic single-celled organisms, like bacteria or *Amoeba*, have a large surface area : volume ratio, so they can exchange gases quickly directly though their cell surface.



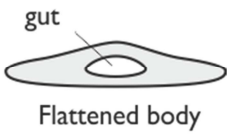
Sponges – Hollow Body

Sponges are the simplest of all animals and are all marine. Their tube-shaped bodies can grow quite large (50 mm in diameter). Sponges increase their surface area : volume ratio by being hollow, with thin walls only a few cells thick. Beating flagella maintain a flow of water through the body cavity.



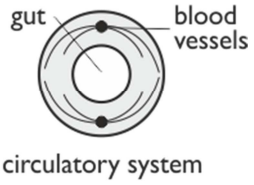
Tapeworms – Flattened Body

Tapeworms are parasites that live in the digestive systems of many animals including humans. They can be very long. Tapeworms increase their surface area : volume ratio by having flattened bodies, typically only 0.2 mm thick. This also decreases the diffusion distance. Tapeworms are sedentary and have an extremely low metabolic rate.



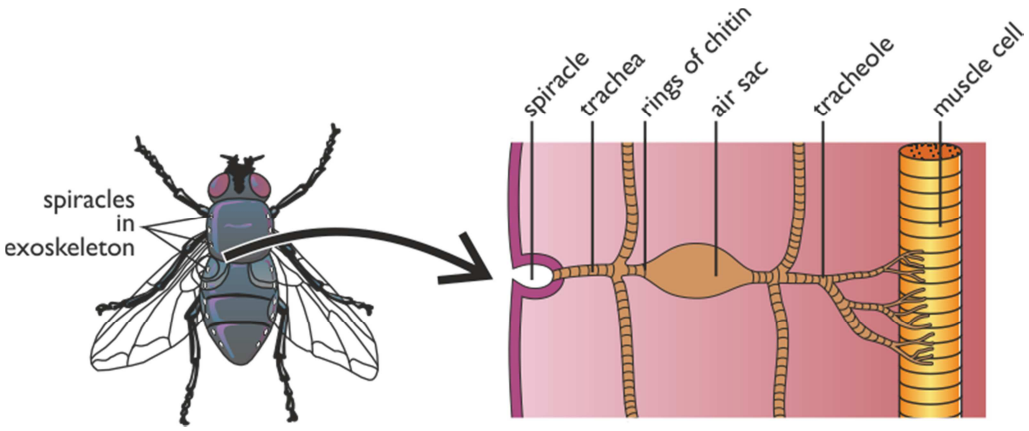
Earthworms – Circulatory System

Earthworms can grow to be several mm in diameter, but most of this is the worm's gut, with the tissues taking up a thin layer on the outside. This layer is still too thick for diffusion, so earthworms have developed a rudimentary circulatory system (containing haemoglobin) to carry gases between the body surface and the underlying tissues.

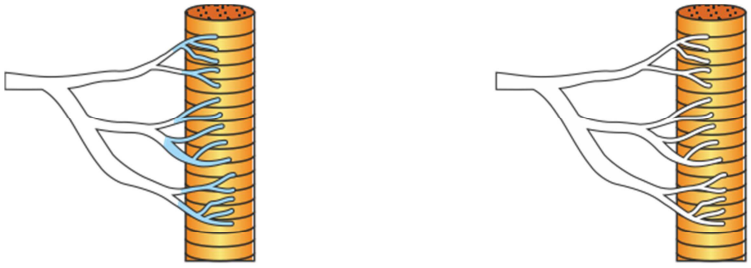


Gas Exchange in Insects

Insects are fairly small, but they are also very active, so they need to respire quickly. They have a rigid exoskeleton, which is waterproof to prevent the insects drying out, but it also prevents gas exchange. Insects increase their rate of gas exchange by having openings in the exoskeleton called spiracles, which lead to a network of tubes called tracheae, which branch into many smaller tracheoles that carry air directly to the cells. These tracheae and tracheoles are held open by rings of hard chitin (a polysaccharide). The tracheoles penetrate deep into the insects tissues, carrying air quickly and directly to every cell. At the ends of the tracheoles oxygen diffuses directly into the cells, and carbon dioxide diffuses out, down their concentration gradients.



When the insect is at rest, water diffuses out of its cells into the ends of the tracheoles, just as it does in human alveoli. This reduces the surface area in contact with the cells and reduces the rate of diffusion. But when insects are flying their muscle cells produce lactic acid, which lowers the water potential in the cells, so the water diffuses by osmosis from the tracheoles into the muscle cells. This makes diffusion of oxygen much faster, so actively-respiring cells automatically get oxygen quicker.



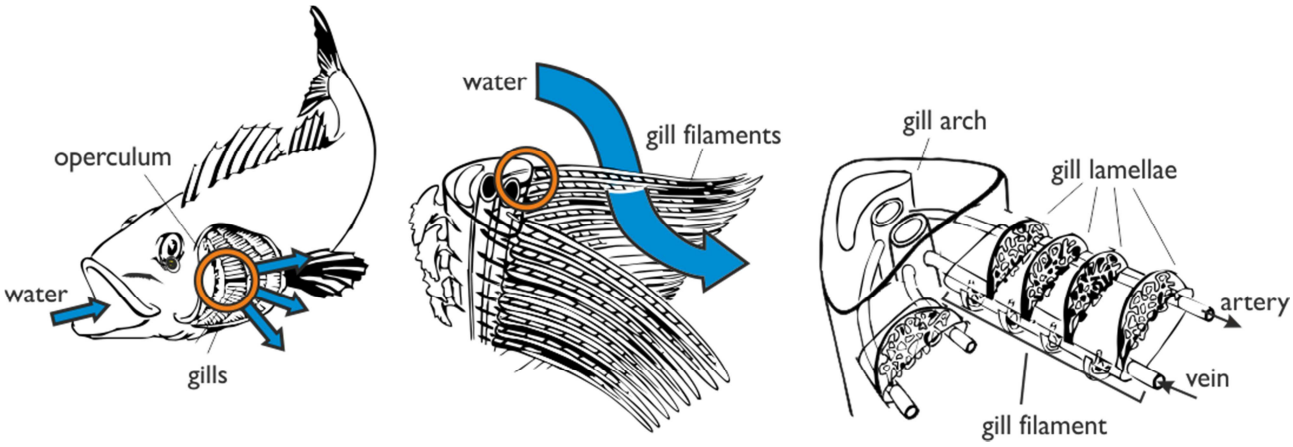
At rest water fills the ends of the tracheoles

During flight the water diffuses into the muscle

Some larger insects, like houseflies and grasshoppers, ventilate their tracheal system by using muscles to squeeze the trachea and so suck air in and out. This increases their rate of gas exchange. To counteract problems of water loss some insects have hairs around the spiracles, and some can close their spiracles when they are inactive.

Gas Exchange in Fish

Gas exchange is more difficult for fish than for mammals because the concentration of dissolved oxygen in water is less than 1%, compared to 20% in air. Fish have developed specialised gas-exchange organs called gills, which are composed of thousands of filaments. The filaments in turn are covered in feathery lamellae each only a few cells thick containing blood capillaries. This structure gives a large surface area and a short distance for gas exchange.

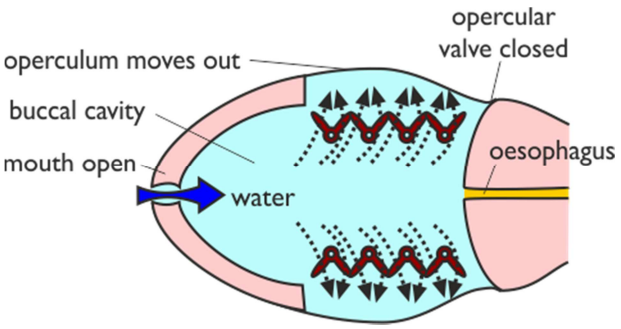


Water flows over the filaments and lamellae, and oxygen can diffuse down its concentration gradient the short distance between water and blood. Carbon dioxide diffuses the opposite way down its concentration gradient. The gills are covered by muscular flaps called opercula on the side of a fish's head. The gills are so thin that they cannot support themselves without water, so if a fish is taken out of water the gills collapse and the fish suffocates.

Ventilation in Fish

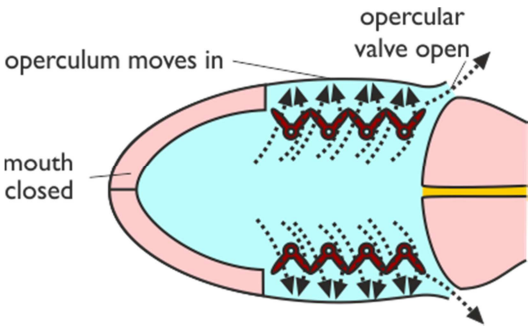
Fish ventilate their gills with sea water to maintain the gas concentration gradient. But, unlike humans, fish ventilation is one-way rather than tidal. Water enters through the mouth but exits through the opercula valves. This one-way ventilation is necessary because water is denser and more viscous than air, so it would take too much energy to change its momentum every breath. Some fish (like tuna, mackerels and anchovies) swim constantly with their mouths open, using their swimming movement to ventilate their gills, but most fish use their mouth muscles for ventilation, which means they can ventilate even when not swimming.

Inspiration



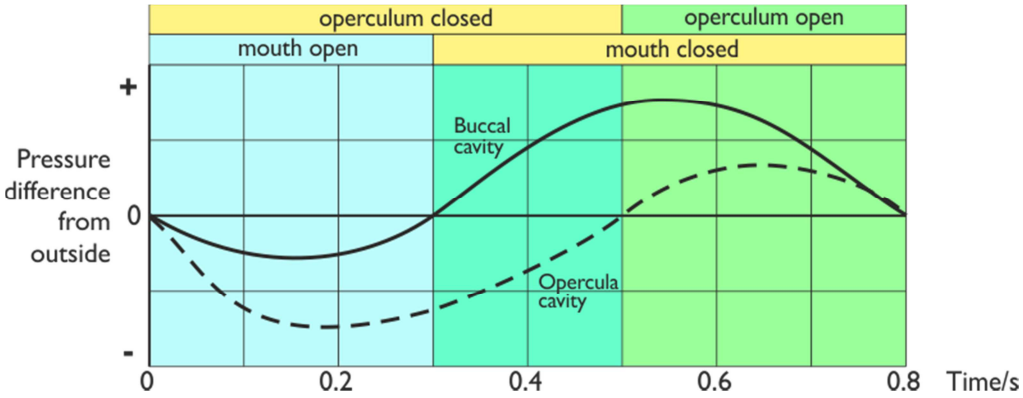
1. The mouth opens.
2. The muscles in the mouth contract, lowering the floor of the mouth, and the opercula muscles contract, pushing the opercula outwards.
3. This increases the volume of the buccal cavity and the opercular cavity.
4. This decreases the pressure of water in the buccal cavity below the outside water pressure.
5. The outside water pressure closes the opercular valve.
6. Water flows in through the open mouth and over the gills from high pressure to low pressure.

Expiration



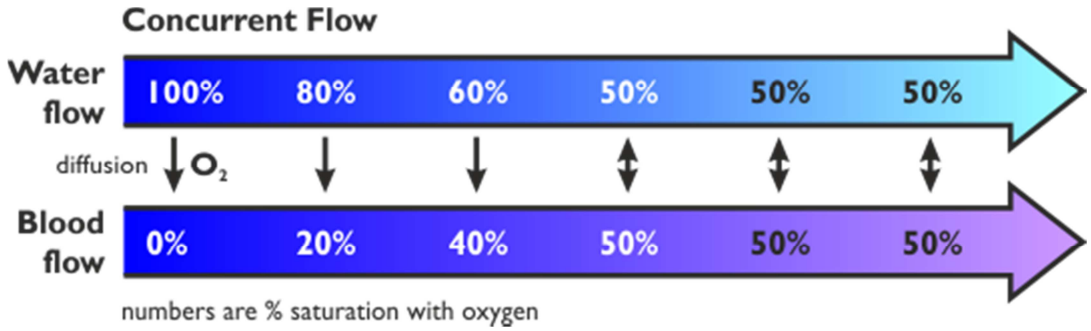
1. The mouth closes.
2. The mouth and opercular muscles relax, raising the floor of the buccal cavity.
3. This decreases the volume of the buccal cavity.
4. This increases the pressure of water in the buccal cavity above the outside water pressure.
5. This pressure forces the opercula valves open.
6. Water flows out over the gills and through the opercula valve from high pressure to low pressure.

These pressure changes are shown in this graph. The rule is that water always flows from a high pressure to a low pressure. This graph shows that water flows in one direction only.

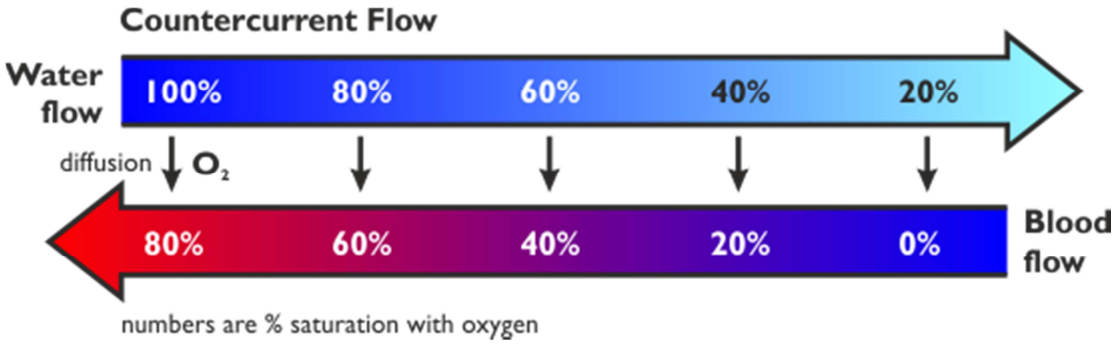


Counter Current Exchange

Because fish have a one-way flow, they can make use of another trick to improve their efficiency of gas exchange: a counter current system. If water and blood flowed past each other in the same direction (parallel or concurrent flow) then the oxygen concentration in the water and blood quickly becomes the same, so no further diffusion can take place, and only 50% of the oxygen can be extracted from the water:

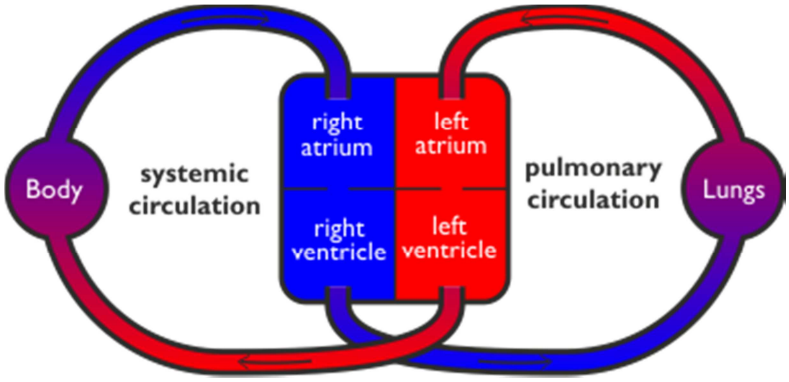


In the countercurrent system the blood flows towards the front of the fish in the gill lamellae while the water flows towards the back. This means that there is always a higher concentration of oxygen in the water than in the blood, so oxygen continues to diffuse into the blood along the whole length of the lamellae. Using this system fish gills can extract about 80% of the dissolved oxygen from the water:

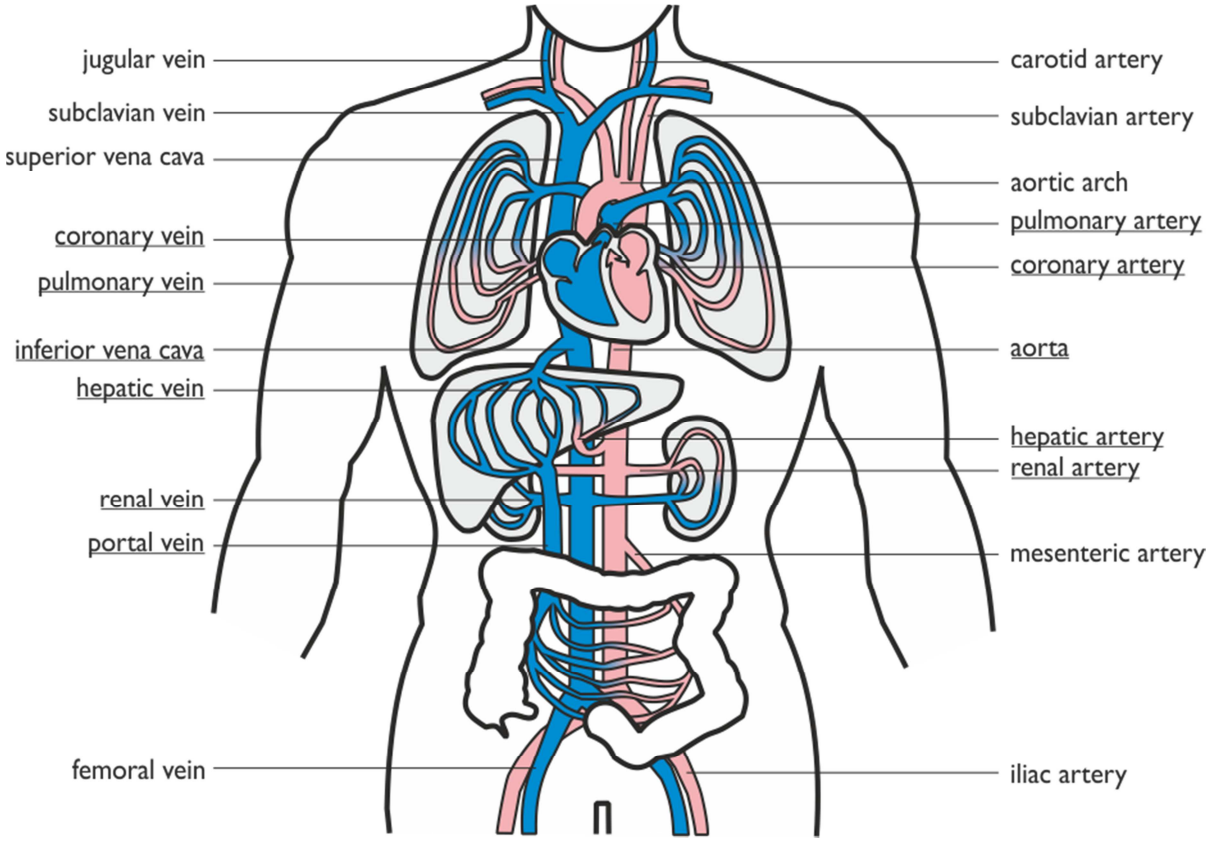


Human Circulatory System

Humans have a double circulatory system with a 4-chambered heart. In humans the right side of the heart pumps blood to the lungs only and is called the pulmonary circulation, while the left side of the heart pumps blood to the rest of the body – the systemic circulation.



The circulation of blood round the body was first observed by Ibn-Al-Nafis (1213-1288) in Cairo and independently rediscovered by William Harvey in England in 1628. Until then people assumed that blood ebbed and flowed through the same tubes, because they hadn't seen capillaries. This diagram illustrates the blood vessels to the main organs. The underlined vessels are listed in the specification.

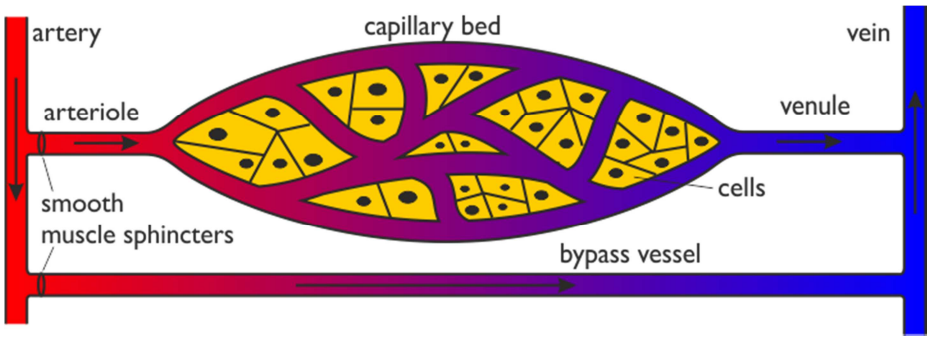


Blood Vessels

Blood circulates in a series of different kinds of blood vessels as it circulates round the body.

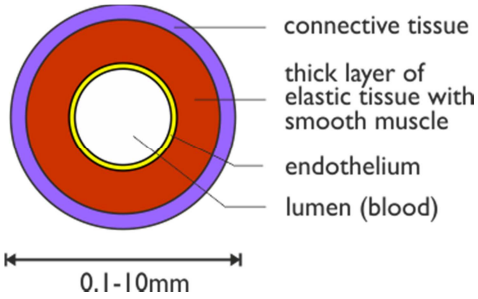
Heart → Aorta → Arteries → Arterioles → Capillaries → Venules → Veins → Vena Cava → Heart

The purpose of these different vessels is to deliver blood to capillary beds, where substances are exchanged between cells and blood. No cell in the body is more than 100µm away from a capillary.

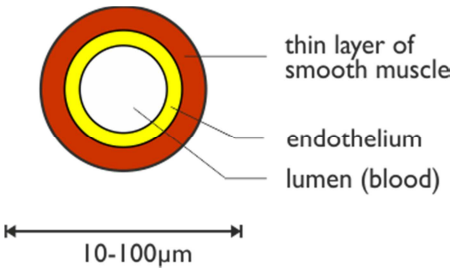


Each kind of vessel is adapted to its function.

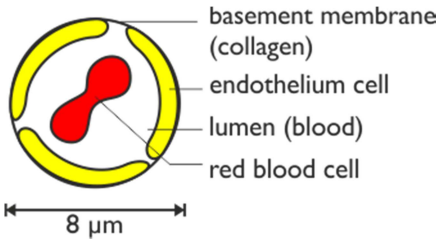
Arteries carry blood from the heart to every tissue in the body. They continually branch into smaller and smaller vessels. Arteries have thick walls (over 100 cells thick) composed mainly of elastic tissue allowing the artery to expand without bursting and so withstand the high pressure of blood from the heart. The arteries close to the heart are particularly elastic and expand during systole and recoil again during diastole, helping to even out the pulsating blood flow.



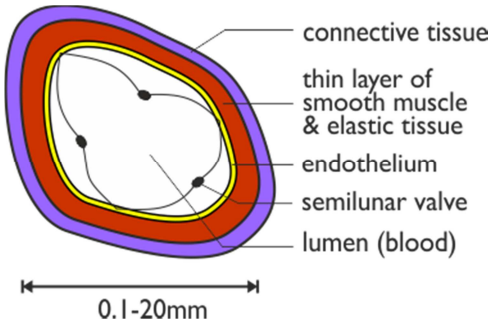
Arterioles are the smallest arteries. Each arteriole leads to one capillary bed. Arterioles have thinner walls (about 10 cells thick), composed mainly of smooth muscle tissue to regulate the blood flow to the capillary bed. The muscles can contract (vasoconstriction) to close off the capillary beds; or relax (vasodilation) to open up the capillary bed. These changes are happening constantly under the involuntary control of the medulla in the brain, and are most obvious in the capillary beds of the skin, causing the skin to change colour from pink (skin arterioles dilated) to blue (skin arterioles constricted). There is not enough blood to fill all the body's capillaries, and at any given time up to 20% of the body's capillary beds are closed off.

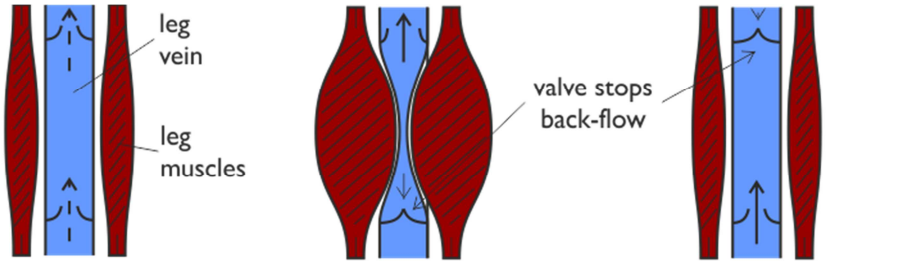


Capillaries are where the transported substances actually enter and leave the blood. Capillaries are very narrow and their walls are composed of single squamous endothelial cells with gaps between them, making capillaries very permeable. There are a vast number of capillaries (10^8 m in one adult!), so they have a huge surface area : volume ratio, helping the rapid diffusion of substances between blood and cells.



Veins carry blood from every tissue in the body to the heart. The smallest veins, called <u>venules</u>, collect the blood from capillary beds and feed into larger veins. The blood has lost almost all its pressure in the capillaries, so it is at low pressure inside veins and is moving slowly. Veins therefore don't need thick walls and they have a larger lumen than arteries, to reduce the resistance to flow. They also have semi-lunar valves to stop the blood flowing backwards. It is particularly difficult for blood to flow upwards through the legs to heart, and the flow is helped by contractions of the leg and abdominal muscles:





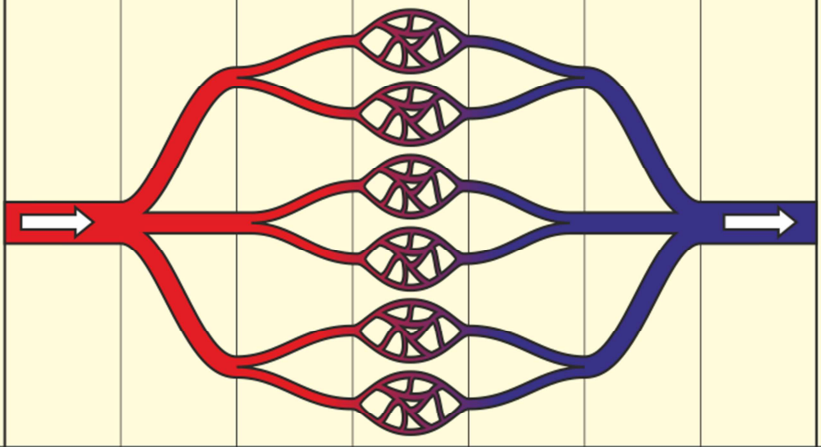
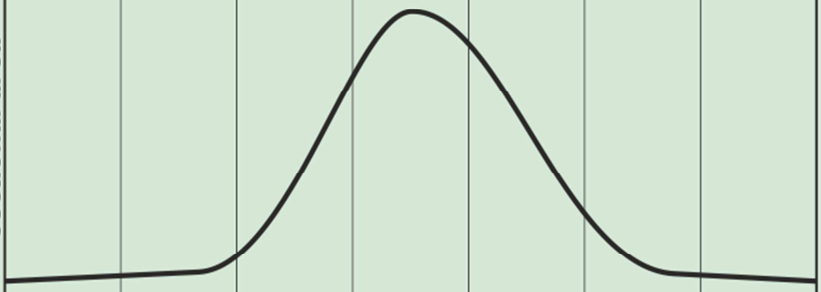
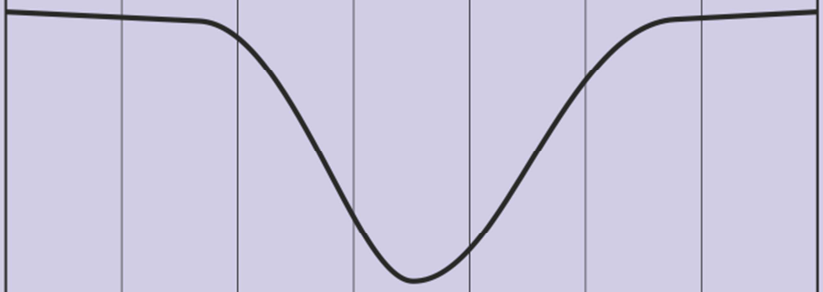
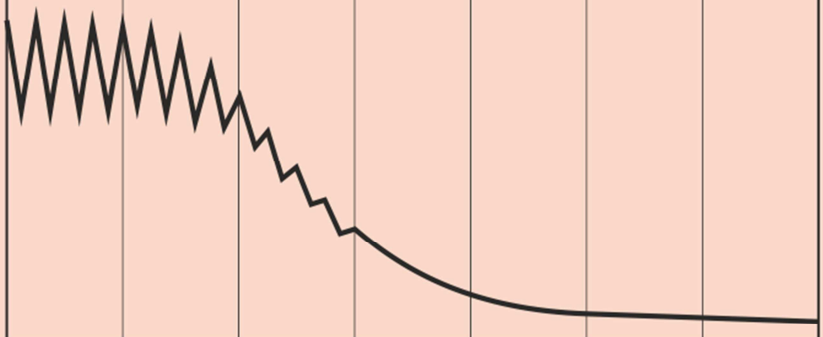
The body relies on constant contraction of these muscles to get the blood back to the heart, and this explains why soldiers standing still on parade for long periods can faint, and why sitting still on a long flight can cause swelling of the ankles and Deep Vein Thrombosis (DVT or "economy class syndrome"), where small blood clots collect in the legs.

Note the correct words:	
Muscles	contract and relax
Elastic tissues	stretch and recoil
Tubes	constrict and dilate

Summary of Different Blood vessels

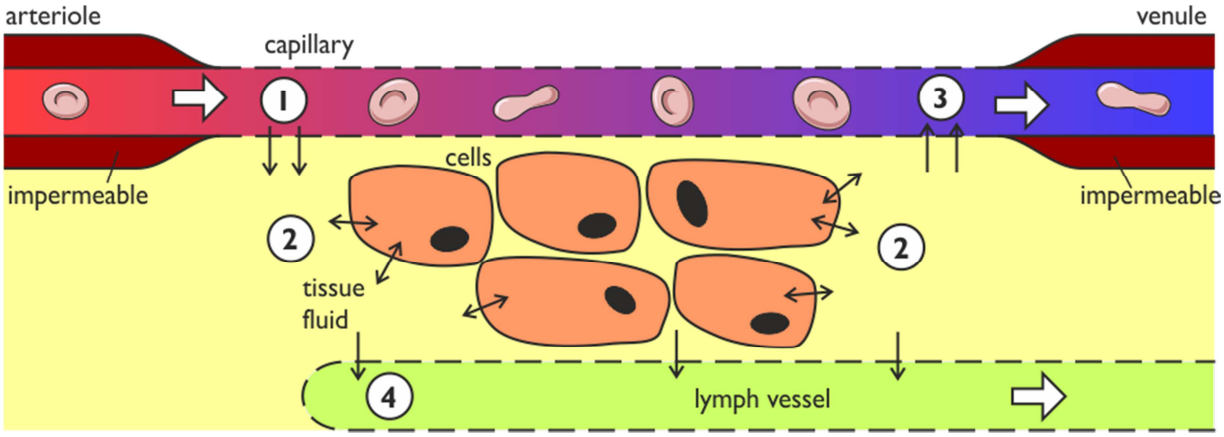
Arteries	Arterioles	Capillaries	Veins
Function is to carry blood from the heart to the tissues	Function is to carry blood from arteries to one capillary bed	Function is to allow exchange of materials between the blood and the tissues	Function is to carry blood from tissues to the heart
Thick walls with elastic layers to resist high pressure	Thick walls with smooth muscle to control flow to capillary bed	Very thin, permeable walls, only one cell thick to allow exchange of materials	Thin walls, mainly collagen, since blood at low pressure
Small lumen	Small lumen	Very small lumen. Blood cells must distort to pass through.	Large lumen to reduce resistance to flow
No valves (except in heart)	No valves	No valves	Many valves to prevent back-flow
Blood at high pressure	Blood pressure falls	Blood pressure falls	Blood at low pressure
Blood usually oxygenated (except in pulmonary circulation)	Blood usually oxygenated (except in pulmonary circulation)	Blood changes from oxygenated to deoxygenated (except in pulmonary circulation)	Blood usually deoxygenated (except in pulmonary circulation)

This diagram shows some of the changes that take place as the blood flows round the body.

	Aorta	Arteries	Arterioles	Capillaries	Venules	Veins	Vena Cava	
Anatomy								As the vessels branch and become thinner and they become more numerous.
Total cross-sectional area								Although each capillary has a tiny cross-sectional area, there are so many of them that the total cross-sectional area of all the capillaries is huge.
Velocity of flow								As the total area increases, the flow velocity (in m/s) decreases, since the volume flow rate (in mL/s) is constant. This means that blood flows very slowly through the capillaries, giving more time for diffusion.
Pressure								The blood pressure gradually decreases as the blood flows away from the heart. Most of the decrease is in the arterioles and capillaries due to resistance and leakage. The pressure in the big arteries is highly pulsate with each heart beat.
	Aorta	Arteries	Arterioles	Capillaries	Venules	Veins	Vena Cava	

Tissue Fluid

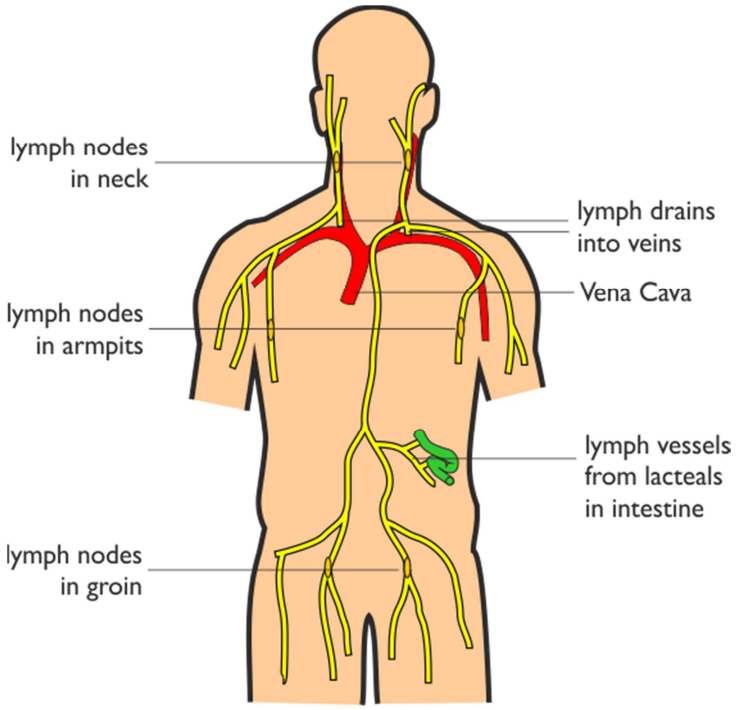
No exchange of materials takes place in the arteries and veins, whose walls are too thick and impermeable. Substances are all exchanged between the blood and the cells in capillary beds, but they do not actually move directly between the blood and the cell: they first diffuse into the tissue fluid that surrounds all cells, and then diffuse from there to the cells.



1. At the arterial end of the capillary bed the blood is still at high pressure, so blood plasma is forced out through the permeable walls of the capillary. Cells and proteins are too big to leave the capillary, so they remain in the blood. So tissue fluid is formed by pressure filtration, not diffusion.
2. This fluid now forms tissue fluid surrounding the cells. Materials are exchanged between the tissue fluid and the cells by all four methods of transport across a cell membrane.
    - gases and lipid-soluble substances (such as steroids) cross by lipid diffusion;
    - water crosses by osmosis;
    - ions cross by facilitated diffusion;
    - glucose and amino acids cross by active transport.
3. At the venous end of the capillary bed the blood is at low pressure, since it has lost so much plasma. The blood and tissue fluid are now at around the same pressure, so tissue fluid returns by diffusion, not mass flow.
    - Solutes (such as carbon dioxide, urea, salts, etc.) enter the blood by diffusion, down their concentration gradients.
    - Water returns to the blood by osmosis down its water potential gradient. The blood has lost a lot of water but retained soluble proteins, so has a low water potential.
4. Not all the fluid that left the blood returns to it, so there is excess tissue fluid. This excess drains into lymph vessels, which are found in all capillary beds. Lymph vessels have very thin walls, like capillaries, and tissue fluid can easily diffuse inside, forming lymph.

The Lymphatic System

The lymphatic system consists of a network of lymph vessels flowing alongside the veins. The vessels lead towards the heart, where the lymph drains back into the blood system near the superior vena cava. There is no pump, but there are numerous semi-lunar valves, and lymph is helped along by contraction of body muscles, just as in veins.



The lymphatic system has three different functions:

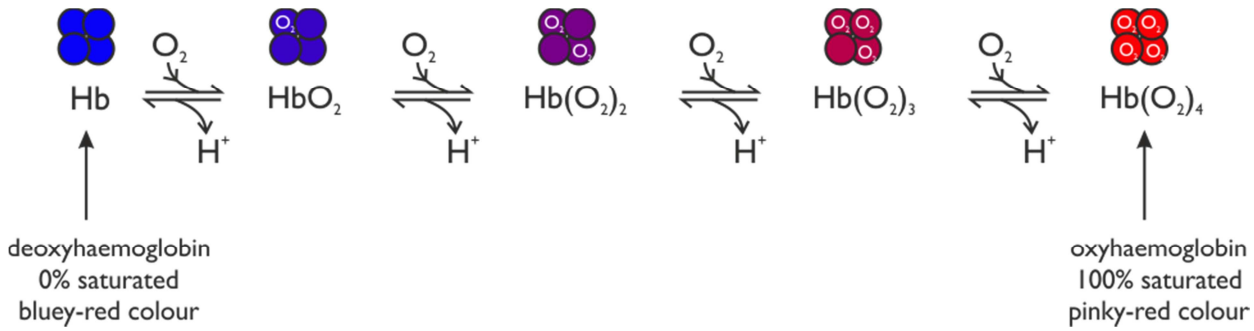
- It drains excess tissue fluid
- It absorbs fats from the small intestine, via the lacteals inside each villus.
- It is part of the immune system. There are networks of lymph vessels at various places in the body (such as tonsils and armpits) called lymph nodes where white blood cells develop. These become swollen if more white blood cells are required to fight an infection.

Remember the difference between these four fluids:

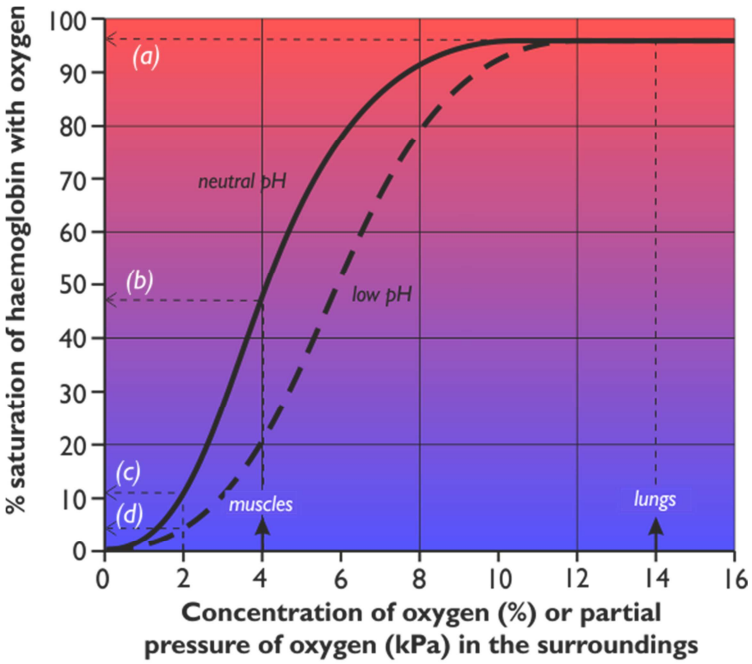
Plasma	The liquid part of blood. It contains dissolved glucose, amino acids, salts and vitamins; and suspended proteins and fats.
Serum	Purified blood plasma, with blood clotting proteins removed, used in hospitals for blood transfusions.
Tissue Fluid	The solution surrounding cells. Its composition is similar to plasma, but with fewer proteins (which stay in the blood capillaries).
Lymph	The solution inside lymph vessels. Its composition is similar to tissue fluid, but with more fats (from the digestive system).

Transport of Oxygen

Oxygen is carried in red blood cells bound to the protein haemoglobin. A red blood cell contains about 300 million haemoglobin molecules and there are 5 million red blood cells per cm^3 of blood. The result of this is that blood can carry up to 20% oxygen, whereas pure water can only carry 1%. The haemoglobin molecule consists of four polypeptide chains, with a haem prosthetic group at the centre of each chain. Each haem group contains one iron atom, and one oxygen molecule binds to each iron atom. So one haemoglobin molecule can bind up to four oxygen molecules. This means there are 4 binding steps, as shown in this chemical equation:



A sample of blood can therefore be in any state from completely deoxygenated (0% saturated) to fully oxygenated (100% saturated). Since deoxyhaemoglobin and oxyhaemoglobin are different colours, it is easy to measure the % saturation of a sample of blood in a colorimeter. As the chemical equation shows, oxygen drives the reaction to the right, so the more oxygen there is in the surroundings, the more saturated the haemoglobin will be. This relation is shown in the oxygen dissociation curve:



The concentration of oxygen in the surroundings can be measured as a % (there's about 20% oxygen in air), but it's more correct to measure it as a partial pressure (PO_2, measured in kPa). Luckily, since the pressure of one atmosphere is about 100 kPa, the actual values for PO_2 and $\%O_2$ are the same (e.g. 12% O_2 has a PO_2 of 12 kPa).

The graph is read by starting with an oxygen concentration in the environment surrounding the blood capillaries on the horizontal axis, then reading off the state of the haemoglobin in the blood that results from the vertical axis.

This curve has an S (or sigmoid) shape, and shows several features that help in the transport of oxygen in the blood:

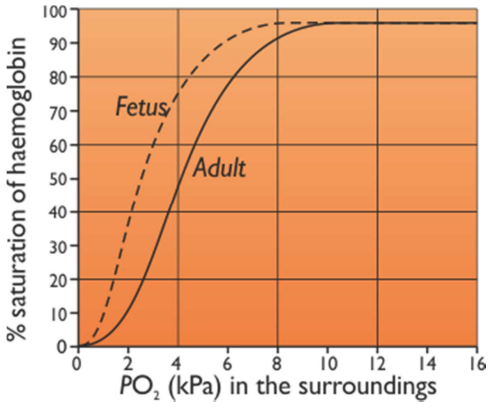
- In the alveoli of the lungs oxygen is constantly being brought in by ventilation, so its concentration is kept high, at around 14 kPa. As blood passes through the capillaries surrounding the alveoli the haemoglobin binds oxygen to become almost 100% saturated (point *a*). Even if the alveolar oxygen concentration falls a little the haemoglobin stays saturated because the curve is flat here.
- In tissues like muscle, liver or brain, oxygen is used by respiration, so its concentration is low, typically about 4 kPa. At this PO_2 the haemoglobin is only 50% saturated (point *b*), so it unloads about half its oxygen (i.e. from about 100% saturated to about 50% saturated) to the cells, which use it for respiration.
- In tissues that are respiring quickly, such as contracting muscle cells, the PO_2 drops even lower, to about 2 kPa, so the haemoglobin saturation drops to about 10% (point *c*), so almost 90% of the oxygen is unloaded, providing more oxygen for the muscle cells.
- Actively-respiring tissues also produce a lot of CO_2, which dissolves in tissue fluid to make carbonic acid and so lowers the pH. The chemical equation on the previous page shows that hydrogen ions drive the reaction towards the deoxyhaemoglobin state, so low pH reduces the % saturation of haemoglobin at any PO_2. This is shown on the graph by the dotted line, which is lower than the normal dissociation curve. This downward shift is called the Bohr effect, after the Danish scientist who first discovered it. So at a PO_2 of 2kPa, the actual saturation is nearer 5% (point *d*), so 95% of the oxygen loaded in the lungs is unloaded in respiring tissues.

Remember that oxygen can only diffuse in and out of the blood from capillaries, which are permeable. Blood in arteries and veins is "sealed in", so no oxygen can enter or leave the blood whatever the conditions surrounding the blood vessel. So as haemoglobin travels from the lungs to a capillary bed in a body tissue and back to the lungs, it "switches" from one position on the dissociation curve to another position, without experiencing the intermediate stages of the curve.

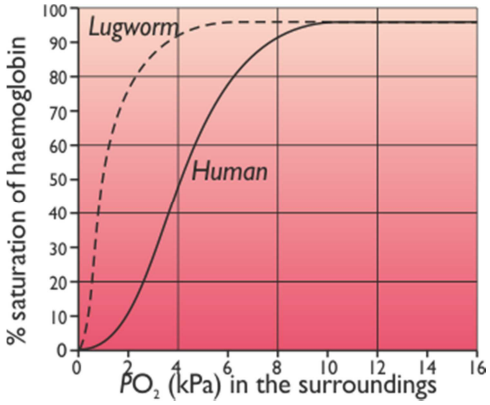
Different Haemoglobins

Different animals possess different types of haemoglobin with different oxygen transporting properties. These properties are related to the animal's way of life, so they are an adaptation that helps the animal survive in its environment.

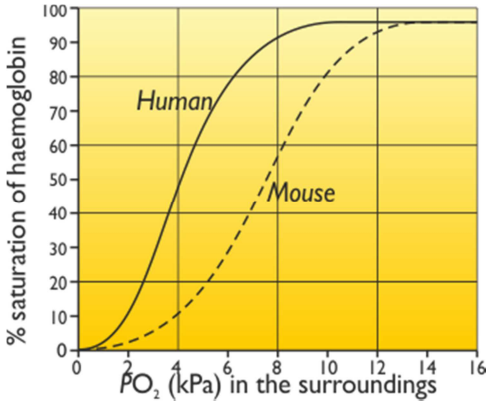
A **human fetus** obtains its oxygen from the placenta not the lungs. In the placenta the mother's and fetus's capillary beds are intertwined (but the bloods don't mix). Fetal haemoglobin is a different kind from the "adult" form, with a higher affinity for oxygen at low partial pressures, so its oxygen dissociation curve is shifted up. So this different haemoglobin allows oxygen to diffuse from the mother's blood to the fetus, yet still be unloaded in the fetal tissues. Fetal haemoglobin is gradually replaced by "adult" haemoglobin during the first year after birth.



Lugworms live in the mud in estuaries and seashores. When the tide is out the lugworm stays in a burrow filled with sea water. But the oxygen concentration in this burrow can fall very low as the lugworm respires, so the lugworm has haemoglobin with a very high affinity for oxygen: its oxygen dissociation curve is shifted up. This allows the lugworm to obtain oxygen even when the PO_2 is as low as 2kPa.



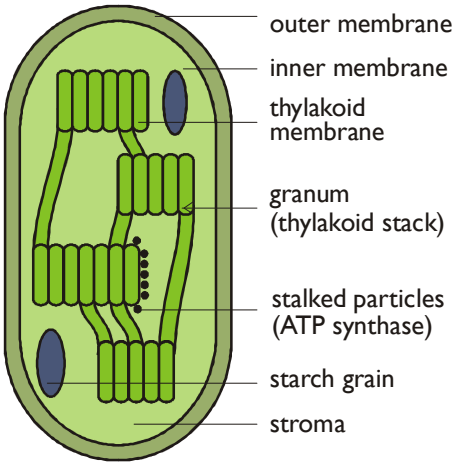
Mice lose heat very quickly due to their large surface area : volume ratio, so they have a high metabolic rate to generate more heat. Their tissues therefore have a constant demand for oxygen for respiration. The oxygen dissociation curve for mouse haemoglobin is shifted down compared to humans, so plenty of oxygen is unloaded to all tissues all the time.



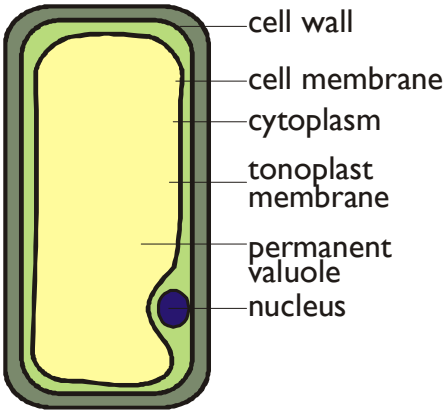
Plant Cells

The next section is on exchange and transport systems in plants. Plant cells contain a number of organelles not found in animal cells.

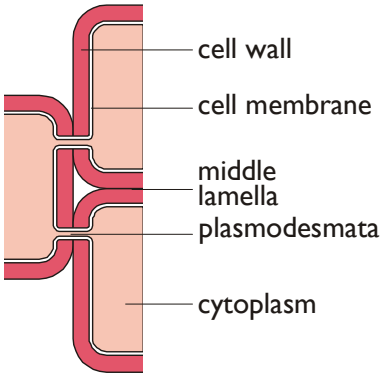
- **Chloroplasts**. Bigger and fatter than mitochondria, chloroplasts are where photosynthesis takes place, so are only found in photosynthetic organisms (plants and algae). Like mitochondria they are enclosed by a double membrane, but chloroplasts also have a third membrane called the thylakoid membrane. The thylakoid membrane is folded into thylakoid disks, which are then stacked into piles called grana. The space between the inner membrane and the thylakoid is called the stroma. The thylakoid membrane contains chlorophyll and chloroplasts also contain starch grains, ribosomes and circular DNA.



- **Vacuoles**. These are membrane-bound sacs containing water or dilute solutions of salts and other solutes. Most cells can have small vacuoles that are formed as required, but plant cells usually have one very large permanent vacuole that fills most of the cell, so that the cytoplasm (and everything else) forms a thin layer round the outside. Plant cell vacuoles are filled with cell sap, and are very important in keeping the cell rigid, or turgid. Some unicellular protoctists have feeding vacuoles for digesting food, or contractile vacuoles for expelling water.



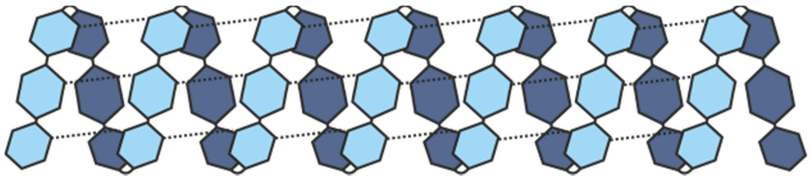
- **Cell Wall**. This is a thick layer outside the cell membrane used to give a cell strength and rigidity. Cell walls consist of a network of fibres, which give strength but are freely permeable to solutes (unlike membranes). A wickerwork basket is a good analogy. Plant cell walls are made mainly of cellulose, but can also contain hemicellulose, pectin, lignin and other polysaccharides. There are often channels through plant cell walls called plasmodesmata, which link the cytoplasms of adjacent cells. Fungal cell walls are made of chitin.



Polysaccharides

In unit 1 we looked at monosaccharides and disaccharides. Here we look at polysaccharides. Polysaccharides are long chains of many monosaccharides joined together by glycosidic bonds. There are three important polysaccharides:

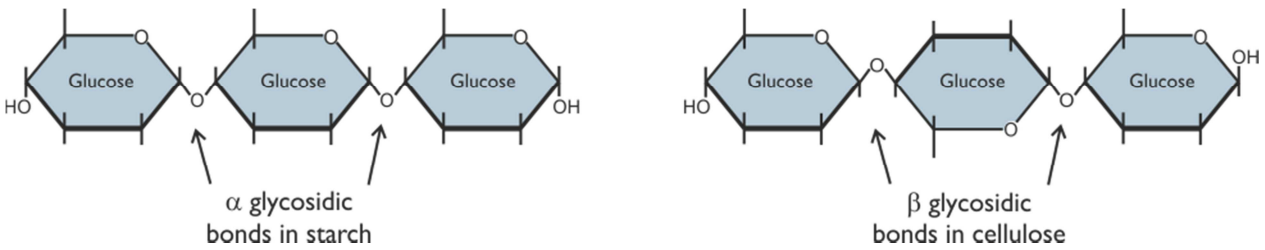
1. **Starch** is the plant storage polysaccharide. It is insoluble and forms starch granules inside many plant cells. Being insoluble means starch does not change the water potential of cells, so does not cause the cells to take up water by osmosis. It is not a pure substance, but is a mixture of amylose and amylopectin. Amylose is poly-(1-4) glucose, so is a long glucose chain that coils up into a helix held together by hydrogen bonds.



Amylopectin is poly(1-4) glucose with about 4% (1-6) branches. This gives it a more open molecular structure than amylose. Because it has more ends, it can be broken more quickly than amylose by amylase enzymes. Both amylose and amylopectin are broken down by the enzyme amylase into maltose, though at different rates.

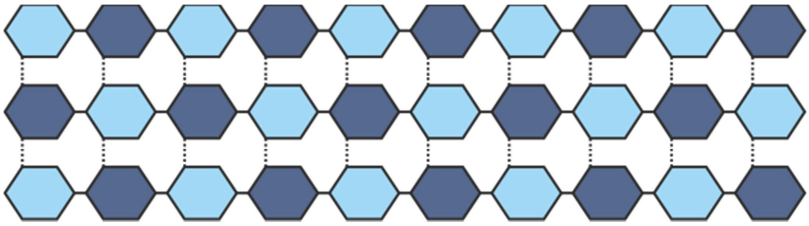
2. **Glycogen** is the animal storage polysaccharide, is found mainly in muscle and liver cells. It is similar in structure to amylopectin: poly (1-4) glucose with 9% (1-6) branches. Because it is so highly branched, it can be mobilised (broken down to glucose for energy) very quickly. It is broken down to glucose by the enzyme glycogen phosphorylase.

3. **Cellulose** is only found in plants, where it is the main component of cell walls. It is poly (1-4) glucose, but with a different isomer of glucose. Starch and glycogen contain α-glucose, while cellulose contains β-glucose, with a different position of the hydroxyl group on carbon 1. This means that in a cellulose chain alternate glucose molecules are inverted.



This apparently tiny difference makes a huge difference in structure and properties. The α bond is flexible so starch molecules can coil up, but the β bond is rigid, so cellulose molecules form straight chains. Hundreds of these chains are linked together by hydrogen bonds between the chains to form

cellulose microfibrils. These microfibrils are very strong and rigid, and give strength to plant cells, and therefore to young plants and also to materials such as paper, cotton and sellotape.



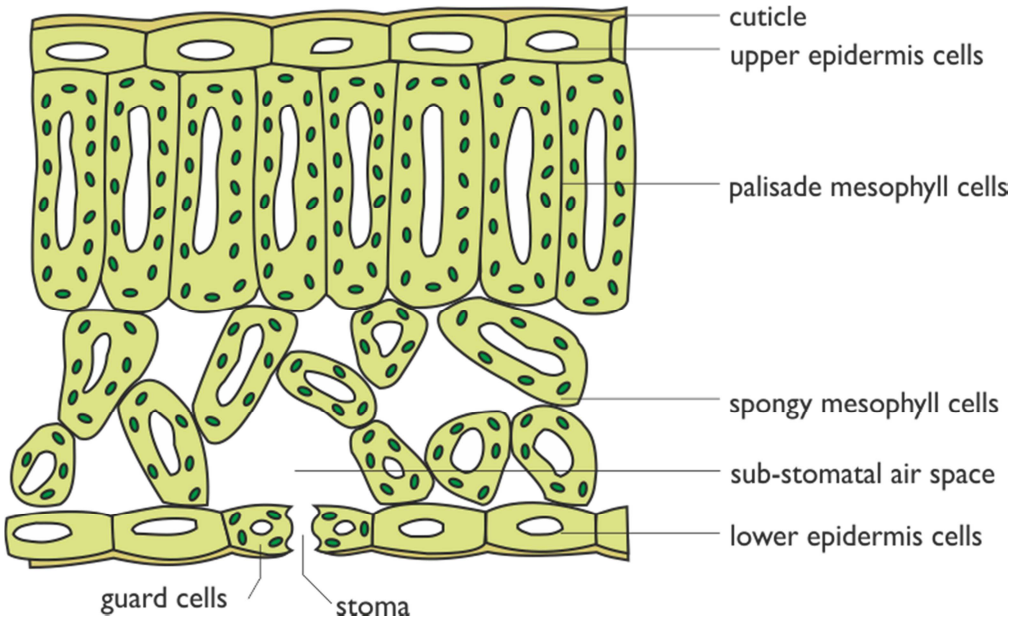
hydrogen bonds between chains forming microfbirils

The β-glycosidic bond cannot be broken by amylase, but requires a specific cellulase enzyme. The only organisms that possess a cellulase enzyme are bacteria, so herbivorous animals, like cows and termites whose diet is mainly cellulose, have mutualistic bacteria in their guts so that they can digest cellulose. Carnivores and omnivores cannot digest cellulose, and in humans it is referred to as fibre.

Starch and Glycogen	Cellulose
α glycosidic bonds	β glycosidic bonds
flexible chains	straight chains
H bonds within each chain, forming helix	H bonds between chains, forming microfibrils
Can form H-bonds with water, so can be soluble	Can't form H bonds with water, so insoluble
Reacts with iodine to form blue-black complex	Doesn't react with iodine
Easy to digest	Difficult to digest
Storage role	Structural role

Gas Exchange in Plants

All plant cells respire all the time, and during the day many plant cells also photosynthesise, so plants also need to exchange gases. The main gas exchange surfaces in plants are the spongy mesophyll cells in the leaves. Leaves of course have a huge surface area, and the irregular-shaped, loosely-packed spongy cells increase the area for gas exchange still further. Leaves therefore have a large internal surface area : volume ratio.



Gases enter the leaf through stomata (singular stoma), which are usually in the under surface of the leaf. There are often several thousand stomata per square centimetre of leaf surface. Stomata are enclosed by guard cells, which can close the stomata to reduce water loss. Since leaves are so thin, gases can quickly diffuse through the intercellular air spaces inside the leaf, which are in direct contact with the spongy and palisade mesophyll cells.

Like terrestrial animals, plants have a problem of water loss. Water diffuses down its concentration gradient from the xylem vessels and mesophyll cells into the air spaces in the leaves. Plants have a number of strategies for reducing this loss:

- The upper surface of the leaf is covered in a waterproof cuticle, made of lipids secreted by the upper epidermal cells.
- The sub-stomatal air space remains moist (like the alveolar air space in lungs) to reduce the water concentration gradient so less water evaporates from the spongy cells.
- The guard cells can close the stomata to stop water loss when conditions are very dry. Unfortunately this also prevents gas exchange, stopping photosynthesis and respiration. So plants can't close their stomata for very long.

Plants do not need a ventilation mechanism because their leaves are highly exposed, so the air surrounding them is constantly being replaced in all but the stillest days. In addition, during the hours of daylight photosynthesis increases the oxygen concentration in the sub-stomatal air space, and decreases the carbon dioxide concentration. These increase the concentration gradients for these gases, speeding up the rate of diffusion.

The cells in leaf tissues are highly adapted to their functions:

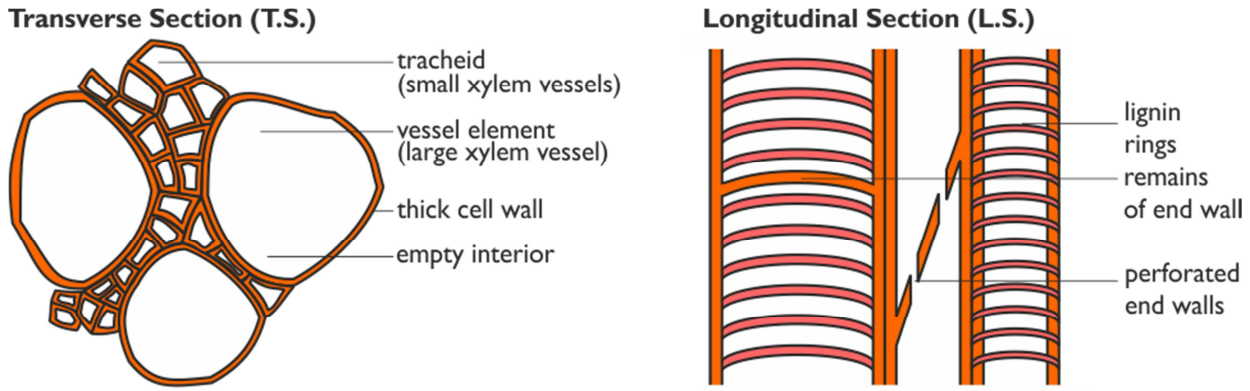
- The palisade mesophyll cells are adapted for photosynthesis. They have a thin cytoplasm densely packed with chloroplasts, which can move around the cell on the cytoskeleton to regions of greatest light intensity. The palisade cells are closely packed together in rows to maximise light collection, and in plants adapted to low light intensity there may be two rows of palisade cells.
- The spongy mesophyll cells are adapted for gas exchange. They are loosely-packed with unusually large intercellular air spaces where gases can collect and mix. They have fewer chloroplasts than palisade cells, so do less photosynthesis.

Water Transport in Plants

Vast amounts of water pass through plants. A large tree can use water at a rate of 1 dm^3 min^{-1}. Only 1% of this water is used by the plant cells for photosynthesis and turgor, and the remaining 99% evaporates from the leaves and is lost to the atmosphere. This evaporation from leaves is called transpiration. Plants don't have a circulatory system like animals, but they do have a sophisticated mass transport system for carrying water and dissolved solutes to different parts of the plant, often over large distances. Both diffusion and mass flow are used to move substances, just as in animals. We shall look at the transport system in dicotyledonous (broad-leaved) plants only. Monocotyledons (narrow-leaved plants) have slightly different structures.

Xylem Tissue

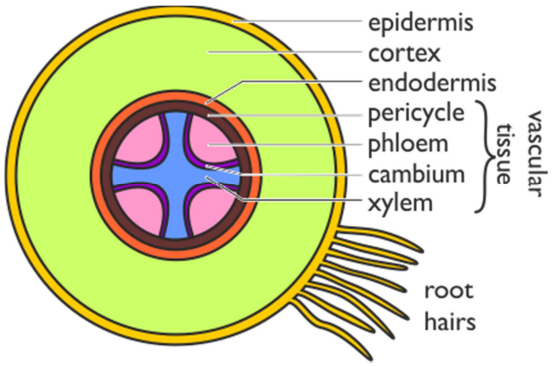
Water is transported through plants through xylem vessels. Xylem tissue is composed of dead cells joined together to form long empty tubes. Different kinds of cells form wide and narrow tubes, and the end cells walls are either full of holes, or are absent completely. Before death the cells form thick cell walls containing lignin, which is often laid down in rings or helices, giving these cells a very characteristic appearance under the microscope. Lignin makes the xylem vessels very strong, so that they don't collapse under pressure, and they also make woody stems strong.



To help to understand how water moves through a plant, its movement can be split into three sections: through the roots, stem and leaves:

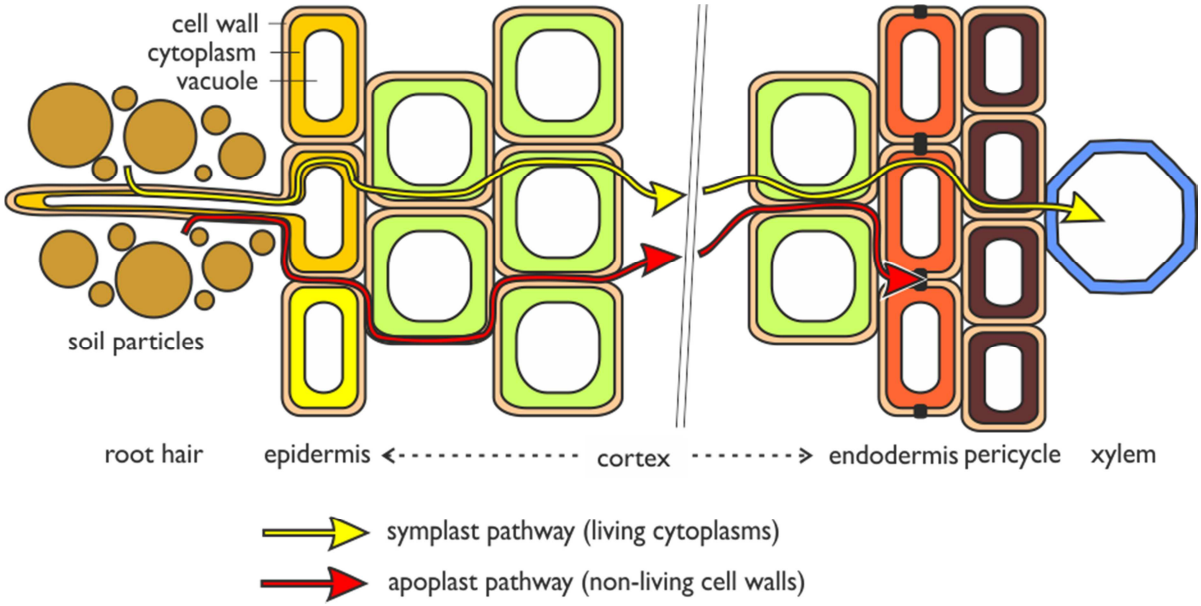
1. Movement through the Roots (Diffusion)

Roots are composed of many different tissues, each with a specific function.



- Epidermis. A single layer of cells often with long extensions called root hairs, which increase the surface area enormously. A single plant may have 10^{10} root hairs.
- Cortex. A thick layer of packing cells often containing stored starch.
- Endodermis. A single layer of tightly-packed cells containing a waterproof layer called the casparian strip. This prevents the movement of water between the cells.
- Pericycle. A layer of undifferentiated meristematic (growing) cells.
- Vascular Tissue. This contains xylem and phloem cells, which are continuous with the stem vascular bundles. The arrangement is different, and the xylem usually forms a star shape with 2-6 arms, called the stele.

Water moves through the root by two pathways:



- The Symplast Pathway consist of the living cytoplasms of the cells in the root. Water is absorbed into the root hair cells by osmosis, since the cells have a lower water potential that the water in the soil. Water then diffuses from the epidermis through the root to the xylem down a water potential gradient. The cytoplasms of all the cells in the root are connected by plasmodesmata through holes in the cell walls, so there are no further membranes to cross until the water reaches the xylem, and so no further osmosis.

- The Apoplast Pathway consists of the cell walls between cells. The cell walls are quite thick and very open, so water can simply diffuse through cell walls down the water potential gradient. There are no cell membranes to cross so this is diffusion, not osmosis. However the apoplast pathway stops at the endodermis because of the waterproof casparian strip, which seals the cell walls. At this point water has to cross the cell membrane by osmosis and enter the symplast. This allows the plant to have some control over the uptake of water into the xylem. Around 90% of water transport through the root uses the apoplast pathway, as the available volume is greater.

The uptake of water by osmosis actually produces a force that pushes water up the xylem. This force is called root pressure, which can be measured by placing a manometer over a cut stem, and is of the order of 100 kPa (about 1 atmosphere). This helps to push the water a few centimetres up short and young stems, but is nowhere near enough pressure to force water up a long stem or a tree. Root pressure is the cause of guttation, sometimes seen on wet mornings, when drops of water are forced out of the ends of leaves.

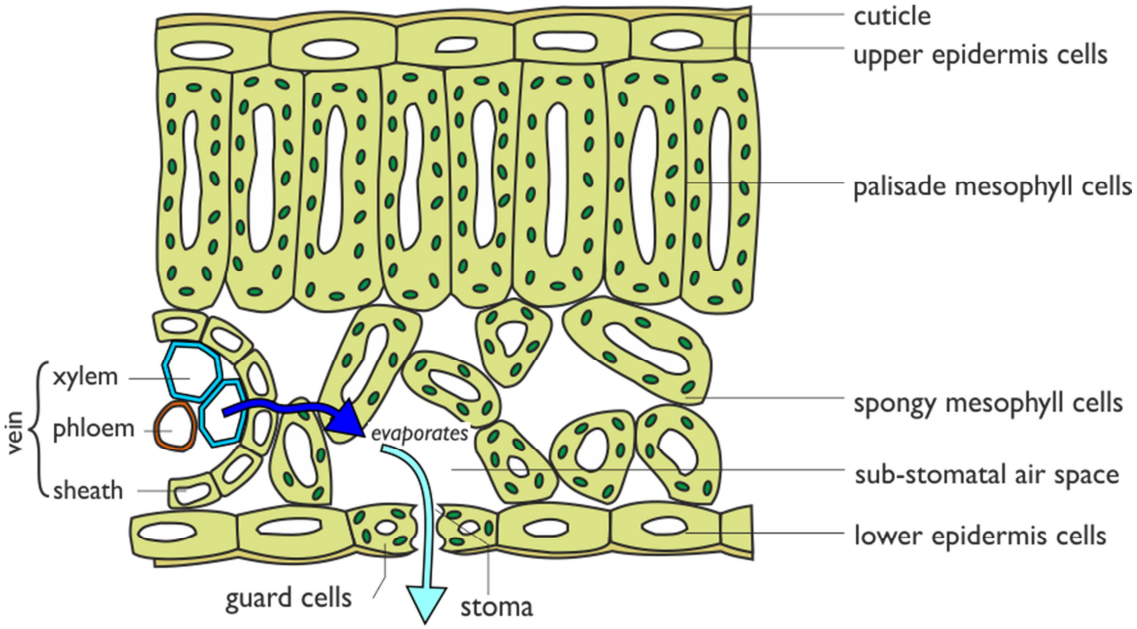
2. Movement through the Stem (Mass Flow)

The xylem vessels form continuous pipes from the roots to the leaves. Water can move up through these pipes at a rate of 8m h^{-1} (2 mm s^{-1}), and can reach a height of over 100m. Since the xylem vessels are dead, open tubes, no osmosis can occur within them, and water moves by mass flow. The driving force for the movement is transpiration in the leaves. This causes low pressure in the leaves, so water is sucked up the stem to replace the lost water. The column of water in the xylem vessels is therefore under tension (a stretching force). Fortunately water has a high tensile strength due to the tendency of water molecules to stick together by hydrogen bonding (cohesion), so the water column does not break under the tension force. This mechanism of pulling water up a stem is sometimes called the cohesion-tension mechanism.

The very strong lignin walls of the xylem vessels stops them collapsing under the suction pressure, but in fact the xylem vessels (and even whole stems and trunks) do shrink slightly during the day when transpiration is maximum.

3. Movement through the Leaves (Diffusion)

The xylem vessels ramify in the leaves to form a branching system of fine vessels called leaf veins. Water diffuses from the xylem vessels in the veins through the adjacent cells down its water potential gradient. As in the roots, it uses the symplast pathway through the living cytoplasm and the apoplast pathway through the non-living cell walls. Water evaporates from the spongy cells into the sub-stomatal air space, and diffuses out through the stomata.

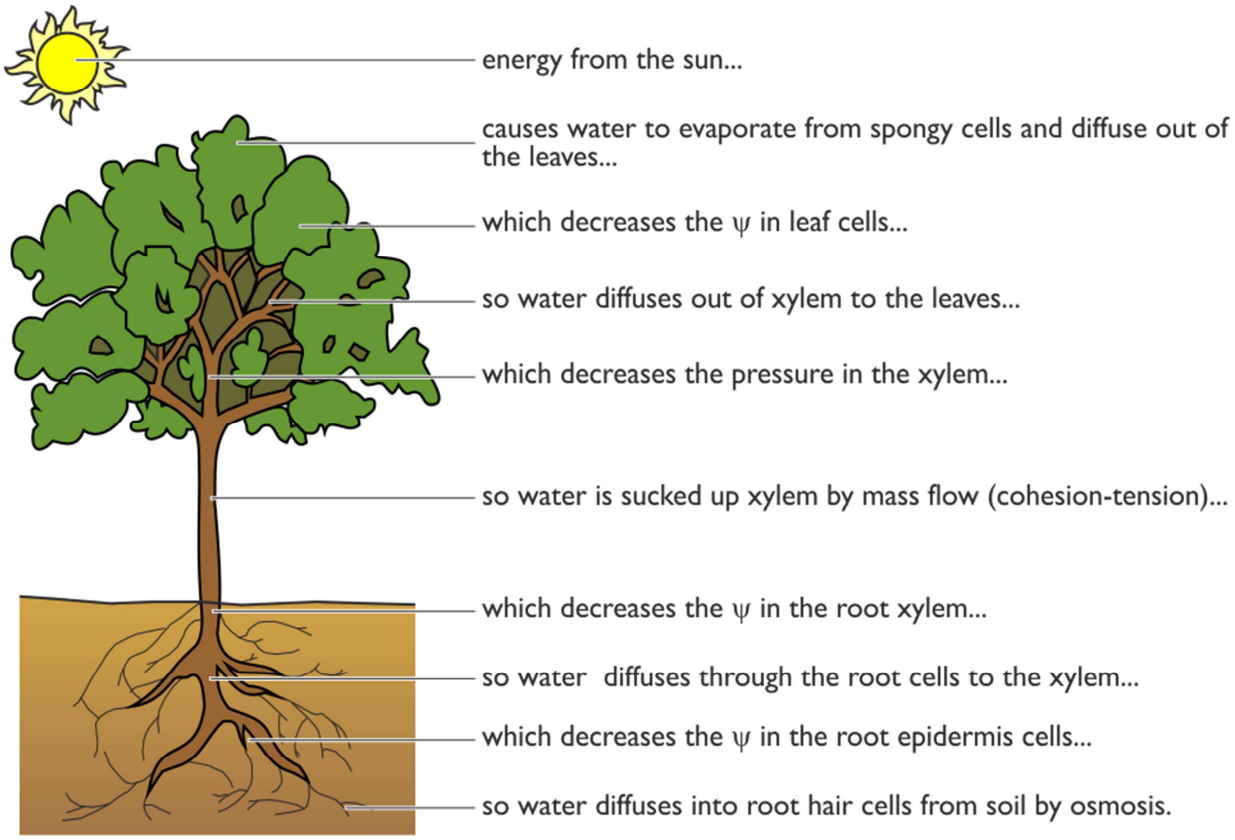


Each stoma is surrounded by two guard cells, which, unlike the rest of the epidermal cells, contain chloroplasts. The chloroplasts allow the guard cells to photosynthesise and produce ATP, which they use to drive active transport ion pumps, which mean they can quickly alter their water potential.

- To open the stoma the guard cells pump ions into the cell, which lowers their water potential so water enters by osmosis. The cells become turgid and bend apart so the stoma between them opens.
- To close the stoma the guard cells pump ions out of the cell, which raises their water potential so water leaves by osmosis. The cells become flaccid and straighten so the stoma between them closes.

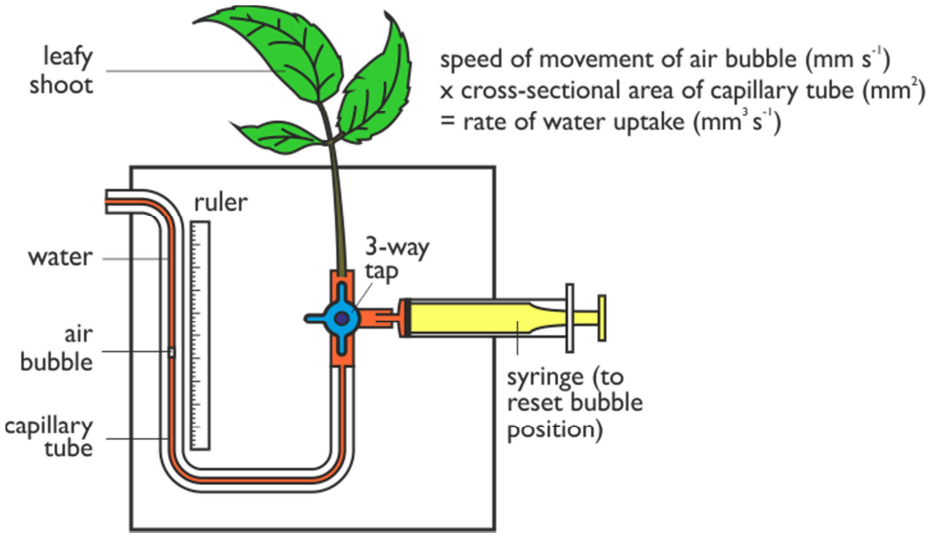
In this way exit of water can be controlled.

Evaporation of water is an endothermic process, since it requires energy to turn water from a liquid to a gas. This energy is provided by heat from the sun, so the sun is therefore the source of energy for all the water movements in plants. This is separate from the sun's role in providing light energy for photosynthesis. The mechanism of water movement in plants is summarised in this diagram:



Factors affecting Transpiration

The rate of transpiration can be measured in the lab using a potometer ("drinking meter"):



A potometer actually measures the rate of water uptake by the cut stem, not the rate of transpiration; and these two are not always the same. During the day plants often transpire more water than they take up (i.e. they lose water and may wilt), and during the night plants may take up more water than they transpire (i.e. they store water and become turgid). The difference can be important for a large tree, but for a small shoot in a potometer the difference is usually trivial and can be ignored.

The potometer can be used to investigate how various environmental factors affect the rate of transpiration.

- **Temperature**. High temperature increases the rate of evaporation of water from the surface of spongy cells because it increases the kinetic energy of the water molecules. This raises the water potential in the sub-stomatal air space and means the molecules are moving faster, so transpiration increases.
- **Humidity**. High humidity means a higher water potential in the air surrounding the stomata, so a lower water potential gradient between the sub-stomatal air space and the air outside, so less evaporation.
- **Air movements**. Wind blows away saturated air from around stomata, replacing it with drier air with a lower water potential, so increasing the water potential gradient and increasing transpiration.
- **Light**. Light stimulates plants to open their stomata to allow gas exchange for photosynthesis. As a side effect this also increases the rate of transpiration. This is a problem for some plants as they may lose water during the day and wilt.

If plants are losing too much water and their cells are wilting, they close their stomata, reducing transpiration and water loss. So long periods of light, heat, or dry air could result in a decrease in transpiration when the stomata close.

Adaptations to dry habitats

Plants in different habitats are adapted to cope with different problems of water availability.

Xerophytes plants adapted to a dry habitat

Halophytes plants adapted to a salty habitat – in practice this is effectively a dry habitat

Hydrophytes plants adapted to a freshwater habitat

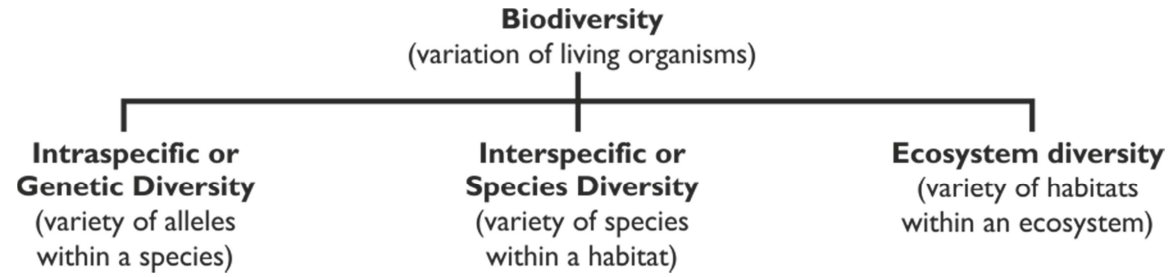
Mesophytes plants adapted to a habitat with adequate water

Some adaptations of xerophytes are:

Adaptation	How it works	Example
thick waxy cuticle	stops uncontrolled evaporation through palisade cells	conifer needles
small leaf surface area	less area for evaporation	conifer needles, cactus spines
low stomata density	fewer gaps in leaves	marram grass, pine
sunken stomata	maintains humid air around stomata	marram grass, pine
stomatal hairs	maintains humid air around stomata	marram grass, couch grass
folded leaves	maintains humid air around stomata	marram grass
succulent leaves and stem	stores water	cacti
extensive roots	maximise water uptake	cacti

Biodiversity

Biodiversity simply means the variety of all the life on Earth. The 1992 United Nations Earth Summit in Rio de Janeiro defined biodiversity as "*the variability among living organisms from all sources, including, 'inter alia', terrestrial, marine, and other aquatic ecosystems, and the ecological complexes of which they are part: this includes diversity within species, between species and of ecosystems*". This definition is adopted by the United Nations Convention on Biological Diversity. There are thus three levels of biodiversity:



All three levels of biodiversity are important because all living organisms are inter-related and depend upon each other in numerous ways. Human activities are reducing biodiversity at all three levels, and these losses may impact on the well-being and survival of humans. Understanding of biodiversity has led to conservation – the attempt to conserve biodiversity worldwide.

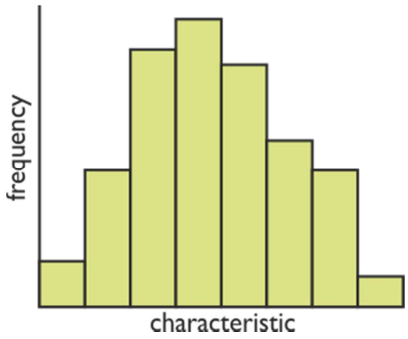
In this unit we will study intraspecific and interspecific diversity, and how the diversity is being reduced. We study ecosystem diversity in unit 4.

Intraspecific Diversity (Genetic Diversity)

Intraspecific diversity can be due to variation in DNA (i.e. different alleles) or variation in environment. Members of the same species all have the same genes, but different combinations of alleles. New alleles arise through mutation and existing alleles are recombined by meiosis and random fertilisation during sexual reproduction so that every individual within a species is genetically unique. The number of different alleles present within a species is called the genetic diversity of the species. There are two types of variation within a species: continuous variation and discontinuous variation.

Continuous Variation

Sometimes the character has a continuous range of values (like height). The frequency histogram is a fairly smooth curve.



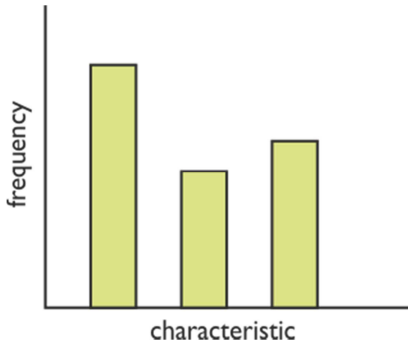
In continuous variation the characteristics:

- have no distinct categories into which individuals can be placed
- tend to be quantitative, with each category continuous with the next one
- are controlled by a large number of genes (i.e. polygenic characteristics)
- are significantly affected by the environment

Continuous characteristics are very common in humans and other organisms. Some examples are height, hair colour, heart rate, muscle efficiency, intelligence, growth rate, rate of photosynthesis, etc.

Discontinuous Variation

Sometimes the characteristic has just a few discrete categories (like blood group). The frequency histogram has separate bars (or sometimes peaks).



In discontinuous variation the characteristics:

- have a few distinct categories into which individuals can be placed
- tend to be qualitative, with no overlap between categories (e.g. red, male)
- are controlled by one gene, or a small number of genes
- are unaffected, or only slightly affected, by the environment.

Discontinuous characteristics are rare in humans and other animals, but are more common in plants. Some examples are human blood group, detached ear lobes, flower colour, seed colour, etc. These characteristics are very useful for geneticists because they give clear-cut results.

The vast majority of intraspecific variation is caused by a combination of genes and environment. In some cases this is obvious, such as human height, which is a combination of genes and diet (you won't reach your potential "genetic height" if you have poor diet). Some cases are less obvious. Cat coat colour is controlled by a small number of genes coding for enzymes that make coloured pigments in skin cells. But some alleles of these genes form enzymes that are temperature-sensitive, giving different coloured cells in warm parts of the body (near the core) and cold parts (the extremities). The development of cancer in humans depends on having certain alleles and certain environmental factors like smoking or viral infection.

Twin Studies

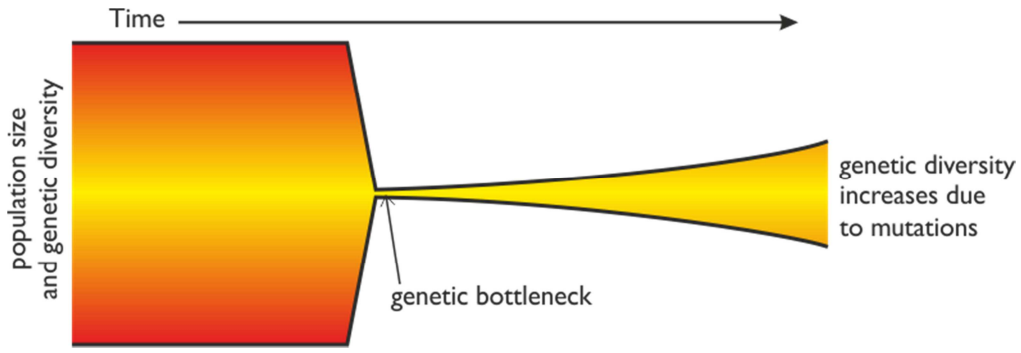
It is very difficult to determine the relative effects of genetics and environment on variation. A useful technique for studying the causes of variation in humans is twin studies. Variation in characteristics between identical twins is compared to variation in the same characteristics between non-identical twins (or just normal siblings). Since the identical twins have identical genes, then differences between them are probably due to environmental causes.

Loss of Intraspecific Diversity

As we've seen, intraspecific or genetic diversity means the number of different alleles present within a species. Genetic diversity is important because it is the basis of evolution and survival of a species. A species with a high genetic diversity is likely to have some individuals with the characteristics required to survive a change in the environment, so some members of the species will survive. Low genetic diversity means a species is more likely to become extinct due to environmental changes. Genetic diversity is generally higher in large populations and lower in small populations. Some populations have very low genetic diversity, due to natural or human causes. These causes include genetic bottlenecks, the founder effect and selective breeding.

Genetic Bottlenecks

A genetic bottleneck happens when a population is drastically reduced in size due to a natural catastrophe or a continual more gradual change in the environment. The few individuals left will only have a small range of alleles between them, so if they reproduce and the population increases again there will be reduced genetic diversity. Many of the original variety of alleles will have been lost in individuals who didn't survive.



- A classic example of a population bottleneck is the northern elephant seal, which was hunted almost to extinction by humans, with a population of just 20 by the end of the 19th century. Although the population has now recovered to around 30 000, the northern elephant seal has a far lower genetic diversity than the southern population, which was not intensely hunted.
- Cheetahs are a threatened species partly due to their very low genetic diversity. This is probably due to a genetic bottleneck at the end of the last glacial period ten thousand years ago.
- An extreme example is the Golden Hamster, of which the vast majority are descended from a single litter found in the Syrian Desert around 1930.
- We now know that humans have very low genetic diversity compared to other primate species. Analysis of mitochondrial and Y-chromosome DNA from humans suggests that modern humans went through a genetic bottleneck 70 000 years ago, when the world population fell to 15 000 due to environmental changes following the eruption of the Toba supervolcano in Indonesia.

The Founder effect

The founder effect occurs when a small number of individuals colonise a new habitat and start a new, isolated population. Since the few individuals will only have a small range of alleles between them, the founder effect is an example of a genetic bottleneck, and is sometimes called a colonisation bottleneck. Founder effects are common throughout evolutionary history, and are readily seen in remote islands (such as the Hawaiian or Galapagos islands), where colonisation is difficult and rare. A few animals or a few plant seeds may by chance float or "raft" to a remote island during a storm, and give rise to new populations. These modern populations will have low genetic diversity, reflecting the small range of alleles in the small founding population. In extreme cases a founding population can be as small as a single pregnant female animal or a single plant seed.

The founder effect can also be seen in human populations. For example the island of Pingelap in Micronesia suffered a typhoon in 1775 that reduced the population on the island to only 20. The islanders today have a high frequency of a particular form of total colour blindness, since one of the typhoon survivors was a carrier for this allele. The Afrikaners of South Africa have a high incidence of Huntington's disease, since one of the original Dutch settlers had the disease due to the presence of a dominant allele.

Selective Breeding

Selective breeding, or artificial selection, means the controlled breeding of animals or plants by humans so that only individuals with certain characteristics are allowed to reproduce. Since these characteristics are (at least partly) genetically controlled, this means selecting certain alleles and rejecting others, so the genetic diversity of these animals and plants is reduced. The purpose of selective breeding is to change species so that they are more useful to humans, resulting in new breeds of animals and varieties of plants. These can be very different from the wild populations and are sometimes recognised as new species, since they can no longer interbreed with the wild populations. Humans have been practicing selective breeding for ten thousand years, when humans first became farmers, gradually resulting in all our domesticated farm animals, pets, crops and house plants we have today.

Since domesticated animals and plants have such a low genetic diversity they are not able to survive well in the wild, being out-competed by wild species with greater diversity. They are often highly susceptible to changes in the environment, such as drought, predators or disease.

In the case of domesticated animals, the intense selection can lead to the development of physical problems with the animals, which would normally disappear in the wild due to competition. This leads to ethical problems of whether we are causing harm to the animals by selective breeding, and we must weigh the advantages to humans against the harm to the animals. Some examples will illustrate the problems.

Modern cattle (*Bos Taurus*) were domesticated from the wild auroch (*Bos primigenius*) around 6000 BC in Asia and Africa. Wild aurochs are now extinct, the last one dying in Poland in 1627. Different breeds have different selected characteristics.

- Dairy cattle are selected for milk yield and now produce 35 litres per day (ten times the production in the wild). They produce calves, and therefore milk, constantly from the age of two, and their calves, who would normally suckle for 6-12 months, are removed after just two days, so the milk can be collected for humans. 90% of all dairy cows in Europe are the same *Holstein-Friesian* breed, with very little genetic diversity anywhere.
- Beef cattle are selected for rapid growth and large muscle mass. Some are so large that they can barely walk and suffer from arthritis and other joint problems; and many are unable to reproduce without artificial insemination. While the natural lifespan of a cow is 25 years, beef cattle are slaughtered at 5 years old.

Chickens were domesticated from wild Jungle Fowl, which still exist in India, some 3400 years ago. Different breeds of chicken are bred with different characteristics.

- Egg-laying chickens lay around 30 eggs each year, compared to 20-30 eggs for wild Jungle Fowl. They need to be fed special high-calcium diets so they can make the egg shells, but even so they tend to suffer from bone disease due to a lack of calcium.
- Meat chickens (broilers) are bred to grow quickly and have large leg and breast muscles. Their fast growth makes them susceptible to infectious disease and they also suffer joint problems.

Potatoes (*Solanum tuberosum*) were domesticated from the Peruvian wild potato (*Solanum brevicaule*) ten thousand years ago and introduced to Europe in 1536. Selective breeding for large, toxin-free tubers has resulted in low genetic diversity in the cultivated potato, especially in Europe, where only a few varieties were introduced. The effect of this low genetic diversity was dramatically illustrated by the Irish potato famine of 1845, where the fungal disease "potato blight" completely devastated the entire Irish potato crop. Potatoes were very widely grown in Ireland, and were almost all the same "Lumper" variety, which grew well in the Irish climate but was particularly susceptible to blight. Over a million people died of starvation and a further million escaped famine by emigrating from Ireland, mainly to the USA. In recent years cultivated potatoes have been cross bred with some of the many wild populations that still exist in Central and South America in order to increase genetic diversity and provide resistance to disease.

Interspecific Diversity (Species Diversity)

All the organisms living in a habitat are collectively called its community, and interspecific diversity or species diversity means the variety of species in a community. Species diversity is useful because it tell us about the complexity, quality and stability of an ecosystem.

In order to measure species diversity we need to take samples again. For example we could place a number of random quadrats in the area, or we could draw a line (called a transect) through the area and look at all the species within a certain distance of the line. The same sampling technique must be used in all areas that are to be compared. The simplest measurement is just to count the number of species in the samples - the species richness. However richness alone is not a good measure of diversity because it doesn't take into account the size of each species population – its abundance. For example a wild meadow and a wheat field might both have 25 species, but in the meadow the species are equally abundant, while in the wheat field 95% of all the plants are the single species of wheat. A good measure of diversity takes into account the species richness and their abundance. One common measure is the Simpson Diversity Index (*D*):

Simpson Diversity Index $D = \frac{N(N-1)}{\sum n(n-1)}$

where N = total number of individuals (total abundance)
n = number of individuals in each species

The higher the index, the higher the species diversity. A community where one species is dominant over others has a lower diversity than one where the species are more equitable. For example these two communities each have 100 individuals in 3 species:

(a)

species	abundance	n(n-1)
A	90	8010
B	5	20
C	5	20
total	100	8050

$D = \frac{(100 \times 99)}{8050} = 1.23$

(b)

species	abundance	n(n-1)
A	34	1122
B	33	1056
C	33	1056
total	100	3234

$D = \frac{(100 \times 99)}{3234} = 3.06$

So (b) is more diverse than (a). A few dominant species tend to decrease the diversity index.

Loss of Species Diversity

Species are currently becoming extinct at such an alarming rate that biologist agree we are experiencing a mass extinction. This mass extinction, only the sixth in the history of life of Earth, started almost ten thousand years ago, but has accelerated dramatically in the last 200 years. The current rate of extinction is at least 100 times the usual background level, and around half of all of species could be extinct by the end of the 21st century. This obviously represents a colossal loss of species diversity. What makes this mass extinction unique is that it is largely anthropogenic, i.e. caused by human activities, such as deforestation, agriculture, habitat destruction, hunting, pollution and climate change. We shall examine agriculture and deforestation.

Effect of Agriculture

The huge increases in human population over the last few hundred years has been possible due to the development of intensive farming, including selective breeding; large farms; monoculture; mechanisation and the use of agrochemicals like fertilisers and pesticides.

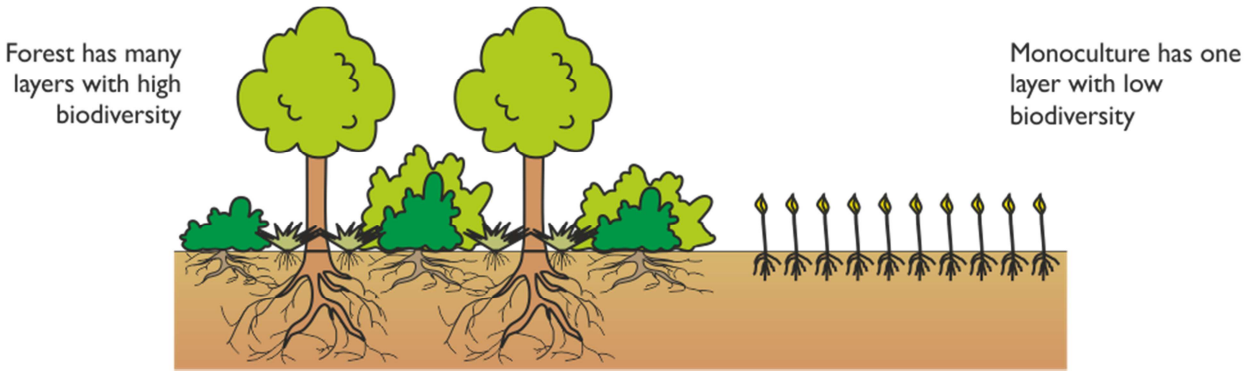
- Selective breeding, as we've already seen, reduces genetic diversity within a species.
- Large farms with large fields are cheaper and more efficient to run, but they have resulted in the destruction of thousands of miles of hedgerows, used as field boundaries. Hedgerows provide habitats for at least 30 species of trees and shrubs, 65 species of nesting birds, 1500 species of insects and 600 species of wildflowers. These in turn provide food for small mammals. Hedgerows also act as wildlife corridors, allowing animals to move safely between woodlands.
- Monoculture increases the productivity of farmland by growing only the best variety of crops, which can be sowed and harvested quickly using dedicated machinery. This increases yield and reduces labour costs. However monoculture reduces species and genetic diversity and renders all crops in a region susceptible to disease. Monoculture also reduces animal species diversity, because there are few niches.
- Fertilisers are required to maintain soil fertility, but they can pollute surrounding groundwater causing eutrophication and killing aquatic animals. Pesticides are sprayed on crops to prevent attack by insects and other invertebrate animals, but many pesticides have a broad spectrum, killing a wide range of animals and so reducing diversity. Herbicides kill competing plants ("weeds") that might reduce crop yield.

Effect of Deforestation

Ten thousand years ago, forests covered most of the land surface of the Earth. Today less than 20% of that forest remains. The UK was once covered with oak and beech woodland, but almost none of this original forest remains. The two main reasons humans clear forests are:

- to use the land for agriculture, housing, mining or reservoirs
- to use the timber for fuel, charcoal, paper or building materials. In Britain much of the oak forests were cut down in the 17th and 18th centuries to make ships for the navy.

Forests have a high biodiversity because a mature forest has many different species of plants in several layers; each adapted to their own conditions of light and nutrient availability. The different plants have different animals feeding on them and living in them; and the different primary consumers have different secondary consumers feeding on them. So forests contain complex food webs with high diversity. By contrast, a field of crops has very low diversity with very few plant species (often just the crop and a few weeds) and so few animal species as well. Deforestation therefore reduces biodiversity.



As the diagram shows, forests have a deeper and more extensive root system, so binding the soil together. Without this root system, soils can be eroded, leading to desertification. Forests also have a high productivity: i.e. there is a lot of plant material produced per square meter of land, and a lot of photosynthesis takes place. So deforestation reduces the rate at which carbon dioxide is removed from the atmosphere and so increases the greenhouse effect and global warming.

The tropical rainforests have a particularly high biodiversity: they cover around 7% of the Earth's surface but account for 50% of the all its species. These rainforests have only recently been targeted by humans, but now they are being cut down at an alarming rate using modern technologies as the local human populations increase.

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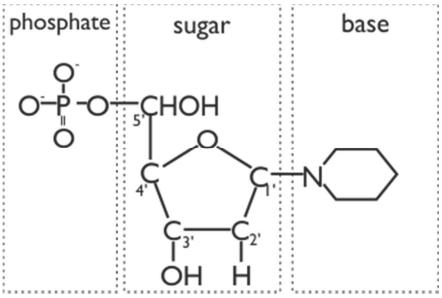
DNA

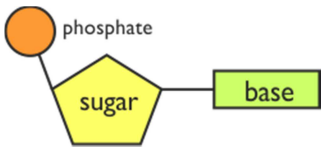
DNA is perhaps the most important molecule in biology. It contains the instructions that make every single living organism on the planet, and yet it is only in the past 50 years that we have begun to understand it. DNA stands for deoxyribonucleic acid, and it is called a nucleic acid because it is a weak acid, first found in the nuclei of cells. DNA is a polymer, composed of monomers called nucleotides.

Nucleotides

Nucleotides contain the elements CHONP, and have three parts to them:



or more simply:



- a phosphate group (PO_4^{2-}), which is negatively charged, and gives nucleic acids their acidic properties.
- a pentose sugar (a 5-carbon sugar) called deoxyribose.
- a nitrogenous base. There are four different bases (and you don't need to know their structures), but they all contain the elements carbon, hydrogen, oxygen and nitrogen. Since there are four bases, there are four different nucleotides:

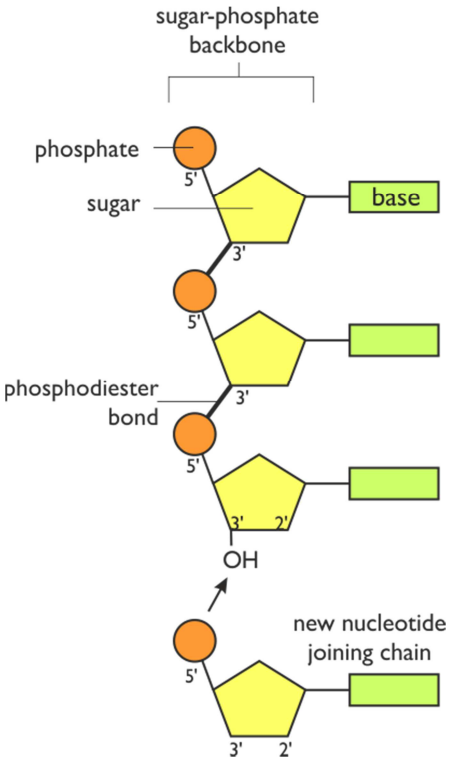
Base:	Adenine (A)	Cytosine (C)	Guanine (G)	Thymine (T)
Nucleotide:	Adenosine	Cytidine	Guanosine	Thymidine

The bases are usually known by their first letters only, so you don't need to learn the full names.

The nucleotide above is shown with a single phosphate group, but in fact nucleotides can have one, two or three phosphate groups. So for instance you can have adenosine monophosphate (AMP), adenosine diphosphate (ADP) and adenosine triphosphate (ATP). These nucleotides are very common in cells and have many roles other than just part of DNA. For example, ATP is used as an energy store, while AMP and GTP are used as messenger chemicals.

Nucleotide Polymerisation

Nucleotides polymerise by forming phosphodiester bonds between carbon 3' of the sugar and an oxygen atom of the phosphate. This is a condensation reaction. The bases do not take part in the polymerisation, so there is a sugar-phosphate backbone with the bases extending off it. This means that the nucleotides can join together in any order along the chain. Two nucleotides form a dinucleotide, three form a trinucleotide, a few form an oligonucleotide, and many form a polynucleotide.

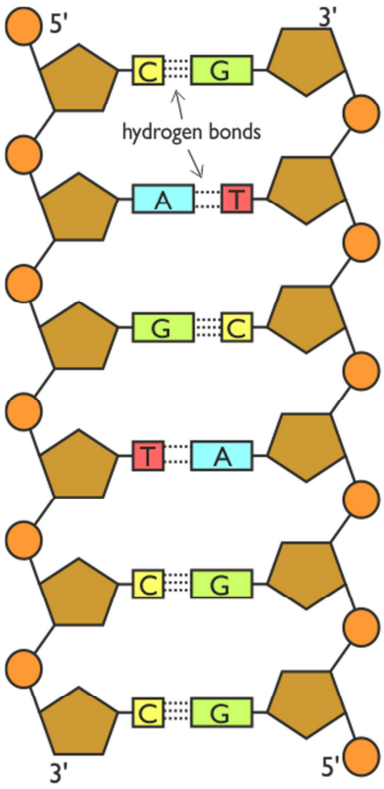


A polynucleotide has a free phosphate group at one end, called the 5' end because the phosphate is attached to carbon 5' of the sugar, and a free OH group at the other end, called the 3' end because it's on carbon 3' of the sugar. The terms 3' and 5' are often used to denote the different ends of a DNA molecule.

Structure of DNA

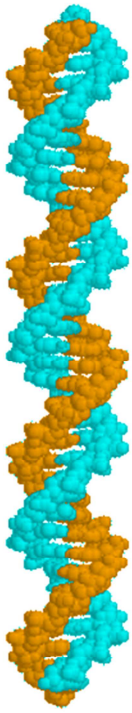
The three-dimensional structure of DNA was discovered in 1953 by Watson and Crick in Cambridge, using experimental data of Wilkins and Franklin in London, for which work they won a Nobel Prize. The main features of the structure are:

- DNA is double-stranded, so there are two polynucleotide stands alongside each other. The strands are antiparallel, i.e. they run in opposite directions.
- The two strands are wound round each other to form a double helix (not a spiral, despite what some textbooks say).
- The two strands are joined together by hydrogen bonds between the bases. The bases therefore form base pairs, which are like rungs of a ladder.
- The base pairs are specific. A only binds to T (and T with A), and C only binds to G (and G with C). These are called complementary base pairs. This means that whatever the sequence of bases along one strand, the sequence of bases on the other stand must be complementary to it. (Incidentally, complementary, which means matching, is different from complimentary, which means being nice.)



DNA showing the complementary base pairing between antiparallel strands

DNA showing the double helix



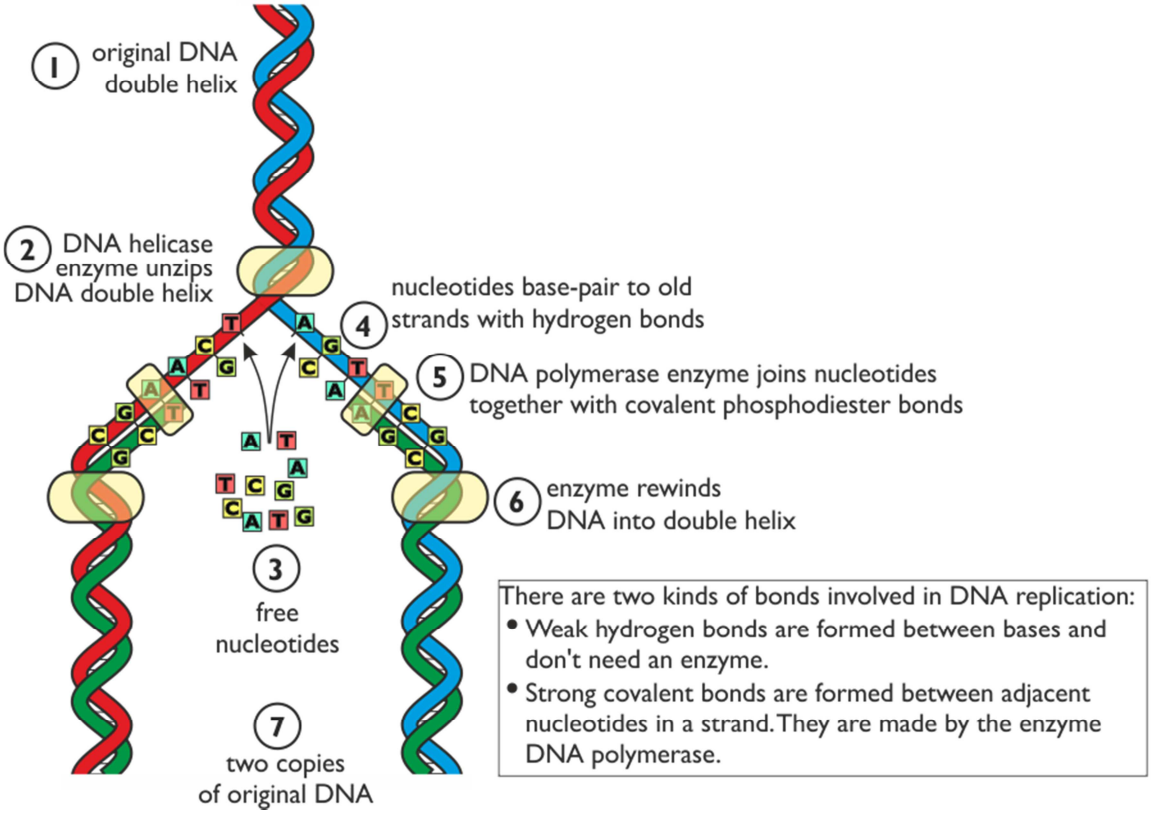
spacefilling model of the double helix

The structure of DNA makes it well-suited to its job of storing and expressing genetic information.

- The bases are protected on the inside of the molecule and the two strands are held together by numerous hydrogen bonds, so DNA a very stable molecule and is not easily damaged.
- There are four different bases, which can appear in any order, so their sequence can encode information, like writing with a 4-letter alphabet.
- DNA is a very long molecule, so it store a great deal of information (human DNA has 3 billion base-pairs).
- The two complementary strands means there are two copies of the information, which is useful for repair, copying and error checking.

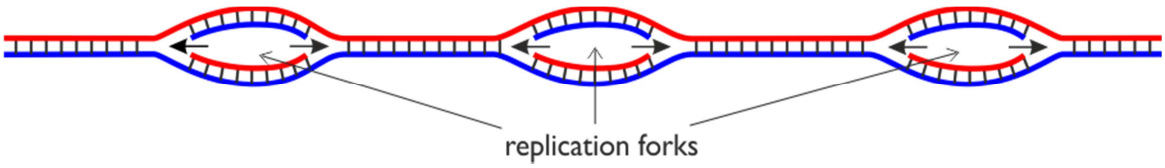
Replication of DNA

DNA is copied, or replicated, before every cell division, so that one identical copy can go to each daughter cell. The method of DNA replication is obvious from its structure: the double helix unzips and two new strands are built up by complementary base-pairing onto the two old strands.



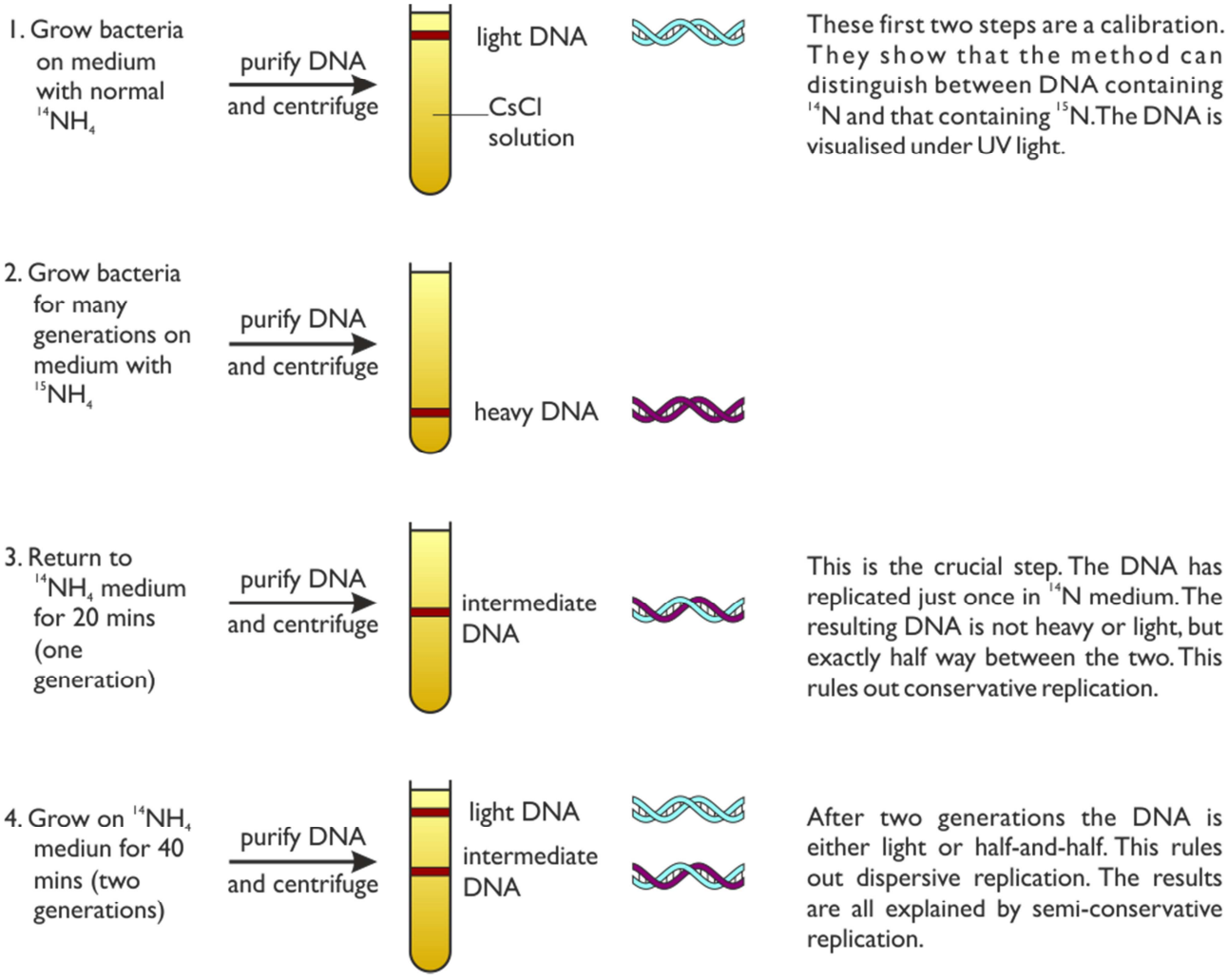
1. Replication starts at a specific sequence on the DNA molecule called the replication origin.
2. The enzyme DNA helicase unwinds and separates the two strands of DNA, breaking the hydrogen bonds between the base pairs.
3. The new DNA is built up from the four nucleotides (A, C, G and T) that are present in the nucleoplasm.
4. These nucleotides attach themselves to the bases on the old strands by complementary base pairing. Where there is a T base, only an A nucleotide will bind, and so on.
5. The enzyme DNA polymerase joins the new nucleotides to each other by strong covalent phosphodiester bonds, forming the sugar-phosphate backbone. This enzyme is enormously complex and contains 18 subunits.
6. Another enzyme winds the new strands up to form double helices.
7. The two new DNA molecules are identical to the old molecule. Each new DNA molecule contains one "new" strand and one "old" strand.

DNA replication can takes a few hours, and in fact this limits the speed of cell division. One reason bacteria can reproduce so fast is that they have a relatively small amount of DNA. In eukaryotes replication is speeded up by taking place at thousands of sites along the DNA simultaneously.



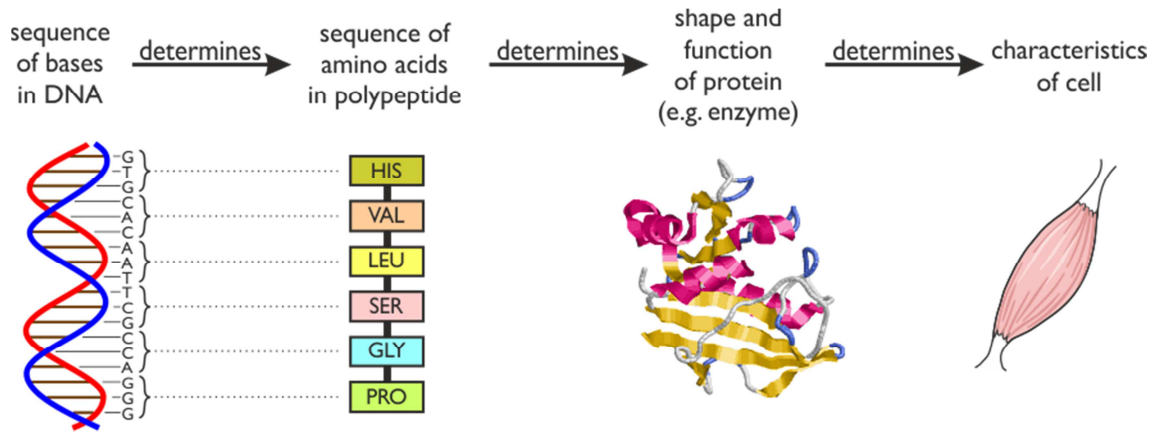
The Meselson-Stahl Experiment

This replication mechanism is sometimes called semi-conservative replication, because *each new DNA molecule contains one new strand and one old strand*. This need not be the case, and alternative theories suggested that a "photocopy" of the original DNA could be made, leaving the original DNA conserved (conservative replication), or the old DNA molecule could be dispersed randomly in the two copies (dispersive replication). The evidence for the semi-conservative method came from an elegant experiment performed in 1958 by Matthew Meselson and Franklin Stahl. They used the bacterium *E. coli* together with the technique of density gradient centrifugation, which separates molecules on the basis of their density.



Function of DNA

Genes are made of DNA, and we know that genes control characteristics (like height or flower colour), so the function of DNA is to control characteristics. But how does a DNA molecule do this? The important feature is the order, or sequence, of bases along the DNA molecule:



So the function of DNA is to make proteins, and indeed a gene can also be defined as a section of DNA that codes for a polypeptide. It is the numerous proteins in a cell (mostly enzymes) that control what the cell does, and therefore the characteristics of the organism. So there are two definitions of a gene that say the same thing:

A gene is an inherited factor that controls a particular characteristic.	A gene is a section of DNA that codes for a particular polypeptide.

This process of making proteins and so controlling characteristics is called gene expression (because the gene "expresses" itself).

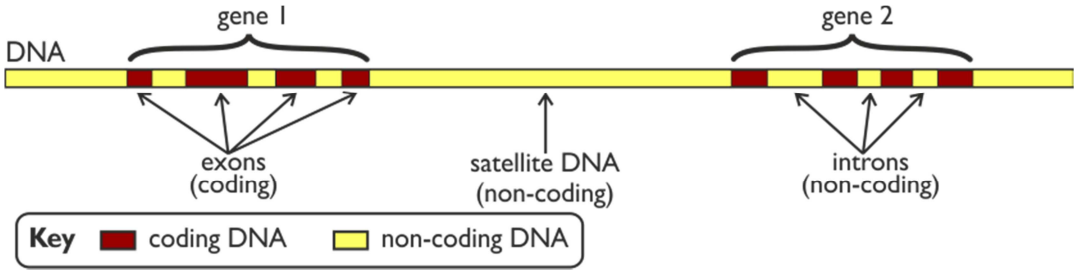
The Genetic Code

There are 20 different amino acids and only 4 different bases, so the bases are read in groups of three. This gives 4^3 or 64 combinations, more than enough to code for 20 amino acids. A group of three bases coding for an amino acid is called a codon, and the meaning of each of the 64 codons is called the genetic code. Because there are more codons than amino acids, most amino acids are coded for by more than codon. For example CCA, CCT, CCC and CCG all code for the amino acid glycine. Some codons also mark the beginning and end of a gene.

Coding and Non-Coding DNA

Surprisingly, a lot of the DNA in eukaryotes does not code for polypeptides. In fact, only about 2% of the DNA in a eukaryotic cell is coding DNA. The rest, called non-coding DNA, does not form genes. There are two kinds of non-coding DNA:

- Non-coding regions of DNA within a gene are called introns (for interruption sequences), while the coding parts of DNA are called exons (for expressed sequences). All eukaryotic genes have introns, and they are usually longer than the exons, so genes are often much longer than they really need to be!
- Non-coding regions of DNA between genes are called satellite DNA. Satellite DNA often contains simple base sequences repeated many times (sometime thousands of times).



Non-coding DNA was originally termed junk DNA, but in fact it probably serves many different functions.

- Some non-coding DNA is structural, helping to coil the DNA molecule into chromosomes.
- Some non-coding DNA has a control function, regulating when genes are expressed.
- Some non-coding DNA is involved in DNA replication.
- Some non-coding DNA contains unused copies of genes (pseudogenes).

No one knows exactly how many genes we humans have to control all our characteristics, but the current best estimate is around 20 thousand. The sum of all the genes in an organism is called the genome, and this table shows the estimated number of genes in different organisms:

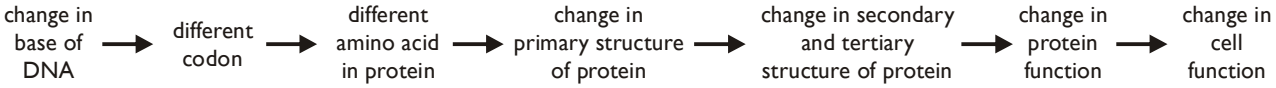
Species	Common name	length of DNA (kbp)*	no of genes
phage λ	virus	48	60
Eschericia coli	bacterium	4 639	4 000
Saccharomyces cerevisiae	Yeast	13 500	6 000
Caenorhabditis elegans	nematode worm	90 000	~10 000
Drosophila melaogaster	fruit fly	165 000	~10 000
Homo sapiens	human	3 150 000	~20 000

*kbp = kilo base pairs, i.e. thousands of nucleotide monomers.

Mutations

Mutations are changes in genes, which are passed on to daughter cells. DNA is a very stable molecule, and it doesn't suddenly change without reason, but bases can change when DNA is being replicated. Normally replication is extremely accurate, and there are even error-checking procedures in place to ensure accuracy, but very occasionally mistakes do occur (such as a T–C base pair). So a mutation is a base-pairing error during DNA replication.

A change in a gene could cause a change in the protein encoded by the gene, and so cause a change in the cell function:



Many of the proteins in cells are enzymes, and most changes in enzymes will stop them working (because there are far more ways of making an inactive enzyme than there are of making a working one). When an enzyme stops working a reaction in a cell doesn't happen, so the cell's function is changed. It's just possible (though unlikely) that a mutation could make a modified enzyme that actually worked faster than the original enzyme. This means cell's function could be improved.

Since mutations change genes, they give rise to new alleles (i.e. different versions of genes). A cell with the original, functional gene has one allele, while a cell with a mutated, non-functional version of the same gene has a different allele. For example in a flower a "red" allele might encode a functional enzyme that makes a red pigment, while a "white" allele might encode a non-functional enzyme so the flower stays white.

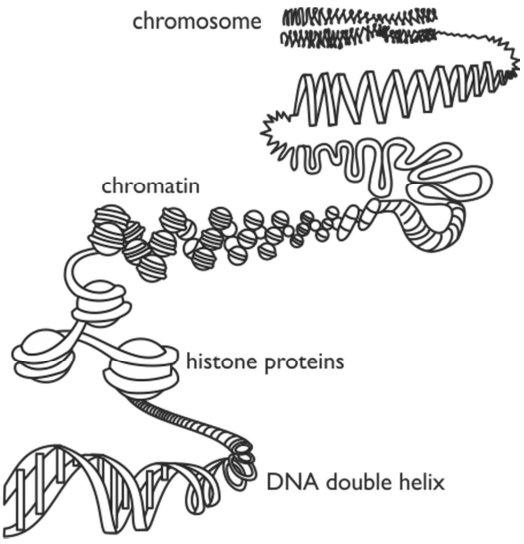
So there are three possible phenotypic effects of a mutation:

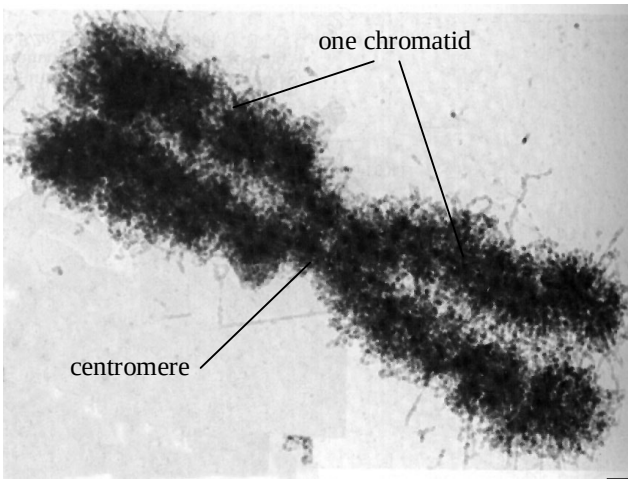
- Most mutations have no phenotypic effect because they don't change the protein or they are not expressed in this cell. These are called silent mutations, and we all have a few of these.
- Of the mutations that have a phenotypic effect, most will have a deleterious effect.
- Very rarely a mutation can have a beneficial phenotypic effect, such as making an enzyme work faster, or a structural protein stronger, or a receptor protein more sensitive. A small mutation in a control gene can have a very large phenotypic effect, such as developing extra limbs or flowering at a different time. Although rare, these beneficial mutations are important as they drive evolution. Examples include modified enzymes that make bacteria resistant to antibiotics, cows that produce milk constantly, sweetcorn that tastes sweet and almonds that aren't poisonous.

DNA and Chromosomes

The DNA molecule in a single human cell is 1 m long, so is 10 000 times longer than the cell in which it resides (< 100μm). (Since an adult human has about 10^{14} cells, all the DNA is one human would stretch about 10^{14} m, which is a thousand times the distance between the Earth and the Sun.) In order to fit into the cell nucleus the DNA in eukaryotes is cut into shorter lengths and each length is tightly wrapped up with histone proteins to form a complex called chromatin.

Just before cell division the DNA is replicated, and more histone proteins are synthesised, so there is temporarily twice the normal amount of chromatin. Following replication the chromatin then coils up even tighter to form short fat bundles called chromosomes. These are about 100 000 times shorter than fully stretched DNA, and therefore 100 000 times thicker, so are thick enough to be seen with the light microscope. Each chromosome is roughly X-shaped because it contains two replicated copies of the DNA. The two arms of the X are therefore identical. They are called chromatids, and are joined at the centromere. (Do not confuse the two chromatids with the two strands of DNA.) The complex folding of DNA into chromosomes is shown below.





micrograph of a single chromosome

Prokaryotic DNA

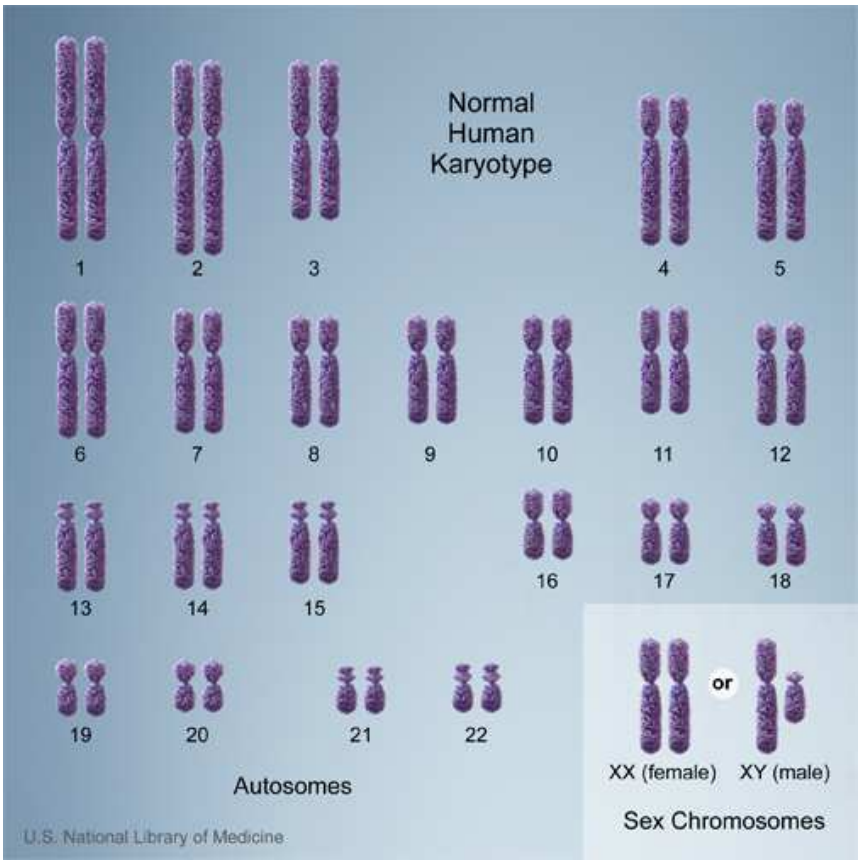
DNA in prokaryotes has the same structure to DNA in eukaryotes, and in fact use genetic engineering techniques (unit 5) bacterial DNA can be inserted into eukaryotic DNA, where it functions normally. However:

- Prokaryotic DNA is much shorter
- Prokaryotic DNA circular (i.e. a closed loop)
- Prokaryotic DNA is not associated with histone proteins.

Karyotypes and Homologous Chromosomes

If a dividing cell is stained with a special fluorescent dye and examined under a microscope during cell division, the individual chromosomes can be distinguished. They can then be photographed and studied. This is a difficult and skilled procedure, and it often helps if the chromosomes are cut out and arranged in order of size.

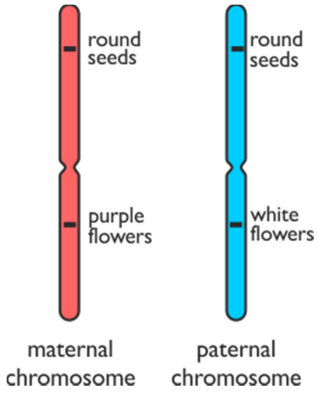
This display is called a karyotype, and it shows several features:



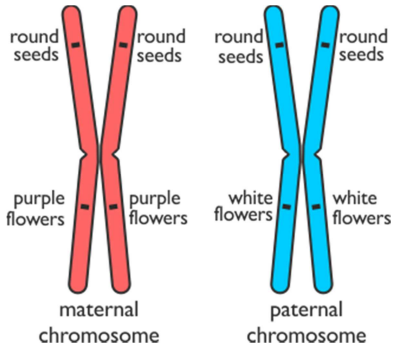
- Different species have different number of chromosomes, but all members of the same species have the same number. Humans have 46 (this was not known until 1956), chickens have 78, goldfish have 94, fruit flies have 8, potatoes have 48, onions have 16, and so on. The number of chromosomes does not appear to be related to the number of genes or amount of DNA.
- Each chromosome has a characteristic size, shape and banding pattern, which allows it to be identified and numbered. This is always the same within a species. The chromosomes are numbered from largest to smallest.
- Chromosomes come in pairs, with the same size, shape and banding pattern, called homologous pairs ("same shaped"). So there are two chromosome number 1s, two chromosome number 2s, etc., and humans really have 23 pairs of chromosomes.
- One pair of chromosomes is different in males and females. These are called the sex chromosomes, and are non-homologous in one of the sexes. In humans the sex chromosomes are homologous in females (XX) and non-homologous in males (XY). In other species it is the other way round. The non-sex chromosomes are called autosomes, so humans have 22 pairs of autosomes, and 1 pair of sex chromosomes.

It is important to understand exactly what homologous chromosomes are. We have two copies of each chromosome because we inherit one copy from each parent, so each homologous pair consists of a maternal and paternal version of the same chromosome. Since the homologous chromosomes contain the same genes, this also means we have two copies of each gene (again, one from each parent). This is why we write two letters for each gene in a genetic cross. The two homologous chromosomes may have the same versions (or alleles) of the gene (e.g. AA), or they may have different alleles, because one copy is a mutation (Aa).

Sometimes the chromosomes in a cell nucleus are represented by rods called ideograms, although these structures never actually exist because the chromatin is usually uncoiled. Each ideogram represents the long coiled DNA molecule in one chromosome. This diagram shows a pair of homologous chromosomes with two genes marked. The plant cell containing these chromosomes is homozygous for the seed shape gene (RR) and heterozygous for the flower colour gene (Pp).



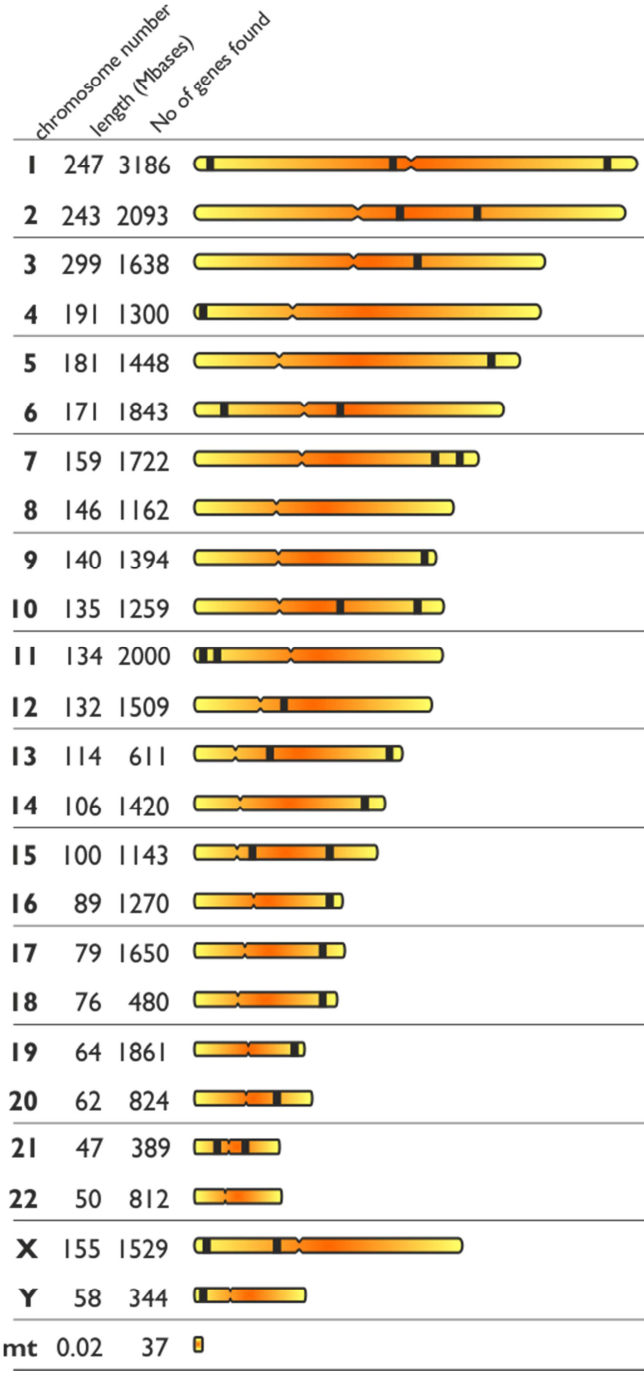
The only time chromosomes can actually be seen is during cell division. At this point in the cell cycle each chromosome is made of two identical chromatids, because each DNA molecule has now been replicated. This diagram shows the same pair of homologous chromosomes during mitosis. The two chromatids in each chromosome contain the same alleles because they're exact replicas of each other. But again the two homologous chromosomes contain the same genes but different alleles.



Chromatin	DNA + histone complex during interphase
Chromosome	compact X-shaped form of chromatin formed (and visible) during mitosis
Chromatids	the two arms of an X-shaped chromosome. The two chromatids are identical since they are formed by DNA replication.
Homologous chromosomes	two chromosome of the same size and shape, one originating from each parent. They contain the same genes, but different alleles.

Gene Loci

Since the DNA molecule extends from one end of a chromosome to the other, and the genes are distributed along the DNA, then each gene has a defined position on a chromosome. This position is called the locus of the gene, and the loci of thousands of human genes are now known. There are on average about 1 000 genes per chromosome, although of course the larger chromosomes have more than this, and the smaller ones have fewer. This diagram shows the loci of a very few example genes in humans:



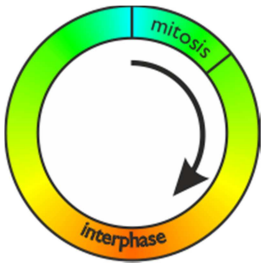
chromosome number	length (Mbases)	No of genes found	Sample Genes
1	247	3186	Elastase (protease); Amylase; Skeletal muscle actin
2	243	2093	Lactase; Glucagon
3	299	1638	Alkaptonuria
4	191	1300	Huntingtin
5	181	1448	Asthma
6	171	1843	Antibodies; Potassium channel
7	159	1722	CFTR; Trypsin (endopeptidase)
8	146	1162	
9	140	1394	Red blood cell antigens (blood groups)
10	135	1259	Smooth muscle actin; Lipase
11	134	2000	Insulin; Haemoglobin
12	132	1509	HOX genes (embryo development)
13	114	611	Breast cancer; skeletal muscle myosin
14	106	1420	AAT
15	100	1143	Cardiac muscle actin; Tay-Sachs disease
16	89	1270	Calcium pump in fast skeletal muscle
17	79	1650	Human Growth Hormone
18	76	480	Leukemia
19	64	1861	Alzheimers
20	62	824	SCID
21	47	389	Enterokinase (endopeptidase); Down syndrome
22	50	812	
X	155	1529	Rhodopsin (retina photoreceptor); Blood clotting factor VIII
Y	58	344	SRY (sex-determining genes)
mt	0.02	37	Respiration enzymes

Mitosis and the Cell Cycle

New cells are formed by division of existing cells using mitosis, forming two "daughter cells", which are genetically identical to each other. Mitosis is used to make new cells for:

- **Growth**, when an organism is growing in mass.
- **Replacement**, to replace cells that are lost e.g. each day humans replace 10^7 gut epithelial cells that are lost in faeces; 10^7 skin epidermal cells that are lost in house dust; and 10^{11} red blood cells that are recycled.
- **Repair**, to replace cells that are damaged or killed by injury e.g. to mend a broken bone or a cut in the skin.
- **Reproduction**, by eukaryotic organisms that reproduce asexually.

The life of a cell from one division to the next is called the cell cycle and has two main phases:



1. **Interphase.** This is when the cell grows and does whatever it does (e.g. respires, synthesises molecules, secretes hormones, contracts, transmits nerve impulses, etc.). Typically 90% of the cell cycle is spent in interphase. Interphase can be sub-divided into:
   - **Growth phase G1**, where the cell grows back to its original size. Genes are expressed into whatever proteins are needed by this cell, and organelles are replicated.
   - **Synthesis phase S**, where DNA and histones are replicated in preparation for mitosis. This can take a few hours.
   - **Growth phase G2**, where spindle proteins are synthesised, ready for mitosis
2. **Mitotic Phase.** This is where the cell divides to make two daughter cells. The mitotic phase can be sub-divided into four phases (prophase, metaphase, anaphase and telophase). Mitosis is actually just nuclear division, and is followed by cytoplasmic division, or cytokinesis, to complete cell division. The details of each of these phases are shown below.

In different cell types the cell cycle can last from hours to years. For example bacterial cells can divide every 30 minutes under suitable conditions, skin cells divide about every 12 hours on average, liver cells every 2 years, and muscle cells never divide at all after maturing, so remain in the growth phase for decades.

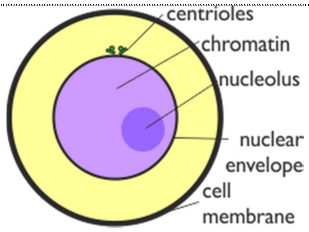
Binary Fission in Prokaryotes

The cell cycle applies to eukaryotic cells only. Prokaryotic cells don't have a nucleus or chromosomes or spindle fibres, so don't carry out mitosis, instead dividing by binary fission. In binary fission the circular DNA is replicated then the cell simply elongates and splits in two.

Details of Mitosis

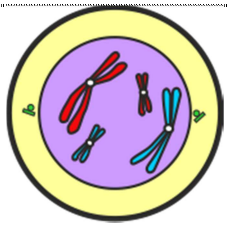
These diagrams show the detailed stages of mitosis. This cell has n = 2; i.e. 2 pairs of homologous chromosomes.

Interphase



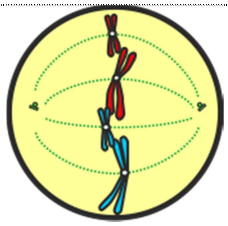
- no chromosomes visible
- DNA, histones and centrioles all replicated

Prophase



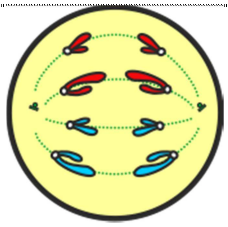
- chromosomes condensed and visible
- centrioles at opposite poles of cell
- nucleolus disappears

Metaphase



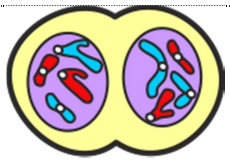
- nuclear envelope disappears
- chromosomes align along equator of cell
- spindle fibres (microtubules) connect centrioles to chromosomes

Anaphase



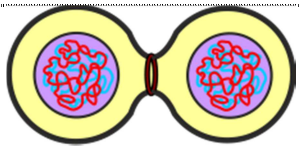
- centromeres split, allowing chromatids to separate
- chromatids move towards poles, centromeres first, pulled by motor proteins "walking" along the microtubule tracks

Telophase

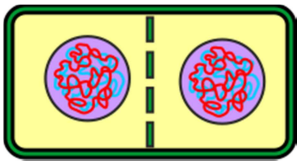


- spindle fibres disperse
- nuclear envelopes form
- chromatids uncoil and become too thin to see

Cytokinesis



- In animal cells a ring of actin filaments forms round the equator of the cell, and then tightens to form a cleavage furrow, which splits the cell in two.



- In plant cells vesicles move to the equator, line up and fuse to form two membranes called the cell plate. A new cell wall is laid down between the membranes, which fuses with the existing cell wall.

Cell Differentiation

Following mitosis in a multicellular organism, cells differentiate to become specialised to perform different functions. Differentiation involves switching on the genes required in that cell type (e.g. the haemoglobin gene in a red blood cell), and switching off all others (e.g. amylase).

Cell differentiation leads to higher levels of organisation:

- **A tissue** is a group of similar cells performing a particular function. Animal tissues include epithelial, connective, nerve, muscle, blood, endocrine, adipose, glandular. Plant tissues include epidermis, meristem, vascular, mesophyll, cortex.
- **An organ** is a group of physically-linked different tissues working together as a functional unit. For example the stomach is an organ composed of epithelium, muscular, glandular and blood tissues. A plant leaf is also an organ, composed of mesophyll, epidermis and vascular tissues.
- **A system** is a group of organs working together to carry out a specific complex function. Humans have seven main systems: the circulatory, digestive, nervous, respiratory, reproductive, urinary and muscular-skeletal systems.

In a unicellular organism (like bacteria or yeast) all the cells are alike, and each performs all the functions of the organism, so there is no differentiation.

Control of the Cell Cycle and Cancer

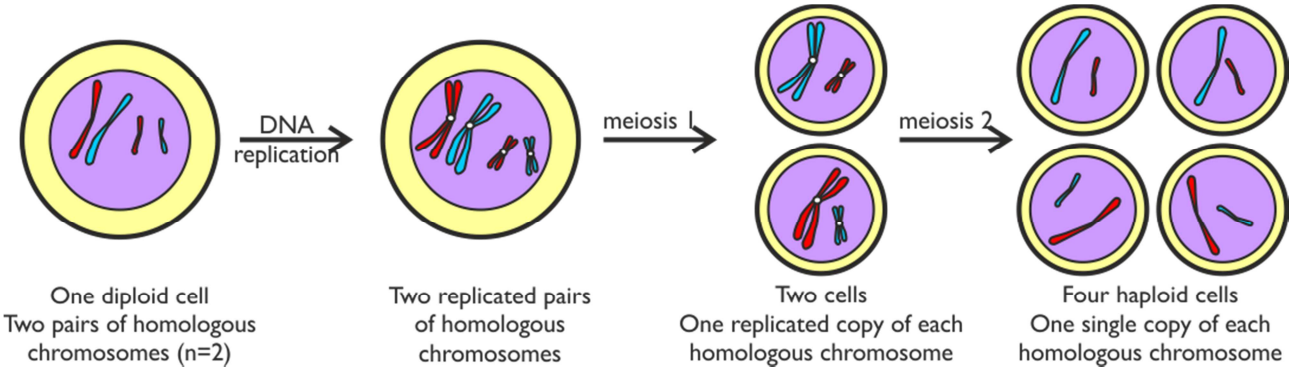
The cell cycle is normally tightly controlled, so that cells only divide when they need to. There are checkpoints at the start of each stage of the cell cycle, where a variety of factors, including control genes, decide whether a cell can continue to the next stage of the cycle. Sometimes the control genes mutate, due to carcinogenic agents such as viruses, ionising radiation, chemicals or other environmental triggers. The mutated control genes won't control the checkpoints properly, so cells divide uncontrollably, leading to cancer.

We can use our knowledge of the cell cycle and its control to devise anti-cancer drugs. These usually block the cell cycle, so compensating for the broken checkpoints. For example (you don't need to learn these):

- Adriamycin and cytoxan inhibit DNA helicase, so stop DNA replication
- Methotrexate inhibits nucleotide synthesis, so stops DNA replication
- Taxol and vincristine inhibit the formation of the mitotic spindle, so stop mitosis

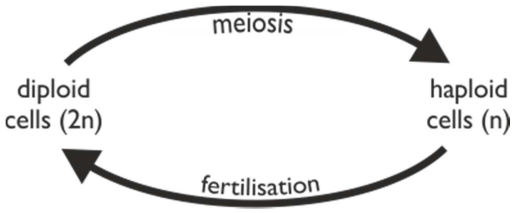
Meiosis and Sexual Reproduction

Meiosis is the special cell division used by sexually-reproducing organisms to make gametes. It starts with DNA replication, like mitosis, but then proceeds with two divisions one immediately after the other. Meiosis therefore results in four daughter cells rather than the two cells formed by mitosis.



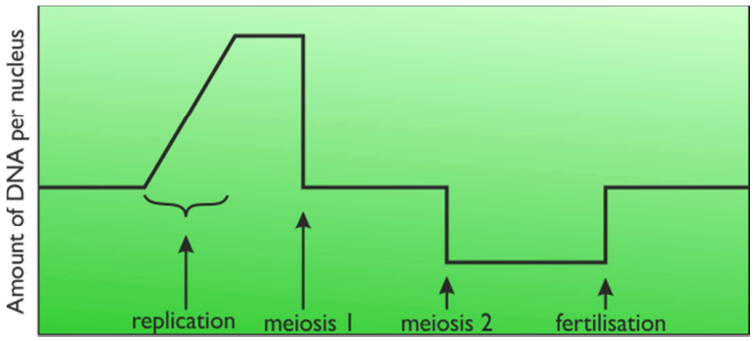
Since there are two divisions we refer to the stages as "metaphase 1" or anaphase 2", etc., but you don't need to know the details of the stages in meiosis. Meiosis differs from mitosis in two important aspects:

Firstly, in meiosis the chromosome number is halved from the normal diploid number (2n) to the haploid (half) number (n). This is necessary so that the chromosome number remains constant from generation to generation, so in sexual reproduction meiosis is always followed by fertilisation at some point in the life cycle:



The halving is done in a particular way: meiosis ensures that each haploid cell has one of each homologous pair of chromosomes. So for example human gametes have 23 chromosomes: one of each homologous pair. Remember that other species have different haploid numbers.

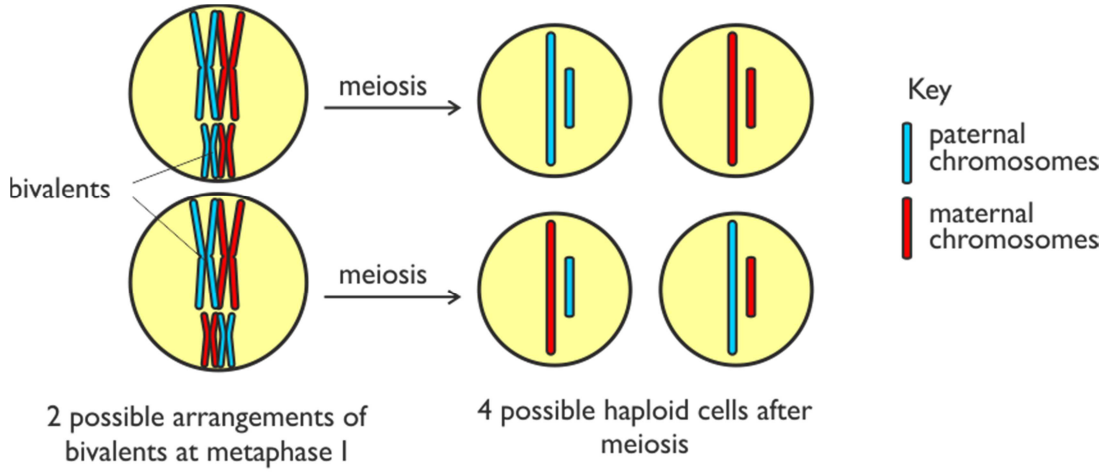
The changes in chromosome number can also be shown as a graph of DNA mass over time:



Secondly, in meiosis the chromosomes are re-arranged during meiosis to form new combinations of alleles. This genetic recombination is vitally important and is a major source of genetic variation. It means for example that of all the millions of sperm produced by a single human male, the probability is that no two will be identical. The whole point of meiosis and sex is to introduce genetic variation, which allows species to adapt to their environment and so to evolve. There are three sources of genetic variation in sexual reproduction: Independent assortment in meiosis; crossing over in meiosis; and random fertilisation. We'll look at each of these in turn.

Independent Assortment

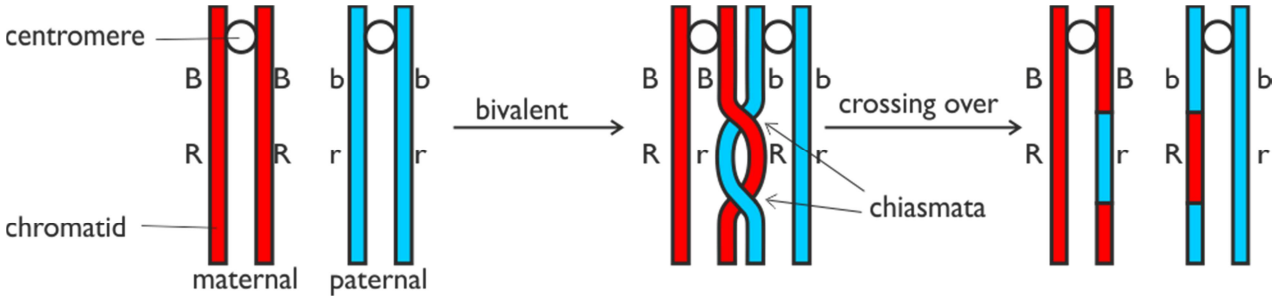
This happens during the first meiotic division, when the homologous chromosomes join together to form bivalents that line up on the equator. Each bivalent is made up of two homologous chromosomes, which originally came from two different parents (they're often called maternal and paternal chromosomes). Since they can line up in any orientation on the equator, the maternal and paternal versions of the different chromosomes can be mixed up in the final gametes.



In this simple example with 2 homologous chromosomes (n=2) there are 4 possible different gametes (2^2). In humans with n=23 there are over 8 million possible different gametes (2^{23}). Although this is an impressively large number, there is a limit to the mixing in that genes on the same chromosome must always stay together. This limitation is solved by crossing over.

Crossing Over

This also happens in the first meiotic division, when the bivalents first form. While the two homologous chromosomes are joined in a bivalent, bits of one chromosome are swapped (crossed over) with the corresponding bits of the other chromosome.



The points at which the chromosomes actually cross over are called chiasmata (singular chiasma), and they involve large, multi-enzyme complexes that cut and join the DNA. There is always at least one chiasma in a bivalent, but there are usually many, and it is the chiasmata that actually hold the bivalent together. The chiasmata can be seen under the microscope and they can give the bivalents some characteristic strange shapes. There are always equal amounts crossed over, so the chromosomes stay the same length.

Crossing over means that maternal and paternal alleles can be combined even though they are on physically different chromosomes. In the example in the diagram some gametes will have the genotype combinations Br or bR, which would not be possible without crossing over. This potentially allows any combination of alleles to form and, since there are 20 000 genes in humans, there is the potential to make an astronomically large number of combinations. This explains why every gamete is genetically unique.

Random Fertilisation

This takes place when two gametes fuse to form a zygote. Each gamete has a unique combination of genes, and any of the numerous male gametes can fertilise any of the numerous female gametes. So every zygote is unique.

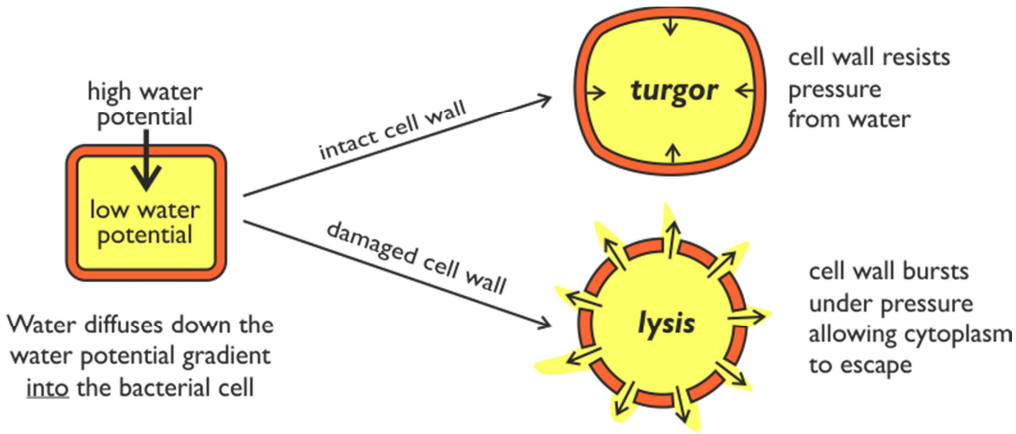
Antibiotics and Resistance

Antibiotics are antimicrobial agents produced naturally by other microbes (usually fungi or bacteria). The first antibiotic was discovered in 1896 by Ernest Duchesne and "rediscovered" by Alexander Flemming in 1928 from the filamentous fungus *Penicilium notatum*. Neither investigator appreciated the importance of what he had found, and the antibiotic substance, named penicillin, was not purified until the 1940s (by Florey and Chain), just in time to be used at the end of the second world war. The discovery of antibiotics was probably the greatest medical advance of the 20th century, saving many millions of lives. When antibiotics were first introduced after the Second World War, they were seen as "miracle drugs" because they cured all bacterial diseases. However, within a few years, some bacteria became resistant to antibiotics and now some common bacterial infections are once again becoming untreatable. Bacterial resistance to antibiotics is due to genetics, mutations and natural selection.

Action of Antibiotics

Many chemicals kill microbes. But a therapeutically useful antimicrobial agent must be selectively toxic i.e. it must kill pathogenic microbes already growing in human tissue, without also killing the host human cells. Antibiotics do this by inhibiting enzymes that are unique to prokaryotic cells, such those involved in synthesising the bacterial cell wall or 70S ribosomes. For example:

- penicillin (and related antibiotics ampicillin, amoxicillin and methicillin) Inhibits an enzyme involved in the synthesis of peptidoglycan for bacterial cell wall. This weakens the cell wall, killing bacterial cells by osmotic lysis.



- Streptomycin, tetracycline and erythromycin inhibit enzymes in 70S ribosomes. This stops protein synthesis so prevents cell division.

Development of Antibiotic Resistance

How do bacteria become resistant to antibiotics? Resistance first develops due to a mutation. Bacteria reproduce asexually, so all the offspring should be the same, but sometimes, at random, mutations occur when DNA is replicated. These mutations may have any effect (and most will be fatal), but just occasionally a mutation occurs that makes that bacterium resistant to an antibiotic. For example

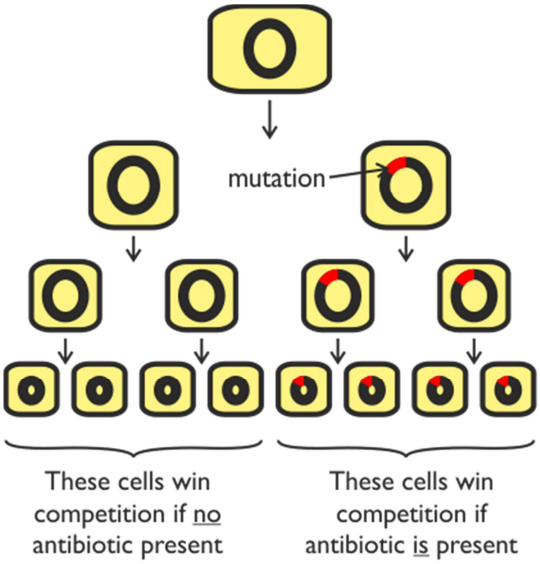
- A mutation could slightly alter an enzyme, changing its substrate specificity so that its active site will now bind penicillin. Some bacteria now have a penicillinase enzyme that breaks down penicillin, rendering the antibiotic useless. Antibiotics are often similar to normal bacterial metabolites, and a small mutation in an existing enzyme can modify its active site to fit an antibiotic.
- A mutation could slightly alter a ribosome enzyme so that the inhibitor streptomycin can no longer bind and inhibit the enzyme.

Such mutations are very rare, but bacteria reproduce so rapidly, and there are so many bacterial cells, that new resistance mutations do crop up at a significant rate (a few times per year somewhere on the planet). Remember that development of antibiotic resistance is a random event, and is not caused by the presence of the antibiotic. It is certainly not an adaptation that bacteria acquire.

How does resistance spread from one mutated bacterial cell to other cells? By vertical and horizontal gene transmission.

Vertical Gene Transmission

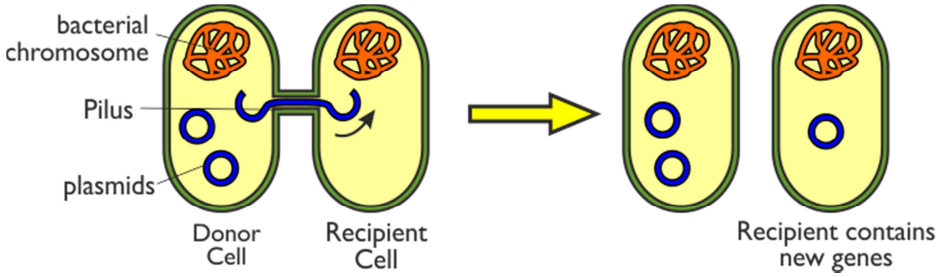
Imagine a community of different bacterial species living in your gut, and one particular cell has just mutated to become resistant to penicillin. What happens next? It will reproduce by binary fission and pass on its resistance gene to all its offspring, forming a new strain of bacteria in your gut. If there is no antibiotic present in your gut (most likely) this mutated strain may well die out due to competition with all the other bacteria, and the mutation will be lost again. However, if you are taking penicillin, then penicillin will be present in the bacteria's environment, and these mutated cells are now at a selective advantage: the antibiotic kills all the normal bacterial cells, leaving only the mutant cells alive.



These cells can then reproduce rapidly without competition and will colonise the whole environment. This a good example of natural selection at work. The mutant cells have been selected by the environment and so the frequency of the resistance allele in the population has increased.

Horizontal Gene Transmission

Bacteria have a trick that no other organisms can do: they can transfer genes between each other by conjugation. This is the transfer of DNA between bacterial cells via a cytoplasmic bridge or pilus. From time to time two bacterial cells can join together (conjugate), and DNA passes from one cell (the donor) to the other (the recipient). The transferred DNA is usually one or more plasmids.



Conjugation means a resistance gene can spread from the bacterium in which it arose to other, perhaps more dangerous, species. It is also the cause of multiple resistance. It is highly unlikely that a single strain will mutate twice to develop resistance to antibiotics, but it is perfectly likely that it could receive genes for resistance to different antibiotics by horizontal gene transfer. This has led to strains of bacteria that are resistant to many (or even all) antibiotics.

Impact of Resistance on the use of Antibiotics

Antibiotic-resistant bacteria can spread to other people by any of the normal methods of spreading an infection: through faeces, water, food, sneezing, infected instruments, etc. A common source of antibiotic-resistant bacteria (and especially multiple-resistant bacteria) is hospitals. This is partly because hospitals have a high concentration of people with bacterial infections, but also because the use of antibiotics means any antibiotic-resistant strains can multiply in the absence of competition.

A good example is *Staphylococcus aureus*, a bacterium responsible for a variety of diseases from staphylococcal food poisoning to toxic shock syndrome. This species has been resistant to penicillin for years, due to the possession of the penicillinase enzyme. Methicillin is unaffected by penicillinase and so was effective against *S. aureus*. However, within a year of the introduction of methicillin, methicillin-resistant strains of *S. aureus* (MRSA) were found in hospitals where methicillin was in regular use. Infections by MRSA were very difficult to treat, responding only to the antibiotic vancomycin. In 1997 vanocmycin-resitant, methicillin-resistant *Staphylococcus aureus* appeared in Japan. These bacteria are effectively untreatable at present.

As we saw in unit 1, *Mycobacterium tuberculosis*, the bacterium that causes TB, has developed resistance to streptomycin. An extreme drug-resistant TB strain (XDR-TB) has been found in South Africa that kills 98% of those infected within two weeks, and is resistant to most antibiotics. Resistant strains of *M. tuberculosis* can only be treated using a cocktail of four different antibiotics over a prolonged period of months, which is expensive and unlikely to be achieved in developing countries.

So what can be done? One solution is to use a wider range of antibiotics, and there is a constant industrial search for new anti-microbial agents. However, as the example of MRSA has shown, sooner or later the bacteria will develop resistance, so this is only a short-term solution.

A better long-term strategy is to stop using antibiotics (or at least minimise their use). This will end the selection pressure in favour of resistant strains. Most resistant strains are inferior to the "wild type" strains in other respects (perhaps they reproduce more slowly), so in an antibiotic-free environment the mutants are generally out-competed and will die out. The antibiotic resistance genes will therefore disappear from the gene pool of that population. Unfortunately we are now in an "antibiotic culture" where many doctors prescribe antibiotics routinely for common ailments such as the flu (even though they have no effect), simply to keep the patient happy. And farmers, especially in the USA, routinely feed their livestock small concentrations of antibiotics, just in case they come into contact with an infection. If this overuse of antibiotics continues, then most antibiotics will become useless, and we will revert to the pre-antibiotic age.

Classification

The Species Concept

There are millions of different types of organisms on the planet, including animals, plants, fungi and bacteria, and each type is unique. Each type has found a unique way of living; of solving the problems of surviving and reproducing successfully. We call each different type a species, but what exactly is a species? For such a fundamental and apparently simple concept, the species is surprising hard to define, but a modern definition has three aspects:

- Organisms in the same species are similar in appearance (morphology), behaviour and biochemistry, and have the same ecological niche.
- Organisms in the same species can breed together in their natural environment to produce fertile offspring but cannot breed with members of other species.
- Organisms in the same species share a common ancestor.

It can still be quite difficult to decide whether two organisms belong to the same species and species allocations are constantly being changed as new evidence is found. There can be problems applying each part of the definition:

- **Morphology**. Decisions based on morphology can be quite arbitrary. For example if two insects have identical anatomy but different coloured wing markings do they belong in different species? A common problem is that two unrelated organisms may have very similar features and niches because they are adapted to living in similar environments. In this case biochemical and DNA analysis can be used to find how closely related they are.
- **Interbreeding**. Two organisms that would not normally mate in the wild (perhaps because they live in different parts of the world) may be able to interbreed in the artificial environment of a zoo or a lab. This is particularly true of plants, which can quite easily be hybridised. Even in the wild, some closely-related species can interbreed, such as a horse and donkey to produce a mule, but the offspring is usually sterile, so not a viable organism. And this part of the definition doesn't apply to the millions of asexually-reproducing organisms at all.
- **Ancestry**. Ancestry is very difficult to determine, and has really only become possible using modern DNA and protein sequence analysis. However even this has pitfalls, as we shall see.

Speciation

How do new species arise? New species arise when one existing species splits into two reproductively-isolated populations that go their separate ways (unit 4). This most commonly happens when the two populations become physically separated from each other and evolve independently in different environments. This process of speciation is gradual and can take tens of thousands of years before the two populations are so different that they meet the criteria for being different species. Populations of the same species that are currently isolated are called subspecies (or sometimes breeds, varieties or races) and they may in time become distinct species, or they may remain an interbreeding single species.

Taxonomy

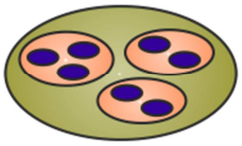
Biologists have so far found and named over a million different species, and the more we find, the more we realise how few we know. The total number of living species may well exceed 10 million, and if we include extinct species the figure is increased by a factor of 100. A good classification system is needed to keep track of all this variety.

Linnaeus

Many different classifications have been devised, but the one biologists use is based on the work of the Swede Carolus Linnaeus in the mid-18th century. Linnaeus introduced three important innovations.

- He devised a hierarchical structure for classification. In a hierarchy organisms with similar characteristics are grouped together, and these groups are contained within larger composite groups. There is no overlap between groups, and a species can only appear once. These two diagrams represent hierarchical classifications, and both forms are used in biology.

Hierarchy displayed as a tree



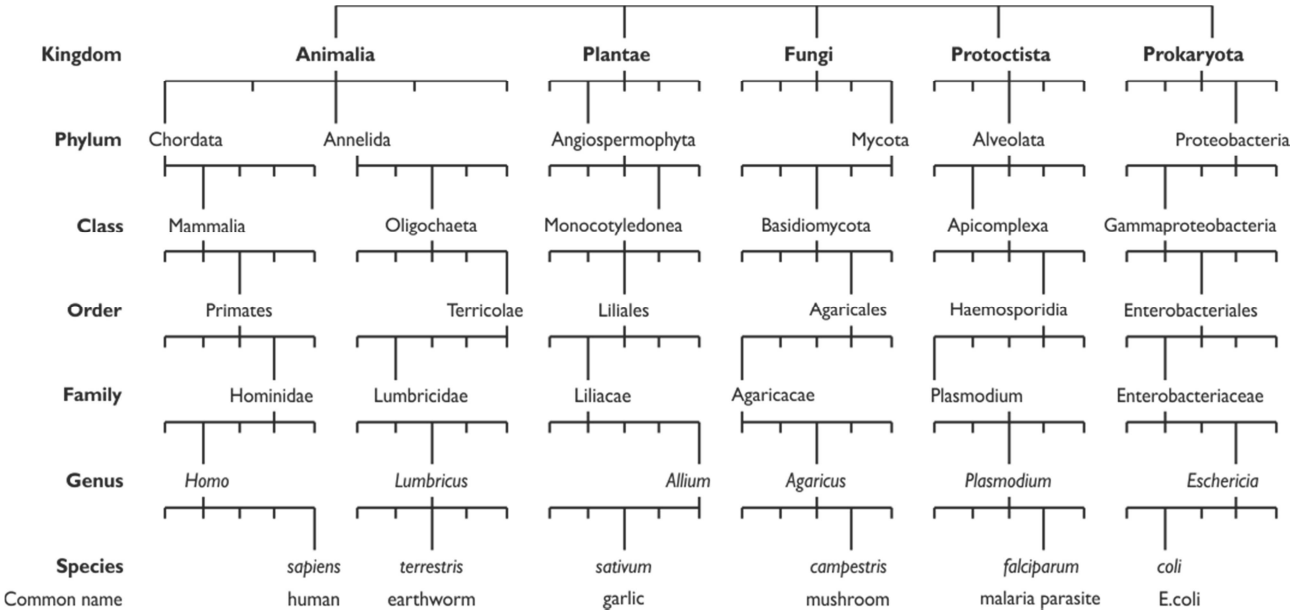
Hierarchy displayed as a Venn diagram

- He gave each rank in the hierarchy a standard name. There are seven ranks or levels in the biologists' classification. The smallest group of similar organisms is the species; closely related species are grouped into genera (singular genus), genera into families, families into orders, orders into classes, classes into phyla (singular phylum), and phyla into kingdoms. So you need to remember KPCOFGS.

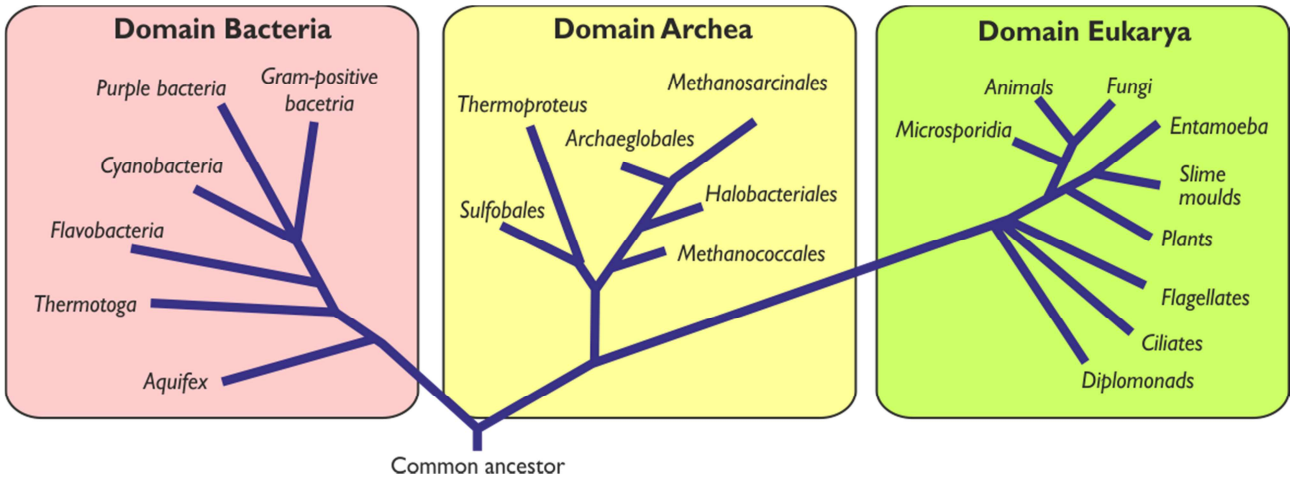
- He introduced the binomial nomenclature for naming organisms unambiguously. This simply consists of the first two ranks: the generic name (with a capital letter) and the specific name (with a small letter), and he used Latin names rather than different local-language names. The binomial names are italicised when printed (or underlined if hand-written) and after a first mention, the generic name can be abbreviated to the first letter e.g. *Panthera leo* (lion) and *P.tigris* (tiger). For most purposes the binomial name is enough to identify an organism, but a full 7-rank lineage can be given to avoid confusion.

Linnaeus's universal standard system replaced non-standard common and local names, and is still universally used today. A group of similar organisms at any level is called a taxon, and the science of classification is called taxonomy.

This tree diagram shows the complete lineages of six species, to illustrate the ranks:

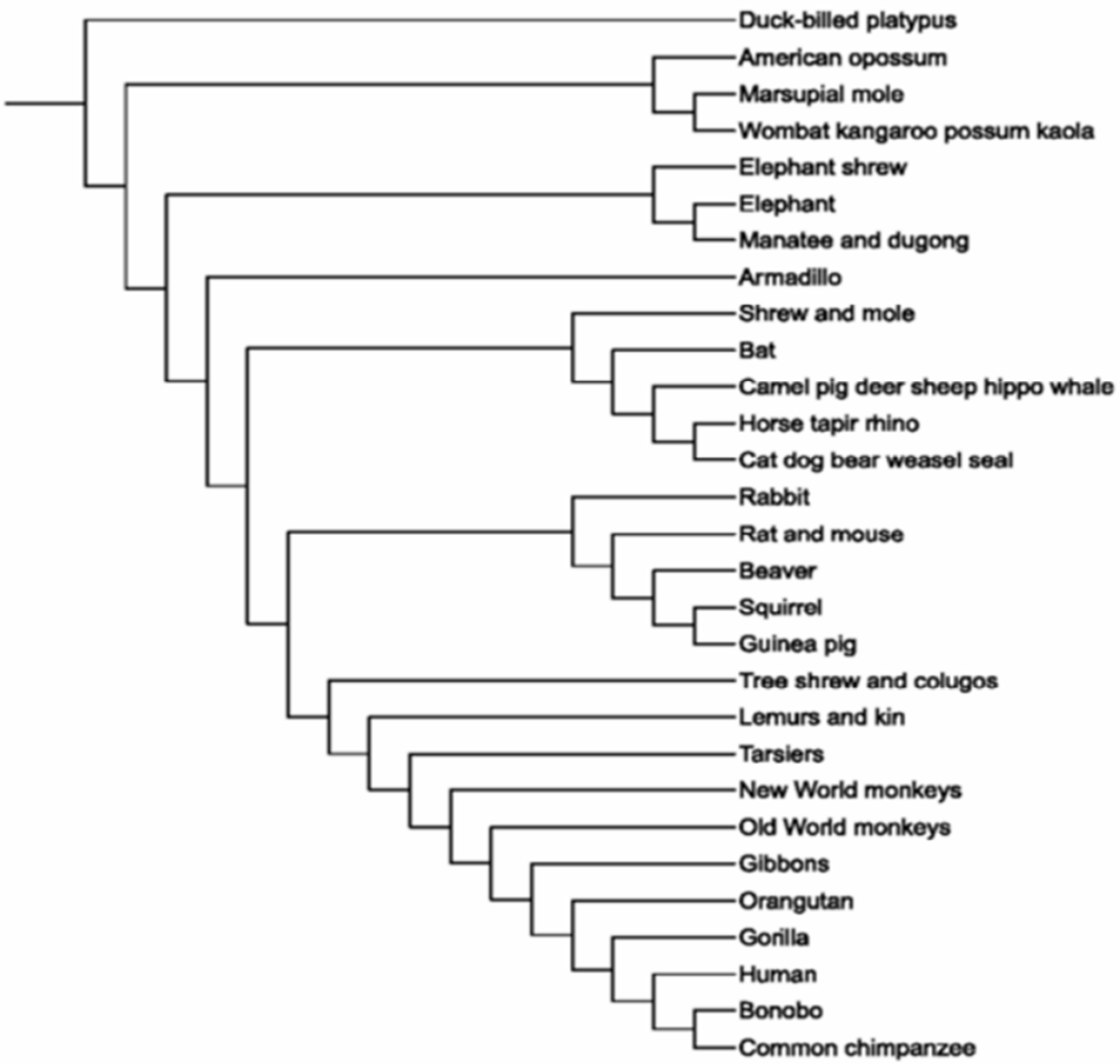


Traditionally, all life has been grouped into five kingdoms (shown above), but recent DNA evidence has shown that there is a huge and fundamental division within the prokaryote kingdom. A new rank has now been introduced above kingdom – the domain. Animals have now been relegated to being just one kingdom out of at least 20!



Phylogenetics

The aim of taxonomists today is to develop phylogenies; family trees representing true evolutionary relationships, rather than just convenient groupings. This is remarkably difficult to do, and phylogenies are constantly being revised in the light of new evidence. This diagram (from the Ancestor's Tale) shows the phylogeny of the mammals:

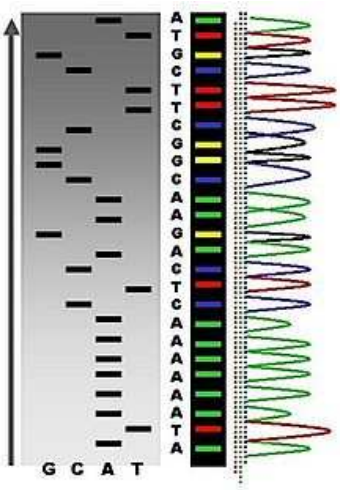


To work out phylogenies, txonomists use a variety of characteristics, including:

- Morphology – visible structures, like number of legs or leaf shape.
- Ultrastructure – microscopic features such as a cell wall or chloroplast
- Embryology – the stages of embryo development from a zygote to an adult.
- Palaeontology – the structure and age of fossils
- Ethology – behaviour patterns (animals only)
- Biochemistry – the metabolic pathways used by an organism
- Molecular biology – the sequence of an organism's DNA or proteins

Classification using DNA

DNA can be extracted from cells and the sequence of bases read using sequencing machines. The base sequence of DNA from different organisms can then be compared to see how similar or different they are. This comparison can tell us about phylogenetic relationships between living organisms, because it is the DNA that is actually passed on down the generations. Over time, DNA slowly accumulates mutations, so closely related species have similar DNA sequences, while more distantly related species have different sequences. There are many millions of bases in the DNA of most organisms, so there is a vast amount of information about the evolutionary history of each organism in its DNA.

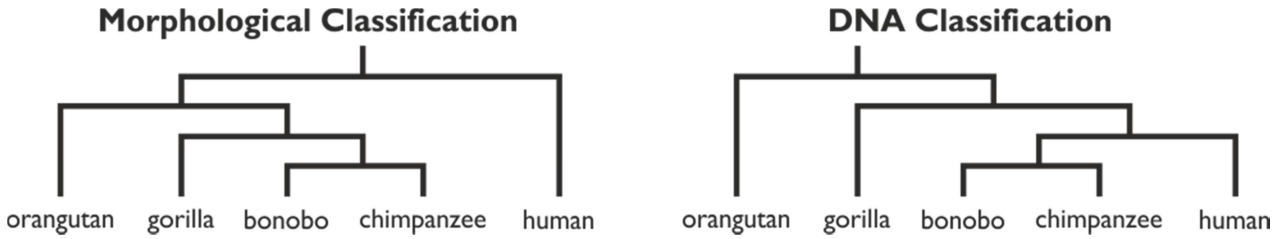


Coding DNA is used for classification since these gene sequences tend to be very similar within a species but different between species. Non-coding DNA can vary considerably within a species (which is why non-coding DNA is used in genetic fingerprints). The amino acid sequence of the proteins can also be deduced.

Sequence of bases in DNA	GTGCACATTCGCCCAGGG
Sequence of amino acids in polypeptide	his val leu ser gly pro

DNA and human classification

DNA sequences have led to a new phylogeny for humans. It used to be thought that humans were separate from all other apes, but we now know that humans are closely related to chimpanzees, and indeed some taxonomists think that humans should be reclassified as the "third chimpanzee":



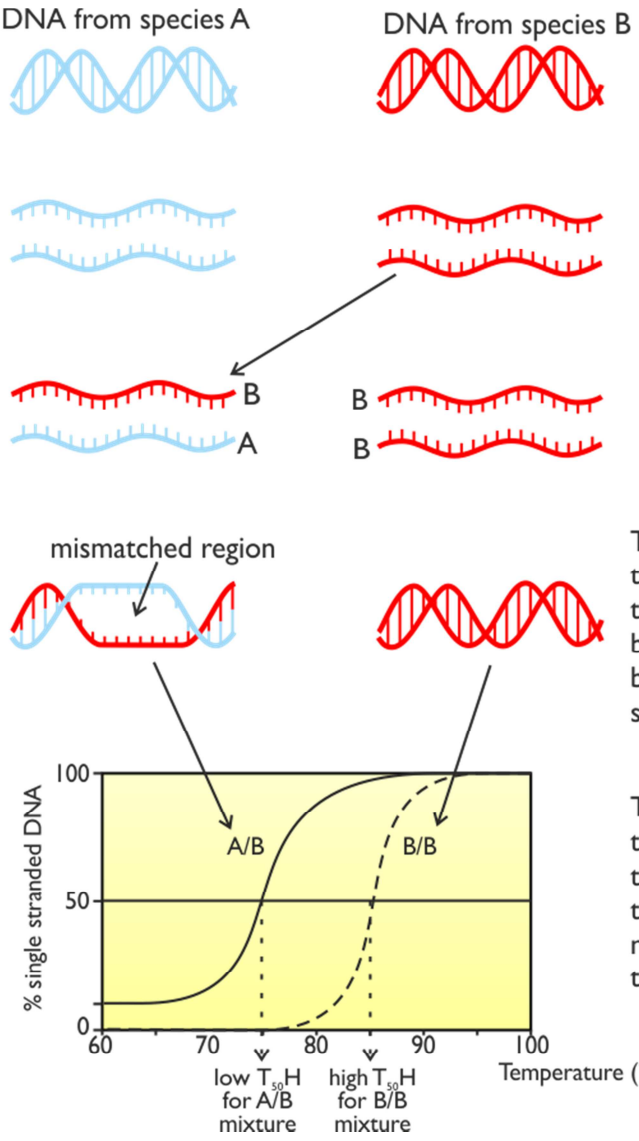
DNA and plant classification

DNA sequences have recently been used to classify flowering plants. Traditional plant classification was based on the morphology and embryology of plants. A team of scientists from the Royal Botanical Gardens, Kew chose 565 species that represented all the known families of flowering plants in the world. They extracted DNA from each plant and sequenced the DNA of three genes (two from chloroplasts and one for ribosomes) and then compared all the gene sequences using a computer. The results showed that the traditional classification of flowering plants into two groups – the monocots and dicots (based on the number of seed leaves or cotyledons) is incorrect, and the old dicot group contains several unrelated species that just happen to have two cotyledons.

DNA hybridisation

Although the complete genomes of a few species have been sequenced (including humans), DNA sequencing is slow and expensive. Furthermore it is usually only practical to compare the sequences of few genes (such as the three in the plant example), and this can give unreliable evidence. A simpler and quicker technique, which can also compare large amounts of DNA at a time, is DNA hybridisation. The method is:

1. Extract DNA from 2 species and remove non-coding regions.
2. Heat DNA to break hydrogen bonds and separate strands
3. Mix DNA from both species in one tube and put DNA from just one species in the other tube.
4. Cool to allow base pairs to form between strands. DNA with complementary sequences will base pair, while mismatched sequences will not.
5. Warm slowly to separate the strands again and measure the amount of single stranded DNA every 2°C.
6. Determine the temperature at which 50% of the DNA has separated into single strands (T_{50}H)



The more similar the base sequence, the more hydrogen bonds form between the two strands.

The more similar the base sequence, the higher the temperature needed to separate the two strands.

The difference between the two T_{50}H temperatures tells us how similar the DNA sequences are. As a general rule, a difference in T_{50}H of 1°C is equivalent to a 1% difference in the base sequences.

DNA hybridisation has been used to investigate the relationship between humans and other apes:

Species whose DNA is being compared	Difference in T_{50}H (°C)
Human + chimpanzee	1.6
Human + gorilla	2.3
Human + orang-utan	3.6

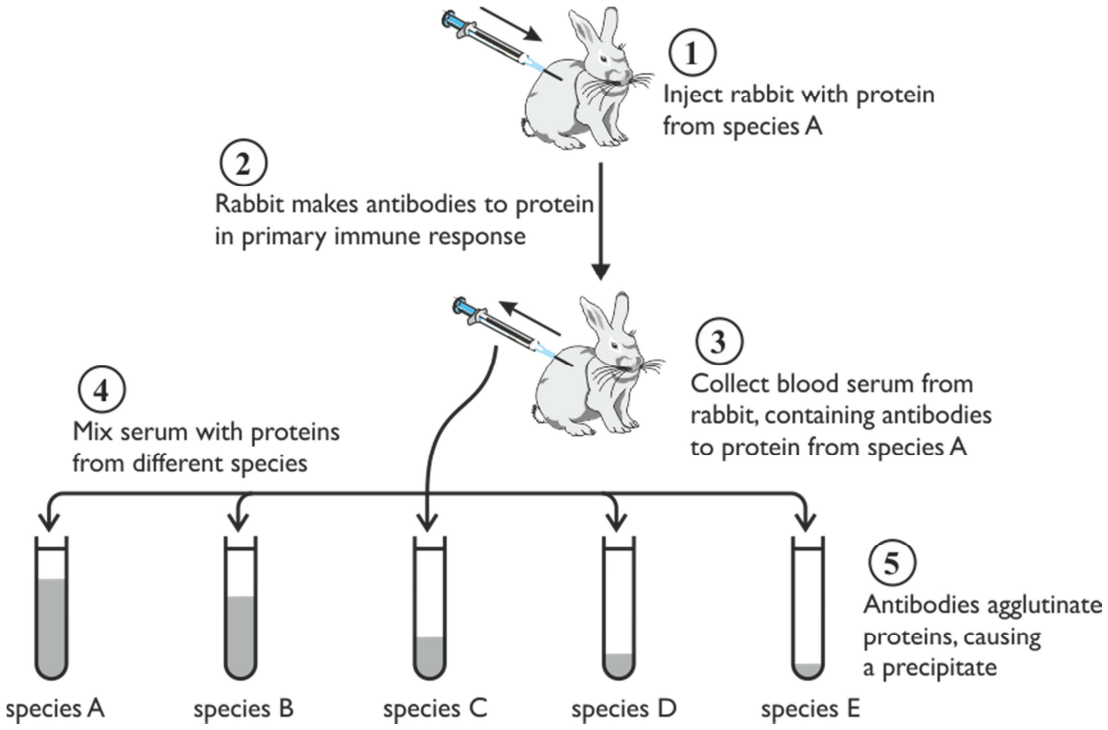
Classification using Proteins

Since protein sequences are determined by DNA sequences, we can also use the amino acid sequence in proteins to investigate phylogenies. Typical proteins used for this purpose are haemoglobin (found in all animals) and cytochrome c (a respiratory enzyme found in all eukaryotic organisms). The β chain of haemoglobin usually contains 146 amino acids, and this table shows the number of differences in amino acid sequence of β-chain of haemoglobin of different species compared to humans.

Animal Species	No. of a.a. differences
Human	0
Gorilla	1
Gibbon	2
Rhesus monkey	8
Dog	15
Horse	25
Mouse	27
Gray Kangaroo	38
Chicken	45
Frog	67

Protein Immunology

Proteins are more difficult to sequence than DNA, and only a few proteins have been sequenced for different species, but again there is a quicker way to compare proteins using immunology. This technique is based on the specific binding of antibodies to proteins, causing agglutination. The method is:



The more similar a protein is to species A protein, the better the antibodies will bind and the more precipitate is formed. This technique has been used to compare the blood protein albumin in different primates:

Species	Human	Chimpanzee	Gorilla	Orang-utan	Gibbon	Lemur
% precipitation	100	95	95	85	82	35

This evidence is not as good as the DNA evidence, but it supports the same phylogeny.

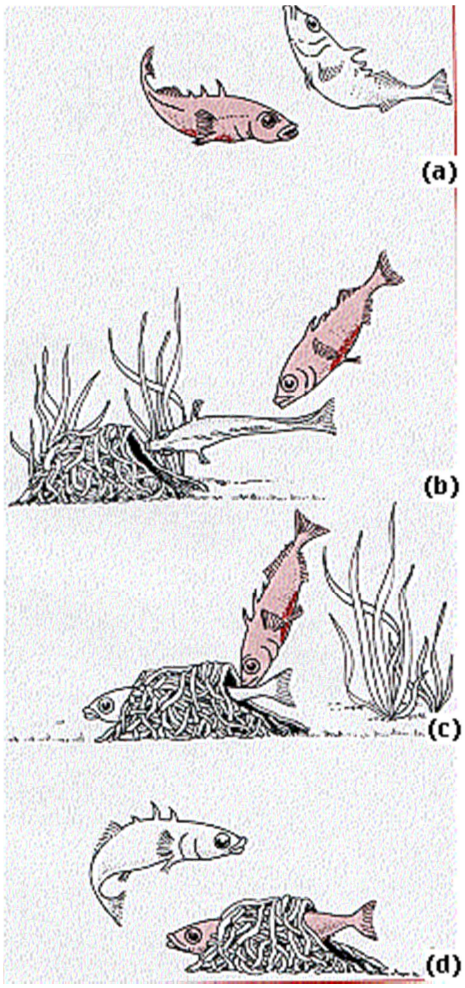
Classification using Courtship Behaviour

Animals use courtship behaviour as part of sexual reproduction. Courtship behaviour is innate, in other words it is genetically programmed, so all members of the same species show exactly the same courtship behaviour, while members of different species show different behaviours. Courtship behaviour can thus be used to identify individuals as members of the same or different species.

Courtship behaviour allows animals to:

- Recognise members of their own species. This is particularly important where many very similar species live in the same habitat. Reproduction between members of different species may be possible, but won't lead to fertile offspring, so should be avoided.
- Attract a mate of the opposite sex.
- Identify a mate that is capable of breeding. Both partners need to be sexually mature, fertile and receptive to mating. Many females only produce eggs at specific times, often just once a year.
- Synchronise the production of eggs and sperm.
- Form a pair bond and help raise the offspring.

Courtship behaviour has been extensively studied in the three-spined stickleback by Niko Tinbergen. During the breeding season, males develop red bellies and build a nest in a territory, which they defend from other males. The female is attracted by the red belly (diagram a). The male performs a zigzag dance and the female follows him to the nest (b). The female enters the nest and the male prods the base of her tail (c), which stimulates her to lays eggs in the nest. The male then drives the female from the nest, enters it himself, and releases sperm to fertilise the eggs (d).

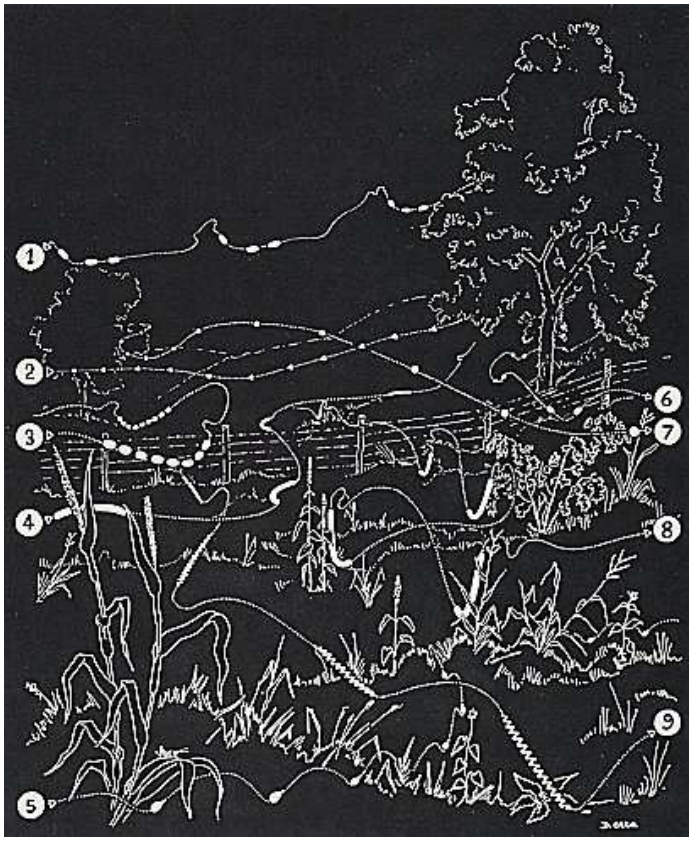


Only members of the same species of stickleback will respond in the correct way, allowing mating to proceed, so this ensures that males don't fertilise eggs from a different species. This is important for species that use external fertilisation.

Tinbergen found that the female will follow almost any small red object to the nest, and any object touching her near the base of her tail will cause her to release her eggs.

Another example of courtship behaviour for species recognition is the firefly. Many very similar species coexist in the same habitat, so species recognition is important.

Fireflies can produce flashes of light using a special chemical reaction catalysed by the enzyme luciferase. Mating takes place at night, and the males of each species of firefly produces a unique pattern of light flashes combined with a unique flight path (straight, zigzag or looping). Females will only mate with males showing the correct pattern of flashes and flight, ensuring mating only takes place between members of the same species. The flashing and flight patterns in males are entirely genetically-determined.



Appendix 1 – Mathematical Requirements

Biology is a quantitative science, and a reasonable mathematical ability is expected in an A-level biology exam. The AQA specification states that you can be tested on any of these mathematical topics:

Calculations

- Use standard form; ratios, fractions and percentages.
- Calculate x^n; $1/x$; $\sqrt{x}$; mean; and standard deviation.
- Calculate percent change and rate of change.
- Calculate circumferences and areas of circles; and surface areas and volumes of cuboids and cylinders when provided with appropriate formulae.
- Use units with prefixes (n, μ, m, k, M, G) and use an appropriate number of significant figures.
- Make estimates of the results of calculations without using a calculator.
- Rearrange equations and substitute numerical values into equations using appropriate units.

Handling data

- Understand the terms mean, median and mode and standard deviation.
- Understand the use of logarithms for quantities that range over several orders of magnitude.
- Construct and interpret frequency tables, bar charts and histograms.
- Use a scatter diagram to identify positive and negative correlation between two variables.
- Plot graphs from data (using appropriate institute of biology conventions) and read data from graphs.
- Understand the principles of sampling as applied to biological data.

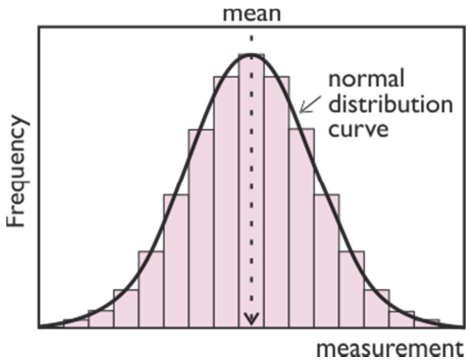
Maths Tips

- There will be maths questions! You must be confident with units and prefixes (especially m, μ and n).
- You need to know the formulae for magnification; percent change and gradient of a graph.

Sampling

In biology investigations we want to find out something about the natural world, but we can't possibly observe every single member of a species. Instead we make our measurements on a sample of the total population, and hope that our conclusion from the sample can be applied to the whole population. Since organisms vary the sample must be chosen carefully:

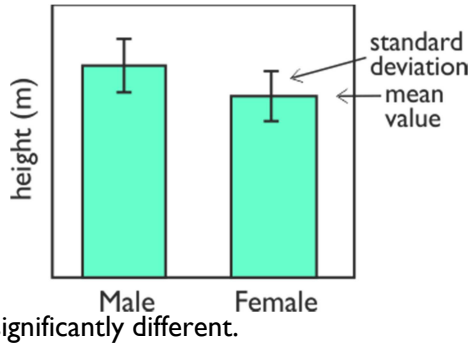
- It must be a random sample, to avoid sample bias, such as accidentally (or deliberately) picking all the tallest individuals. We can use random numbers to choose coordinates to place quadrats or traps, or to pick individuals.
- It must be a large sample, to minimise the chance of picking a skewed sample and to allow for bad measurements or anomalies. The sample size is often called n. How big should n be? This depends on the measurements, but n should never be less than 10, and preferably at least 100 or 1000.



Assuming the characteristic can be measured quantitatively, then the measurements can be summarised on a histogram, where the horizontal axis shows the variable being measured and the vertical axis shows the number of measurements, or frequency, in each group (histograms are also called frequency histograms). If there are enough measurements the histogram approaches a smooth curve. The curve is usually a symmetrical, bell-shaped normal distribution curve, with most of the repeats close to some central value. Many biological phenomena follow this pattern: e.g. peoples' heights, number of peas in a pod, the breathing rate of insects, etc.

The whole sample can be summarised by two parameters:

- The mean ($\bar{x}$; also known as the arithmetic mean or average) is mid-point of the sample (actually the central point of the normal distribution curve).
- The standard deviation (SD) is variation (or "spreadiness") of the sample (actually the width of the normal distribution curve). The more variation there is in the sample, the more spread out the measurements are, and the larger the standard deviation.



Whenever a mean is calculated a standard deviation should also be calculated to show how reliable the mean is. Sample means and standard deviations can easily be calculated using computers or calculators. Standard deviations can be plotted on a chart as error bars to show graphically the reliability of the mean values. If the error bars overlap, then we can say that the samples aren't really different. If they don't overlap, then we can say that the samples are significantly different.

Appendix 2 – The Unit 2 Exam

The three AS biology units are assessed as shown in this table:

Unit	Assessment	Details	Raw marks	UMS marks
Unit 1	1h 15min exam	5-7 short answer questions plus 2 longer questions: 1 comprehension and 1 continuous prose.	60	100
Unit 2	1h 45min exam	9 short answer questions plus 2 longer questions: 1 data handling and 1 HSW.	85	140
Unit 3	AS EMPA	2-3 practical sessions with short written task sheets plus a 1h 15min exam.	50	60

Biology is not just about learning facts (though there is a lot to learn): it's largely about understanding principles and being able to apply these principles to unfamiliar situations (which is what happens in real life). It's also important to understand How Science Works, and the role of evaluation and critical thinking. So the A2 biology exams test all these aspects. Of the 60 raw marks in the unit 1 exam, about 25 will be for biological knowledge; 25 will be for applying that knowledge to unfamiliar situations and analysing data; and 10 will be for How Science Works, including planning, analysing and evaluating experiments. So expect lots of questions about data analysis. These are designed to test your knowledge of unit 1 biology in unfamiliar contexts.

Biological principles

The following basic biological principles from unit 1 can be examined in unit 2.

- Proteins and polysaccharides are made up of monomers that are linked by condensation.
- Many of the functions of proteins may be explained in terms of molecular structure and shape.
- Enzymes are proteins and their rates of reaction are influenced by a range of factors: temperature, the presence of inhibitors, pH and substrate concentration.
- Substances are exchanged by passive or active transport across exchange surfaces. The structure of plasma membranes enables control of the passage of substances across exchange surfaces.

Exam Technique

- 40% of all exam marks lost are lost due to poor exam technique.
- Read the question! You will only get marks for doing exactly what it asks, e.g. if a question says "explain how A causes B" then start at A and finish at B.
- Do what the question says. If it says "use the diagram to..." or "use the graph to...", then you must do so.
- If a question says "give two reasons…" then give exactly two. You will lose marks if you give three.
- Read the whole question before answering any of it. This helps understanding.
- Use technical terms in every answer. In general a technical term used correctly is worth one mark. "Meiosis causes alleles to be recombined" is more likely to earn a mark than "meiosis mixes genes".
- Look at the marks. Don't write too much for a 1-mark answer, and do write 3 good things for a 3-mark answer.

Exam Strategy

- 40% of the marks are aimed at E-grade candidates, so should be fairly easy to get. You could try finding and doing these questions first.
- In longer answers (5 or more marks) try writing your answer in bullet points, where each statement is worth one mark. That will force you to be logical and put a technical term into every sentence, and it will help the examiner to find your points.

Describing and Explaining data

- Underline the words "describe" and "explain" on your paper, to remind you to do the right one.
- If you are asked to describe some results (from a table or a graph) look for different phases e.g. "as X increases Y increases up to 30 days then levels off". Always quote a value from the graph – usually the X-value where the graph chances shape.
- If you have to describe a graph with fluctuating or "noisy" data (a jagged line), try drawing a smooth line of best fit through the data first, and then describe that.
- If you are asked to describe some results from a table it might be a good idea to sketch a quick graph on the exam paper so you can see the pattern more clearly.

How Science Works

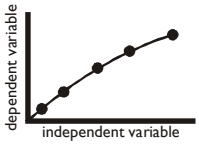
- There will be How Science works questions in all exams, so check you know all the terms.
- If you are asked to design an investigation, the marks will be for fair testing (though don't use this term): how to change the independent variables; how to quantify the dependent variable; naming some control variables; doing repeats.

You need to understand all the How Science Works words on the next page (items marked * are only in A2).

Types of Variable

Dependent Variable
The variable you *measure*, to see how it is affected by the independent variable.

Independent Variable
The variable you *choose to change*, to see how it affects the dependent variable. You may also measure it when you change it.



Confounding Variables
Any variables that could also affect the dependent variable. Confounding variables should be controlled in a fair test.

Control variables
Confounding variables that are kept constant (controlled) during the experiment. If you can't control a variable (such as weather in a field investigation), you should at least monitor it

Experimental Design

Controlled Experiment (FairTest)
When all relevant variables are controlled, so that observed changes in the dependent variable must be due to changes in the independent variable.

Control Experiment (Control)
An additional experiment designed to eliminate alternative explanations for the main experiment, and so show that observed changes in the dependent variable must be due only to changes in the independent variable.

Control Group
A group or sample treated in the same way as the experimental group, except for the factor being investigated e.g. a placebo group in a drugs trial. By comparing the results for two groups it can be shown that observed changes in the dependent variable must be due only to changes in the independent variable.

Placebo
A dummy pill, injection or treatment that has no physiological effect (e.g. a sugar pill or saline injection). Used in a clinical trial to allow for the **placebo effect** - the observation that symptoms can improve when patients believe they are being helped.

RCT
The best experimental design for a drug trial. RCT stands for Randomised Controlled Trial, or in more detail, a Randomised, Placebo-Controlled, Double-blind Trial. This design ensures that the trial is **valid** free from **bias**.

- **Randomised** means the study and control groups are allocated randomly
- **Placebo-controlled** means the study group (taking the drug to be tested) is compared to a placebo group (who are given a placebo).
- **Double-blind** means that neither the subjects nor the investigators know who is in the study or placebo groups. This avoids bias.

Protocol
A method or technique that has been shown to produce valid and reliable results.

Hypothesis
A suggested explanation of observations or results that can be tested. Also known as a scientific hypothesis. A good hypothesis can be used to make **predictions.**

Quality of Data

True Value
The real value of a measurement, if it could be measured with no errors at all.

Precise Data
1. Measurements that give similar values when repeated. The replicates therefore have a small **range**.
2. Data measured on sensitive equipment with a suitably fine scale, e.g. 20 mm is more precise than 2 cm.

Reliable Data
Findings that can be repeated. This includes by the original investigator; by other scientists; by other techniques; or those that agree with secondary sources.

Accurate Data
Measurement that are close to the **true value.**

Valid Data
The best quality data, i.e. data that is **precise** and **reliable** and obtained from an **unbiased**, **controlled** experiment that addresses the stated aim. Valid data is assumed to be accurate.

Evidence
Any data or observations that are used to support a particular hypothesis.

Anecdote
An observation or story from real life. Anecdotes are not evidence and cannot be used to support a hypothesis, but they can be useful to suggest a new testable hypothesis.

Types of Data

Data
(measurements, singular datum)

- **Quantitative or Numeric Data** (numbers)
  - **Continuous Data** — can have any value, e.g. 7.34, -294.6, $2x10^5$
  - **Discrete Data** — only whole numbers, e.g. no. of atoms
- **Qualitative or Categoric Data** (words)
  - **Ordered Data** — can be ranked, e.g. small, medium, large
  - **Nominal Data** — can't be ranked, e.g. male, female

Errors

Random Errors
Inaccuracies due to mistakes, poor technique, or random variation. Random errors are very common, but can be improved by taking many replicates. Data with a small random error is said to be **precise**.

Systematic Errors
Inaccurate measurements in one direction only, due to poor **calibration** or poor technique. Systematic errors can **not** be improved by taking more replicates. Data with a small systematic error is said to be **reliable.**

Zero Error
A particular kind of systematic error, where the instrument does not return to zero.

Bias
When the observer chooses some results and ignores others, to support a particular view. Also called **cherry picking**.

Anomaly or Outlier
A measurement that falls far outside the expected range and is therefore probably due to experimental error. Anomalies should be rejected, since they skew the mean, but it is very difficult to distinguish between anomalies and normal biological variation.

Calibration
Ensuring that a measuring instrument gives correct readings by fixing known points then constructing a scale between them.

Simple Analysis

Replicates
Repeats of a measurement.

Raw Data
The original measurements or recordings before any manipulation or processing.

Mean or **Average**
The mid-point of the replicates.
= sum of replicates / N

Range
The highest and lowest replicates, or the interval between them.

Standard Deviation (SD)
A measure of the dispersal of the replicates about the mean. In a normal distribution 68% of the replicates will be within 1 standard deviation of the mean, and 95% will be within 2 standard deviations of the mean.

Standard Error of the mean (SEM)*
A measure of the uncertainty, or error, of a calculated mean. The smaller the standard error, the more reliable the mean.

95% Confidence Interval (CI)*
Another measure of the error of the mean. We can be 95% confident that the true mean lies in the range (mean ± CI). The top and bottom of this range are called the **confidence limits**.

Statistical Analysis

Correlation (or Association)
When one variable changes with another variable, so there is a relation between them. The strength of a correlation can be measured using a correlation coefficient. A correlation need not be a **causal relation**.

Causal Relation
When changes in one variable cause the changes in another variable. Can only be shown by a controlled experiment.

Statistical Test*
Something that tests whether observed differences or correlations are significant, or just due to chance.

Null Hypothesis*
The statement that is tested by a statistical test. The null hypothesis is fixed for each test, but always says that there is no difference or no association. The null hypothesis has nothing to do with a scientific hypothesis.

P*-value
The result of a stats test, expressed as a probability. It is the probability that the results are due to chance. If $P<0.05$ then we reject the null hypothesis, otherwise we accept it.