TOPIC 1.1: CELL THEORY

Cell Theory

According to the cell theory:

1. Living organisms are composed of cells (or cell products)
2. The cell is the smallest unit of independent life
3. Cells can only arise from pre-existing cells

Caveats to the cell theory include:

- Striated muscle – composed of fused cells that are multinucleated
- Giant algae – unicellular organisms that are very large in size (~7 cm)
- Aseptate hyphae – lack partitioning and have a continuous cytoplasm

Functions of Life

Organisms consisting of only one cell carry out all the life functions in that single cell

- **M**etabolism
- **R**eproduction
- **S**ensitivity
- **H**omeostasis
- **E**xcretion
- **N**utrition
- **G**rowth

Cell Size

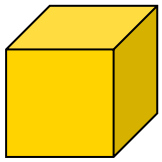
Surface area to volume ratio is important in the limitation of cell size

Cells need to exchange materials with the environment in order to produce the chemical energy required for survival (via metabolism)

- The rate of metabolism is a function of a cell's mass / volume
- The rate of material exchange is a function of a cell's surface area

As a cell grows, volume (units^3) increases faster than surface area (units^2)

- If metabolic requirements exceed material exchange, a cell will die
- Hence, cells must stay small or increase their SA:Vol ratio to survive

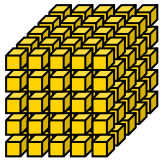


Small SA:Vol Ratio

⬆ metabolic rate

⬇ material exchange

Low survival chances



Large SA:Vol Ratio

⬇ metabolic rate

⬆ material exchange

High survival chances

Magnification

Calculating Magnification (MIA):

Magnification = **I**mage Size ÷ **A**ctual Size

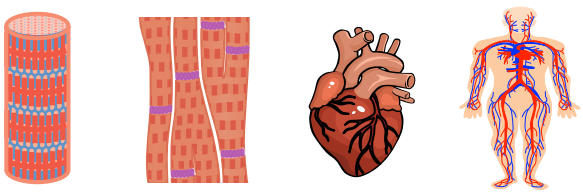
Calculating Actual Size (AIM):

Actual Size = **I**mage Size ÷ **M**agnification

Cellular Organization

In multicellular organisms:

- Cells may be grouped together to form tissues
- Tissues may interact to form functional organs
- Organs may combine to form body systems



Muscle (Cell) ➡ *Cardiac* (Tissue) ➡ *Heart* (Organ) ➡ *Vascular* (System)

Microscopes

Light microscopes use lenses to bend light

- Can view living specimens in natural colour
- Have lower magnification and resolution

Electron microscopes use electromagnets to focus electrons

- Can only view dead specimens in monochrome
- Have higher magnification and resolution
- Can show cross-sections (TEM) or surface renderings (SEM)

Emergent Properties

An emergent property is a function that is present in multicellular organisms, but is not present in its individual component cells

Emergent properties arise from synergistic interactions between the individual cells to produce entirely new aggregate functions

An example of an emergent property is the increased levels of antibiotic resistance that can be seen in bacterial biofilms

'The whole is greater than the sum of its parts' – Aristotle

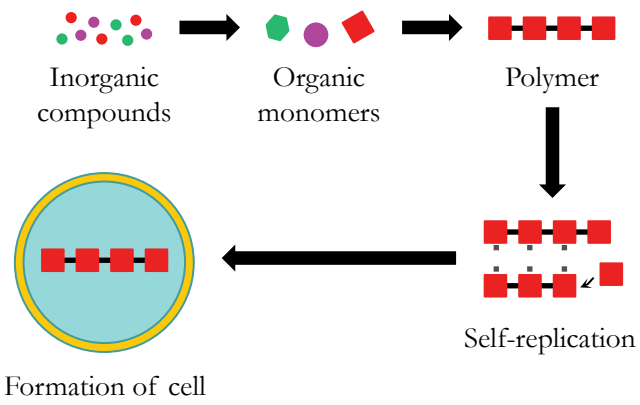
TOPIC 1.5: ORIGIN OF CELLS

Abiogenesis

The formation of living cells from non-living materials (abiogenesis) is theorised to involve 4 four key processes:

- Non-living synthesis of simple organic molecules
- Assembly of organic molecules into complex polymers
- Formation of polymers that can self-replicate
- Packaging of molecules into membranes to create an internal chemistry different from the surroundings

The Miller-Urey experiment replicated the conditions of a pre-biotic Earth in order to synthesize organic molecules



Biogenesis

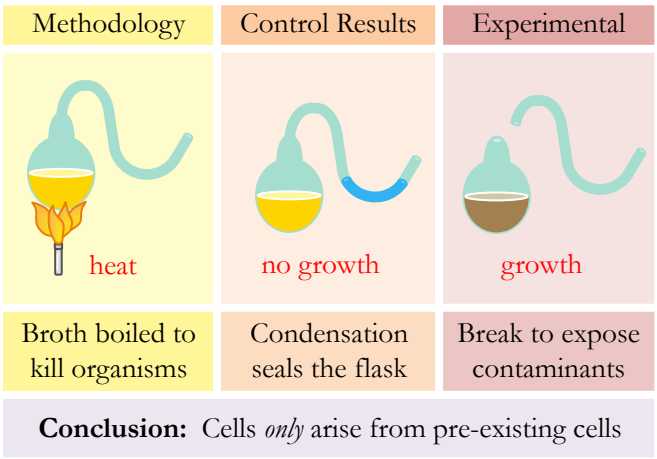
Abiogenesis requires specific conditions in order to proceed

- Including a reducing atmosphere (no oxygen) and either high temperatures (>100°C) or electrical discharges

As these conditions no longer commonly exist on Earth, cells can only be formed from division of pre-existing cells

This law of biogenesis was demonstrated by Louis Pasteur

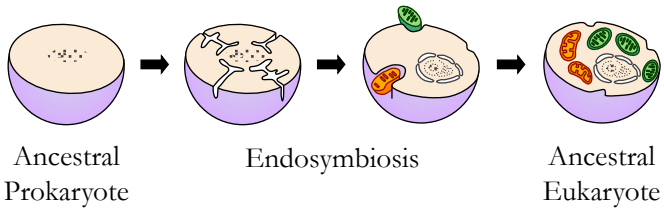
- Broths were stored in sealed vessels that were sterilised
- Bacterial growth occurred if vessel was unsealed, but did not occur if vessel stayed sealed (no contamination)



Endosymbiosis

Eukaryotic cells are believed to have evolved from aerobic prokaryotes that were engulfed by endocytosis

The engulfed cell remained undigested and contributed new functionality to the engulfing cell (i.e. it became an organelle)



Chloroplasts and mitochondria arose via endosymbiosis:

- **M**embranes (have a double membrane)
- **A**ntibiotics (show susceptibility)
- **D**NA (have naked and circular DNA)
- **D**ivision (occurs via a fission-like process)
- **R**ibosomes (have 70S ribosomes)

Oxygenation of Earth

The appearance of photosynthetic organisms lead to the rapidly increasing oxygenation of the Earth's environment

Oceans

- Originally, Earth's oceans had high levels of dissolved iron (released from crust by underwater volcanic vents)
- Oxygen chemically reacted with the iron to form an insoluble precipitate (iron oxide)

Rock Deposition

- Insoluble iron formed banded iron formations (BIFs)
- These deposits are not commonly found in rock that is younger than 1.8 billion years (hence, identifies when photosynthetic organisms first evolved)

Atmosphere

- When dissolved iron was completely consumed, oxygen started accumulating in the anoxic atmosphere

TOPIC 1.6: CELL CYCLE REGULATION

Cell Cycle Checkpoints

A cell cycle contains numerous checkpoints that ensure the fidelity and viability of continued cell divisions

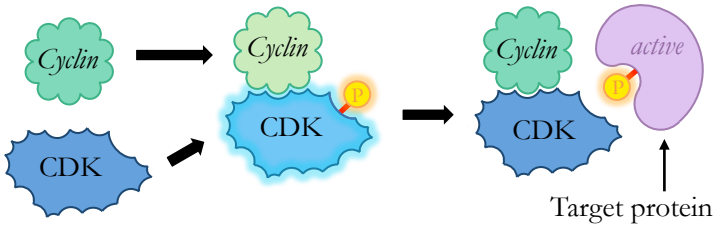
G_1 checkpoint
- Monitors potential growth conditions (nutrients, etc.)
- Assesses level of DNA damage (from UV, etc.)

G_2 checkpoint
- Monitors state of pre-mitotic cell (suitable size, etc.)
- Identifies and repairs any DNA replication errors

Metaphase checkpoint
- Ensures proper alignment (prevents aneuploidy)

Cyclins

Cyclins are proteins that control progression of the cell cycle
- Cyclins bind to cyclin dependent kinases (CDKs)
- The activated complex phosphorylates proteins involved in specific cell cycle events (e.g. centrosome duplication)
- After the event has occurred, the cyclin is degraded and the cyclin dependent kinase is rendered inactive

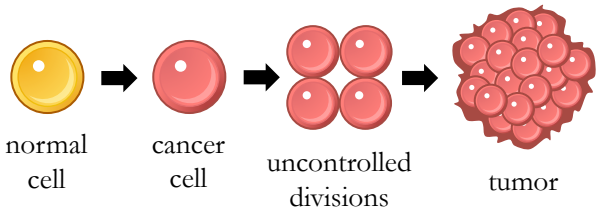


Cancer

Cancers are diseases caused by uncontrolled cell division
- The resulting abnormal cell growths are called tumors

Tumor cells may remain in their original location (benign) or spread and invade neighboring tissues (malignant)

Metastasis is the spread of cancer from an original site to a new body location (forming a secondary tumor)



Cancer Development

Cancers can be caused by many different factors:

Mutagens

Mutagens are agents that change the genetic material of cells
- These agents may be either physical (e.g. UV), chemical (e.g. arsenic) or biological in origin (e.g. certain viruses)
- Mutagens that cause cancer are classified as carcinogens

Genetics

Most cancers are caused by mutations to two classes of genes:
- Proto-oncogenes stimulate cell growth and proliferation
- Tumor suppressor genes repress cell cycle progression

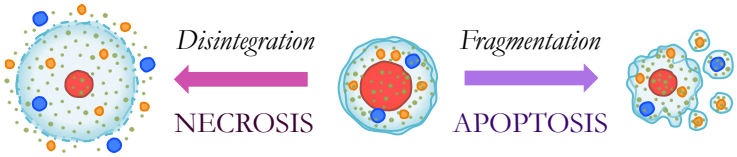
Proto-oncogene mutations create cancer-causing oncogenes

Cell Death

The death of a cell may occur by one of two mechanisms:

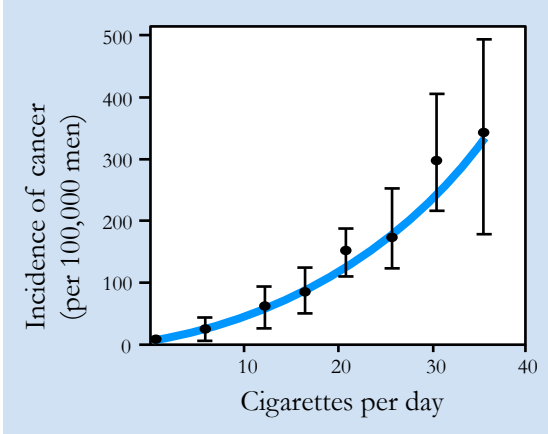
Necrosis (uncontrolled 'cell homicide')
- The cell loses functional control due to injury, toxins, etc.
- There is a destabilization of the membranes, leading to swelling
- The cell bursts and releases its contents (causing inflammation)

Apoptosis (programmed 'cell suicide')
- It is a controlled event triggered by mitochondrial proteins
- Cell contents are packaged in membranous protrusions (blebs)
- The cell fragments into apoptotic bodies which are recycled



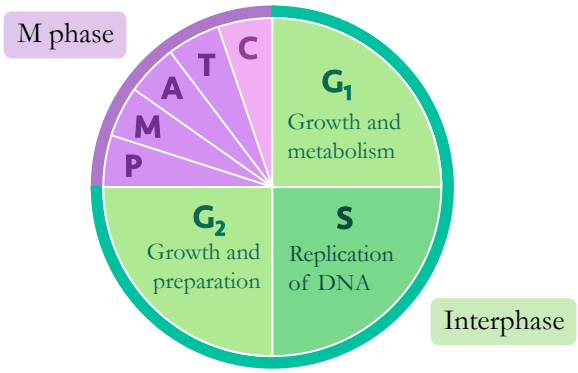
Smoking

There is a strong positive correlation between the frequency of smoking and the incidence of cancer
- Cigarette smoke contains >60 known carcinogens



TOPIC 1.6: CELL DIVISION

Cell Cycle



The cell cycle is an ordered set of events that culminates in cell division

Interphase

An active phase of the cell cycle where many metabolic reactions occur

- Consists of G_1, S and G_2 stages

M phase

The period of a cell cycle in which the cell and contents divide

- Consists of mitosis (P, M, A, T) and cytokinesis

Some cells may also enter a non-proliferative quiescent phase (G_0)

Interphase

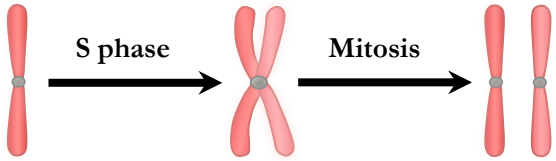
Normal metabolism cannot occur during M phase, so key events must occur during interphase to prepare for division:

- **D**NA replication (during S phase)
- **O**rganelle duplication
- **C**ell growth
- **T**ranscription / translation
- **O**btaining nutrients
- **R**espiration (cellular)

Supercoiling

During mitosis, chromatin condenses via supercoiling to become tightly packed chromosomes

- Due to replication (S phase), chromosomes consist of identical sister chromatids (joined at a centromere)



Mitosis

Mitosis is the division of a diploid nucleus into two genetically identical diploid nuclei

This process of cell cloning is needed for many important processes:

- **T**issue repair
- **O**rganism growth
- **A**sexual reproduction
- **D**evelopment of embryos

Cytokinesis

Cytokinesis is the process of cytoplasm division, whereby a cell splits in two

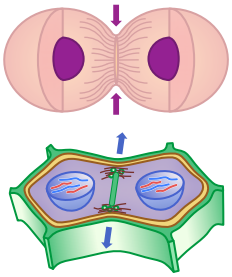
- It occurs concurrently with telophase and differs in plants and animals

Animals:

- Microtubules form a concentric ring and contract towards the centre (centripetal)

Plants:

- Vesicles form at the cell centre and fuse outwards to form a cell plate (centrifugal)



Mitotic Index

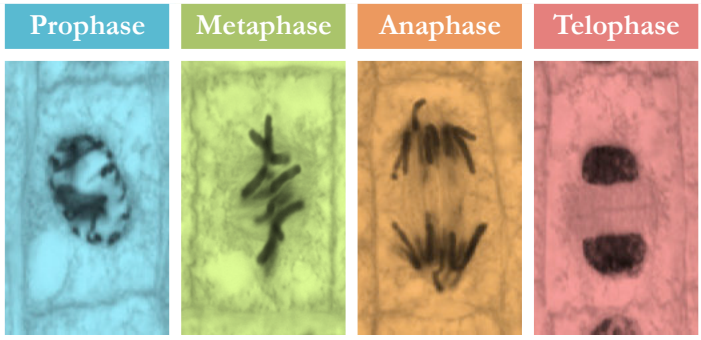
The mitotic index is a measure of the proliferative status of a cell population (i.e. number of dividing cells)

The mitotic index will be elevated during growth and repair processes and acts as a prognostic tool for cancer

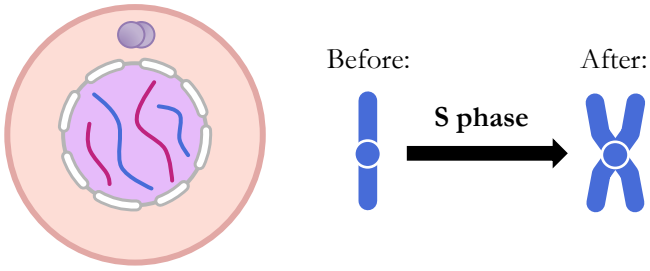
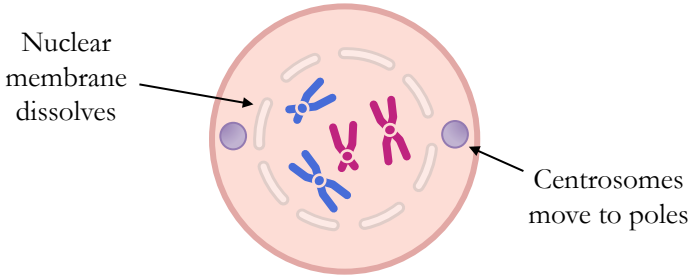
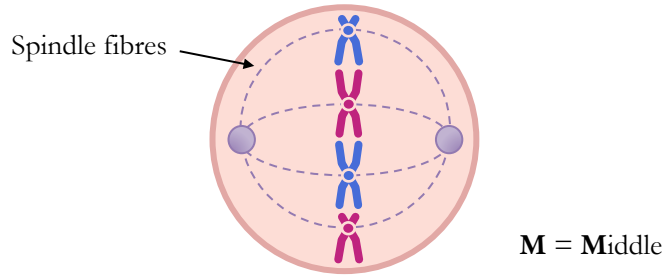
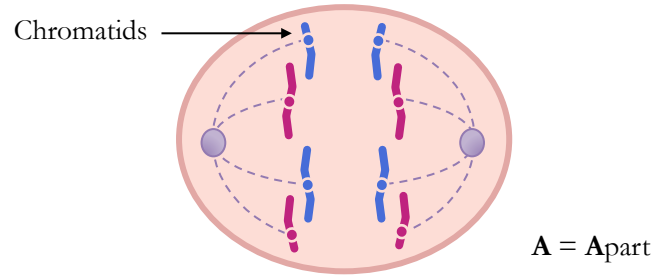
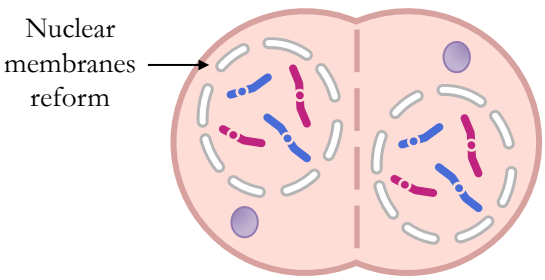
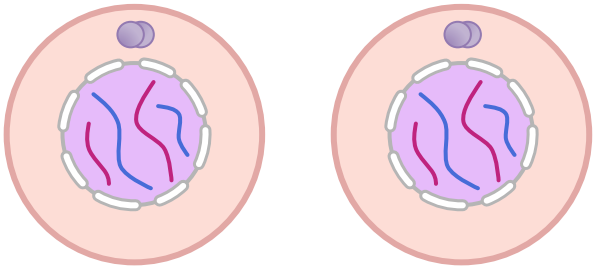
$$\textbf{Mitotic Index} = \frac{\text{Cells in mitosis*}}{\text{Total number of cells}}$$

*Mitotic cells have no nucleus and have visible chromosomes

Mitosis Micrographs



TOPIC 1.6: STAGES OF MITOSIS

Stage	Diagram	Key Events
Interphase (2n)		• DNA is uncondensed (chromatin) • DNA is replicated (S phase) to form genetically identical sister chromatids • Cell grows in size and organelles are duplicated (G_1 and G_2)
Prophase (2n)		• DNA supercoils and condenses (forms visible chromosomes) • Nuclear membrane dissolves • Centrosomes move to poles and begin to produce spindle fibres
Metaphase (2n)		• Centrosome spindle fibres attach to the centromere of each chromosome • Spindle fibres contract and move the chromosomes towards the cell centre • Chromosomes form a line along the equator (middle) of the cell
Anaphase (2n → 4n)		• Spindle fibres continue to contract • Sister chromatids separate and move to opposite sides of the cell • Sister chromatids are now regarded as two separate chromosomes
Telophase (4n)		• Chromosomes decondense (DNA forms chromatin) • Nuclear membranes form around the two identical chromosome sets • Cytokinesis occurs concurrently
Cytokinesis (2n × 2)		• Cytoplasmic division occurs to divide the cell into two daughter cells • Each daughter cell contains one copy of each identical sister chromatid • Daughter cells are genetically identical

TOPIC 2.1: MOLECULAR BIOLOGY

Metabolism

Metabolism describes the totality of chemical processes that occur within a living organism in order to maintain life

- It is the web of all enzyme–catalysed reactions that occur within a particular cell or organism

Molecular biology explains these biological processes in terms of the chemical substances (molecules) involved

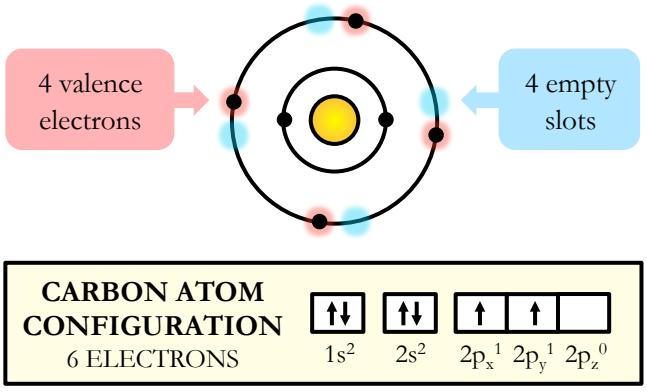
Organic Compounds

Organic compounds are molecules that contain carbon and are found in living things

- Exceptions include carbonates and oxides of carbon

Carbon atoms form the basis of organic life due to their capacity to form four covalent bonds

- This allows a diversity of stable compounds to exist



Biomacromolecules

There are four main groups of organic compounds in cells:

- Carbohydrates, lipids, proteins and nucleic acids

Carbohydrates, proteins and nucleic acids are all made up of recurring subunits (monomers)

CLASS	MONOMER	POLYMER
Carbohydrate	Monosaccharide	Polysaccharide
Protein	Amino acid	Polypeptide
Nucleic Acid	Nucleotide	DNA / RNA

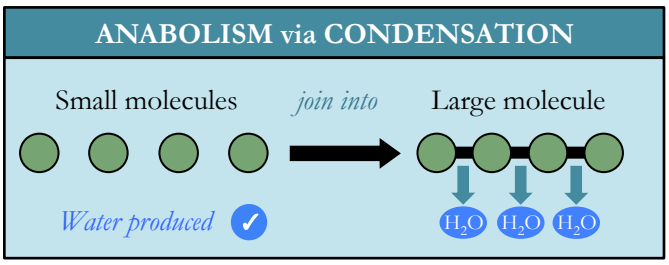
Lipids are <u>not</u> composed of repeating monomers, but *may* contain smaller subunits (e.g. triglycerides)

CLASS	SUBUNITS
Triglyceride	Glycerol + Fatty Acid (×3)

Types of Reactions

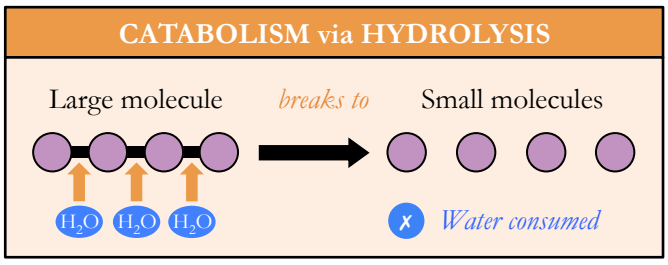
Anabolism

- The synthesis of complex molecules from simpler ones
- Involves condensation reactions (water is produced)
- An example of an anabolic reaction is photosynthesis



Catabolism

- The breakdown of complex molecules into simpler ones
- Involves hydrolysis reactions (water is consumed)
- An example of a catabolic reaction is cellular respiration



Vitalism

Theory of Vitalism

Vitalism was a doctrine that dictated that organic molecules could <u>only</u> be synthesized by living systems

- Living organisms were thought to possess a "vital force" that was required to manufacture organic molecules

Falsification of Vitalism

In 1828, Frederick Woehler disproved the theory of vitalism by artificially synthesizing an organic molecule

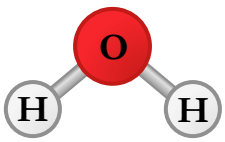
- He heated an inorganic salt (ammonium cyanate) under laboratory conditions to produce urea (organic)

TOPIC 2.2: WATER

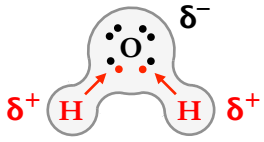
Water Structure

Water is made up of two hydrogen atoms covalently bonded to an oxygen atom (molecular formula: H_2O)

Oxygen has a higher electronegativity and attracts the shared electrons more strongly, resulting in polarity



Water Structure

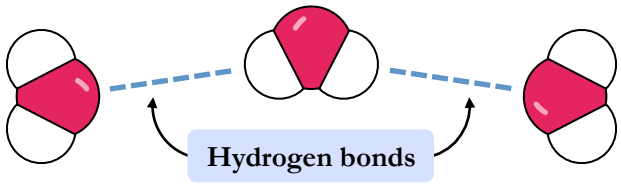


Water Polarity

Hydrogen Bonding

The dipolarity of the water molecule enables it to form polar associations with other charged molecules (polar or ionic)

Water molecules can also form hydrogen bonds with other water molecules (between an δ^+ hydrogen and an δ^- oxygen)



Cohesive Properties

Water can form intermolecular associations with other molecules that share common properties (e.g. polarity)

- Water can form hydrogen bonds with other water molecules (cohesion: like molecules stick together)
- Water can form polar associations with charged molecules (adhesion: unlike molecules stick together)

The cohesive properties of water results in a relatively high surface tension (can resist low level external forces)

The adhesive properties of water allow for potential capillary action (e.g. transpiration stream in plants)

Solvent Properties

Water is commonly referred to as the universal solvent due to its capacity to dissolve a large number of substances (ionic / polar)

- Large quantities of water molecules can sufficiently weaken forces (e.g. ionic bonds) and form dispersive hydration shells

Substances that can dissolve in water are called hydrophilic

- Includes glucose, amino acids, sodium chloride, oxygen (low)

Substances that cannot dissolve in water are called hydrophobic

- Includes lipids (fats and cholesterol)

These solvent properties make water an important medium for metabolic reactions, as well as a necessary transport medium

Thermal Properties

Water has the capacity to absorb large amounts of heat energy before undergoing a resultant change in state

- Extensive hydrogen bonding must first be broken

Water therefore has a very high specific heat capacity

- Energy required to raise temperature of 1g by 1°C

These properties make water a very effective coolant

- Evaporation of sweat requires absorption of heat

Other Properties

Water is transparent, allowing light to pass through it

- Important for photosynthesis and also for vision

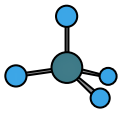
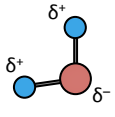
Water expands when frozen, becoming less dense

- Important for life on Earth as it means ice floats and the oceans underneath don't automatically freeze

Water versus Methane

Water and methane differ in thermal properties despite having similar structures (comparable weight, size, valence structure)

The differences are due to the polarity of water and its capacity to form intermolecular hydrogen bonds

	METHANE	WATER
		
Formula	CH_4	H_2O
Polarity	Non-polar	Polar
Heat Capacity ($J.g^{-1}.°C^{-1}$)	2.20	4.186
Boiling Point (°C)	–161	100

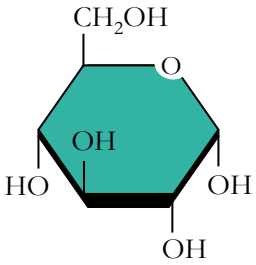
TOPIC 2.3: CARBOHYDRATES

Monosaccharides

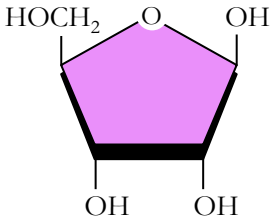
The monomer of a carbohydrate is called a monosaccharide

- Monosaccharides primarily function as an energy source

Examples of monosaccharides include glucose and ribose



Glucose



Ribose

Polysaccharides

Monosaccharides are covalently joined by glycosidic linkages to form polymers (requires condensation reactions)

Monosaccharides may be joined into disaccharides for ease of transport, or may form more complex polysaccharides

Polysaccharides may be used for a variety of cell functions:

- Short term energy storage (e.g. glycogen, starch)
- Structural components (e.g. cellulose)
- Recognition / receptors (e.g. glycoproteins)

The carbohydrate formed depends on the monosaccharide subunits used and the bonding arrangement between them

Types of Polysaccharides

Cellulose *(component of plant cell wall)*

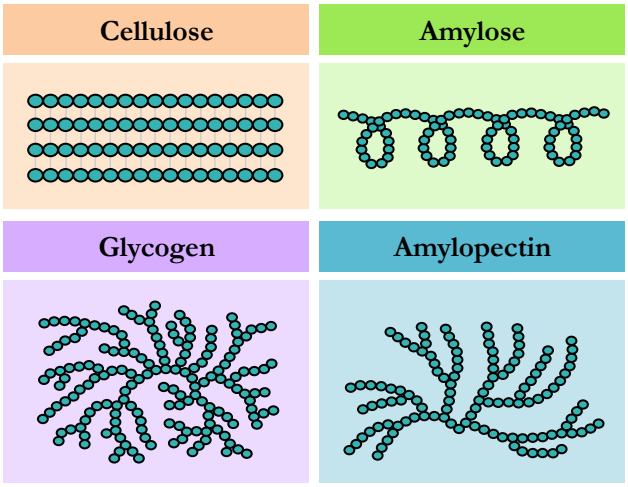
- Linear molecule made of β-glucose subunits
- Subunits bound in a 1-4 arrangement

Starch *(energy storage in plants)*

- Composed of α-glucose subunits and exists in two forms
- Amylose is linear (helical) and bound in 1-4 arrangements
- Amylopectin is branched (bound in 1-4 *and* 1-6 arrangements)

Glycogen *(energy storage in animals)*

- Branched molecule composed of α-glucose subunits
- Is like amylopectin but with more frequent 1-6 bonding



Energy Storage

Carbohydrates and lipids are both used as energy storage molecules, however they differ in certain key aspects:

- **S**torage (lipids used for long term storage)
- **O**smotic pressure (lipids easier to store)
- **D**igestion (carbohydrates easier to utilise)
- **A**TP yield (lipids store more energy per gram)
- **S**olubility (lipids insoluble / harder to transport)

	Carbohydrate	Lipid
Storage	Short term	Long term
Osmolality	More effect	Less effect
Digestion	Easier to digest	Harder to digest
ATP Yield	Smaller	Larger (~2×)
Solubility	Soluble *(mono-/dimer)*	Insoluble in water

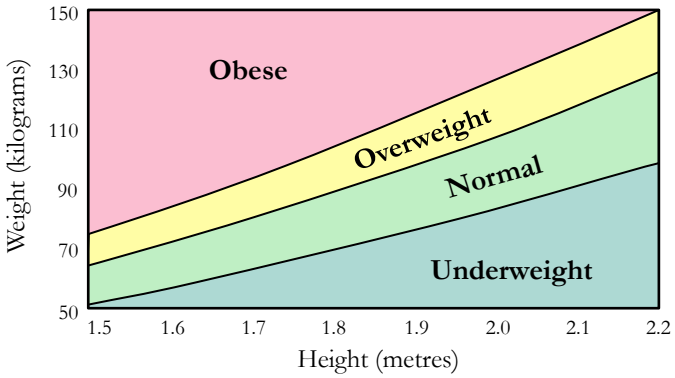
Body Mass Index

While carbohydrates (and lipids) are important components of a healthy diet, excess intake can affect body mass

The body mass index (BMI) can be calculated as follows:

- **BMI** = Mass in kg ÷ (Height in m)^2

BMI can be calculated with an alignment chart (nomogram)



TOPIC 2.3: LIPIDS

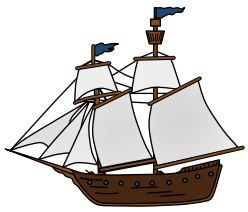
Functions of Lipids

Lipids are a class of non-polar organic molecules

- Include triglyceride (adipose tissue), phospholipid (bilayer), cholesterol (animal cell membrane), steroids (hormones)

Lipids may serve a variety of cellular functions, including:

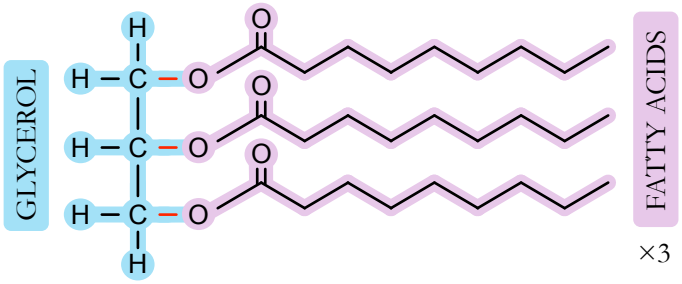
- **S**torage of energy (triglycerides)
- **H**ormonal roles (steroids)
- **I**nsulation (thermal)
- **P**rotection of organs
- **S**tructural roles (cholesterol)



Triglycerides

Triglycerides are lipids used for long-term energy storage

They are composed of a glycerol molecule covalently linked to three fatty acid chains (via condensation reactions)



Fatty Acids

Fatty acids are long hydrocarbon chains found in certain lipids

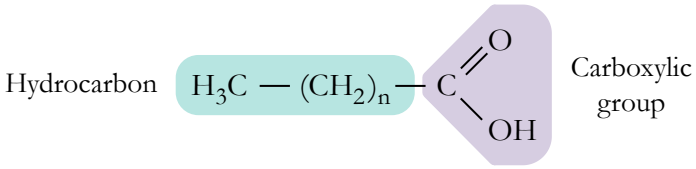
- Principally found in triglycerides and phospholipids

Saturated Fatty Acids

- Possess no double bonds in the hydrocarbon chain
- Are generally solid at room temperatures (e.g. animal fat)

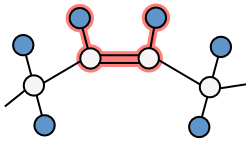
Unsaturated Fatty Acids

- Possess double bonds (mono = one ; poly = many)
- Are generally liquid at room temperature (e.g. plant oils)



General Structure of a Saturated Fatty Acid

Unsaturated fatty acids occur in two distinct configurations

Cis Isomer	Trans Isomer
	
H atoms on the *same side*	H atoms on *different sides*
Double bond creates *kink* in fatty acid chain	Double bond does *not* create kink (linear chain)
Are *loosely* packed and usually *liquid*	Are *tightly* packed and usually *solid*
Occur commonly in *nature*	Occurs in *processed food*
Generally *good* for health	Generally *bad* for health

Lipid Health Risks

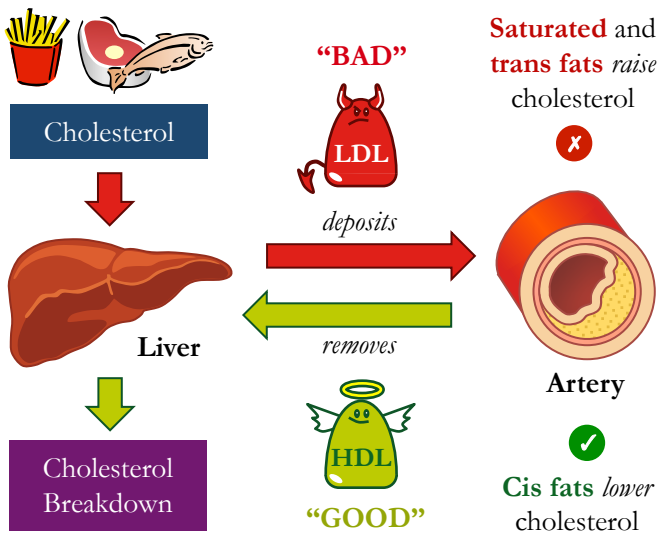
Fats and cholesterol cannot dissolve in the blood and so are packaged with proteins (as lipoproteins) for transport

- Low density lipoproteins (LDLs) transport cholesterol from the liver to the rest of the body (bad for health)
- High density lipoproteins (HDLs) scavenge excess cholesterol and return it to the liver for disposal (good)

Fatty acids can influence the levels of lipoproteins:

- Cis fats raise levels of HDL (⬇ blood cholesterol)
- Saturated fats raise levels of LDL (⬆ blood cholesterol)
- Trans fats raise levels of LDL and lower levels of HDL

High levels of blood cholesterol can cause atherosclerosis and lead to health issues like coronary heart disease (CHD)

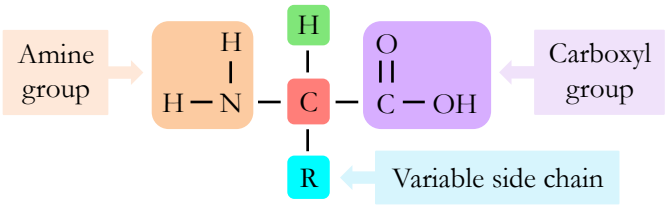


TOPIC 2.4: PROTEINS

Amino Acids

The monomer of a protein is called an amino acid
- Amino acids are linked together to form polypeptides

There are 20 different amino acids that form polypeptides
- These can be linked in any sequence to create variation

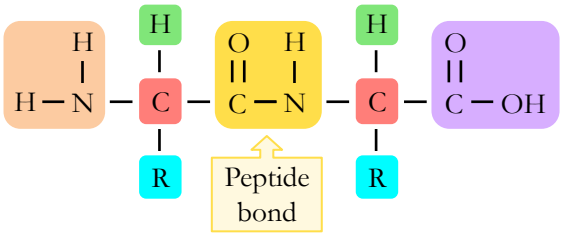


Structure of a Generalised Amino Acid

Peptide Bonds

Amino acids are covalently joined by peptide bonds to form polypeptide chains (requires condensation reactions)

The sequence of amino acids is encoded by genes and the assembly of a polypeptide chain occurs at the ribosome



Structure of a Dipeptide

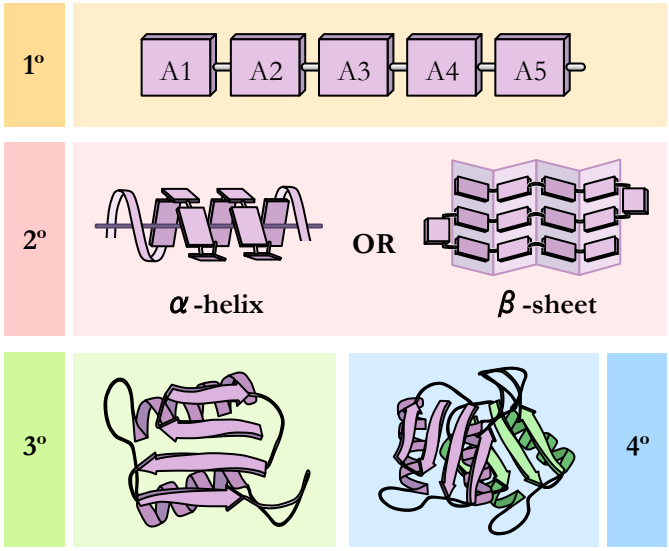
Protein Structure

Primary Structure
- Order of amino acid sequence
- Formed by covalent peptide bonds

Secondary Structure
- Folding into repeat patterns (α-helix or β-pleated sheet)
- By hydrogen bonds between amine and carboxyl groups

Tertiary Structure
- Overall three-dimensional arrangement of a polypeptide
- Determined by interactions between variable side chains

Quaternary Structure *(optional)*
- Presence of multiple polypeptides or prosthetic groups



Functions of Proteins

Proteins are a very diverse class of compounds that may serve a wide range of functions within the cell, including:

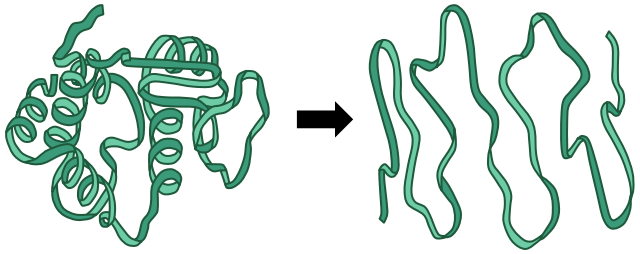
- **S**tructure (collagen, spider silk)
- **H**ormonal (insulin, glucagon)
- **I**mmunity (immunoglobulins)
- **T**ransport (haemoglobin)
- **S**ensation (rhodopsin)
- **M**ovement (actin, myosin)
- **E**nzymatic (Rubisco, catalase)

The totality of all proteins that are expressed within a cell, tissue or organism at a certain time is called the **proteome**
- The proteome of any given individual will be unique as protein expression patterns are influenced by a genome

Denaturation

Denaturation is a structural change in a protein that results in the loss (usually permanent) of its biological properties

Denaturation can be caused by certain conditions:
- **Temperature** (heat may break structural bonds)
- **pH** (alters protein charge ➡ changes solubility & shape)



Folded Protein **Unfolded** *(Denatured)*

TOPIC 2.5: ENZYMES

Catalysis

An enzyme is a globular protein which speeds up the rate of a chemical equation by lowering the activation energy (i.e. it is a biological catalyst)

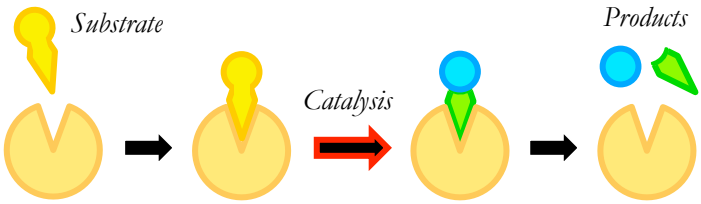
- Enzymes are not consumed by the reactions and can be re-used

The molecule(s) the enzyme reacts with is called the **substrate**, which binds to a complementary region on the enzyme's surface (**active site**)

Specificity

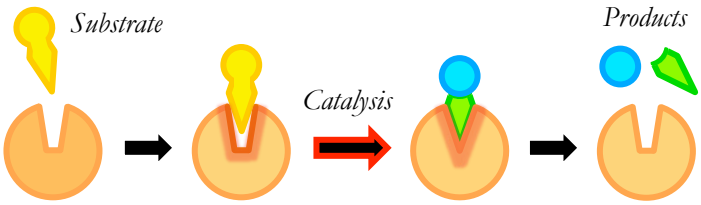
Lock and Key Model

- Enzyme and substrate complement each other precisely in terms of both their shape and chemical properties
- The active site and the substrate will share specificity



Induced Fit Model

- Active site is not a rigid fit for the substrate and changes its conformation to better accommodate the substrate
- This stresses the substrate bonds and induces catalysis



Factors Affecting Enzyme Activity

Temperature

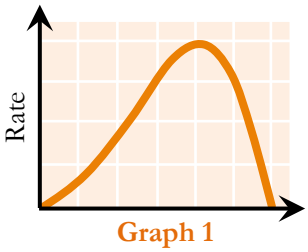
- Increases enzyme activity *(more kinetic energy = more collisions)*
- Enzyme activity peaks at an optimal temperature
- Higher temperatures decrease activity *(causes denaturation)*

pH

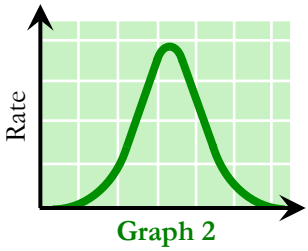
- Enzyme activity is highest at an optimal pH range
- Activity decreases outside of this range *(due to denaturation)*

Substrate Concentration

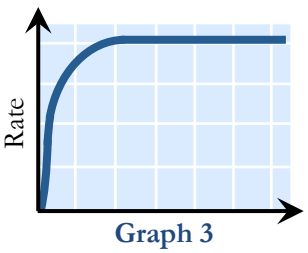
- Increases enzyme activity *(more particles = more collisions)*
- At a certain point, activity plateaus *(saturation of active sites)*



Graph 1



Graph 2



Graph 3

Key:

Graph 1 – *Temperature*

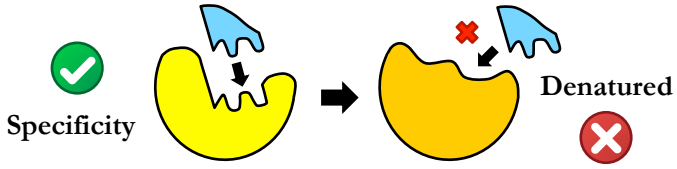
Graph 2 – *pH level*

Graph 3 – *Substrate level*

Enzyme Kinetics

The rate of enzyme catalysis can be increased by increasing the frequency of enzyme-substrate collisions *(molecular motion)*

The rate of enzyme catalysis is decreased by **denaturation**



Industrial Enzymes

Immobilised enzymes are often used in industrial practices

- They are fixed to a static surface to prevent enzyme loss
- This improves separation of product and purity of yield

One application for immobilised enzymes is the production of lactose-free milk and associated dairy products

- Lactase (enzyme) digests lactose into glucose / galactose
- Lactase is fixed to an inert surface (e.g. alginate beads)
- Milk is passed over this surface to become lactose free

There are several benefits associated with lactose-free milk:

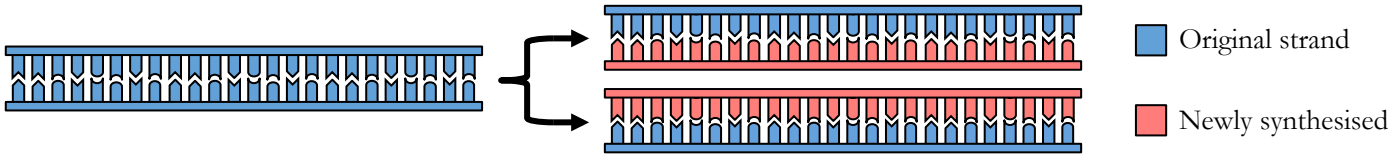
- Provides a source of dairy for lactose-intolerant people
- Increases sweetness of milk (less need for sweeteners)
- Reduces crystallization and production times for cheese

TOPIC 2.7: DNA REPLICATION

Semi-Conservative

DNA replication is semi-conservative – one strand is from an original template molecule and one strand is newly synthesised

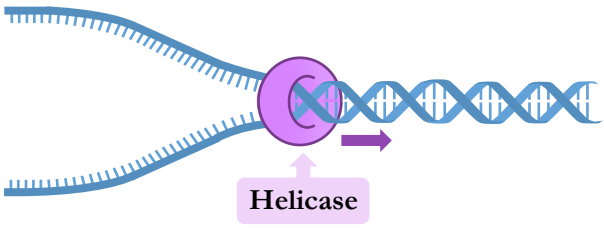
- This occurs because each base will only pair with its complementary partner and thus ensure the sequence is conserved



DNA Replication

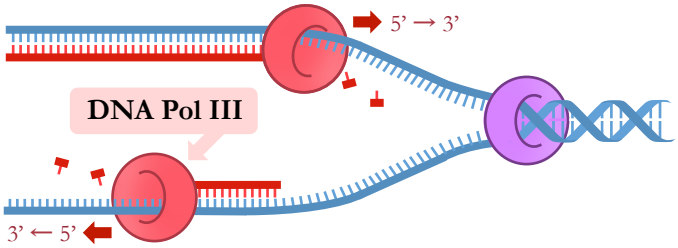
Helicase:

- Unwinds and separates the double stranded DNA
- Breaks the hydrogen bonds between the base pairs



DNA Polymerase III

- Free nucleotides line up opposite complementary partners
- DNA Pol III covalently joins the free nucleotides together



Meselson-Stahl Experiment

The Meselson-Stahl experiment supported the theory that DNA replication occurred via a semi-conservative process

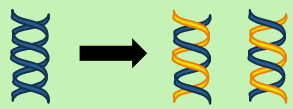
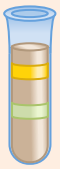
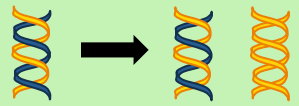
They incorporated radioactive nitrogen isotopes into DNA

- Templates were prepared with heavier ^{15}N
- New sequences were replicated with lighter ^{14}N

The DNA was then separated via centrifugation in order to determine its composition of radioisotopes

- **1st division:** DNA had ^{15}N and ^{14}N (i.e. mixed)
- **2nd division:** DNA is mixed or has ^{14}N only

The results were consistent with a semi-conservative model

	ACTUAL RESULT	SEMI-CONSERVATIVE
1st Division	 N-15 / N-14	 N-15 → Mix (×2)
2nd Division	 N-14 only N-15 / N-14	 Mix → Mix N-14

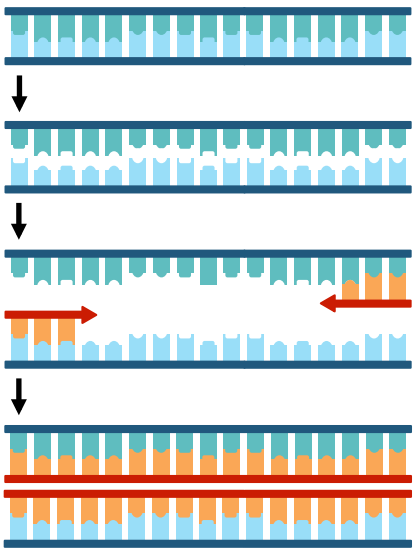
Polymerase Chain Reaction

The polymerase chain reaction (PCR) is an artificial method of DNA replication that is used to rapidly copy sequences

PCR occurs in a thermal cycler over three repeating steps:

- **Denaturation:** DNA heated in order to separate strands
- **Annealing:** Primers attach to ends of a target sequence
- **Elongation:** A heat-tolerant polymerase copies strands

A standard reaction of 30 cycles would generate 2^{30} copies of the target DNA sequence (i.e. >1 billion copies of DNA)



1. Denaturing

Strands separate

(95°C)

2. Annealing

Primers bind

(55°C)

3. Extension

Taq polymerase

(72°C)

TOPIC 2.7: TRANSCRIPTION & TRANSLATION

Transcription

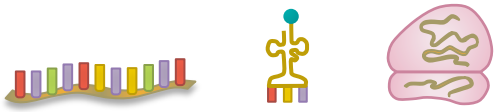
Transcription is the synthesis of an RNA sequence from a DNA template
- This process occurs within the nucleus of a cell

Transcription is mediated by the enzyme RNA polymerase, which:
- Separates the DNA strands (breaks H bonds between base pairs)
- Covalently joins free complementary RNA nucleotides together

After transcription, the RNA is released to the cytoplasm (for translation) and the DNA remains within the nucleus and reforms a double helix

Types of RNA

Three main types of RNA may be produced:
- **mRNA** – Transcript used to make protein
- **tRNA** – Transfers amino acid to ribosome
- **rRNA** – Catalytic component of ribosome



mRNA **tRNA** **rRNA**

Genetic Code

The genetic code is the set of rules by which information encoded in mRNA sequences is converted into a polypeptide sequence

Codons: Triplets of bases which correspond to a particular amino acid

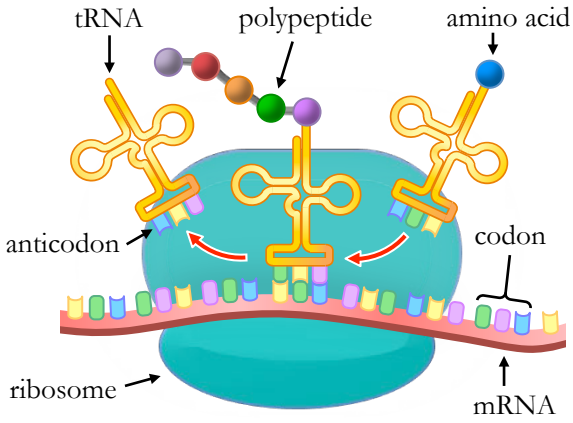
The order of the codons determines the amino acid sequence for a protein
- A coding sequence always begins with a start codon (AUG)
- A coding sequence is terminated with a stop codon

The genetic code has two key features:
- **Universality** – All organisms use the same genetic code
- **Degeneracy** – Multiple codons may code for the same amino acid

UUU	Phe	UCU	Ser	UAU	Tyr	UGU	Cys
UUC		UCC		UAC		UGC	
UUA	Leu	UCA		UAA	STOP	UGA	STOP
UUG		UCG		UAG	STOP	UGG	Trp
CUU	Leu	CCU	Pro	CAU	His	CGU	Arg
CUC		CCC		CAC		CGC	
CUA		CCA		CAA	Gln	CGA	
CUG		CCG		CAG		CGG	
AUU	Ile	ACU	Thr	AAU	Asn	AGU	Ser
AUC		ACC		AAC		AGC	
AUA		ACA		AAA	Lys	AGA	Arg
AUG	Met	ACG		AAG		AGG	
GUU	Val	GCU	Ala	GAU	Asp	GGU	Gly
GUC		GCC		GAC		GGC	
GUA		GCA		GAA	Glu	GGA	
GUG		GCG		GAG		GGG	

Translation

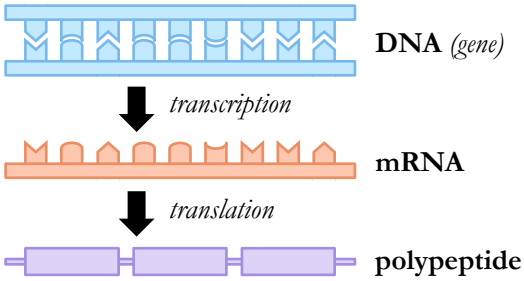
Translation is the process of polypeptide synthesis by the ribosome
- Messenger RNA (mRNA) is transported to the ribosome
- A ribosome reads an mRNA sequence in base triplets called codons
- Each codon codes for a specific amino acid (as per the genetic code)
- Amino acids are transported to ribosomes by transfer RNA (tRNA)
- Each tRNA aligns opposite a codon via a complementary anticodon
- The ribosome moves along the mRNA sequence (5' → 3') and joins amino acids together with peptide bonds (condensation reaction)
- The synthesis of a polypeptide is initiated at a start codon (AUG) and is completed when the ribosome reaches a STOP codon



Gene → Protein

A gene is a sequence of DNA which encodes a polypeptide sequence
- One gene = one polypeptide (proteins may have multiple polypeptides)

There are exceptions to this fundamental relationship:
- Genes may be alternatively spliced (one gene = many polypeptides)
- Genes encoding tRNA or rRNA are transcribed but not translated
- Genes may be mutated to alter the original polypeptide product



TOPIC 3.1: GENES

Genes versus Alleles

A **gene** is a heritable factor that consists of a sequence of DNA and influences a specific trait

- The position of a gene on a chromosome is the **locus**

Alleles are the alternate forms of a gene that code for the different variations of a specific trait

- Alleles for a specific gene will differ by only a few bases

New alleles may be formed as a result of gene mutations

Genome

A **genome** describes the totality of the genetic information in an organism

- It includes all genes and non-coding sequences

The Human Genome Project was completed in 2003 and mapped the entire base sequence of human genes

- Human cells typically have 46 chromosomes
- The human genome consists of ~3 billion base pairs
- It contains roughly 21,000 genes (although estimates vary)

The genomes of other organisms are now being sequenced

Mutations

A **gene mutation** is a change in the base sequence of a section of DNA coding for a particular characteristic

- Gene mutations may be beneficial, detrimental or neutral

Gene mutations may be described as either:

- Somatic – Occurs in a body cell and affects a tissue
- Germline – Occurs in a gamete and affects offspring

Point mutations may include either:

- Substitutions (either silent, missense or nonsense)
- Frameshifts (insertions or deletions)

Mutations can arise spontaneously as copying errors during DNA replication or can be induced by mutagenic agents

		Point Mutation		
Original Sequence		*Silent*	*Missense*	*Nonsense*
DNA	TTC	TT**T**	T**C**C	**A**TC
RNA	AAG	AA**A**	A**G**G	**U**AG
Protein	Lys	Lys	Arg	**STOP**

Genetics Comparisons

There is no clear correlation between genetic complexity and chromosome numbers, genome size or the number of genes

Species	Diploid Number	Genome Size (Mb)	Gene Count	
Virus *T4 Phage*	n/a	0.17	280	
Bacteria *E. coli*	n/a	4.6	4200	
Fruit Fly *D. melanogaster*	8	130	13,000	
Roundworm *P. equorum*	4	185	14,000	
Rice *O. sativa*	24	470	38,000	
Canopy Plant *P. japonica*	40	150,000	?	
Dog *C. familiaris*	78	2,900	20,000	
Chimpanzee *P. troglodytes*	48	3,300	22,000	
Human *H. sapiens*	46	3,200	21,000	

Sickle Cell Anemia

Cause of Sickle Cell Anemia:

Base substitution: GAG → GUG (6th codon: hemoglobin beta)

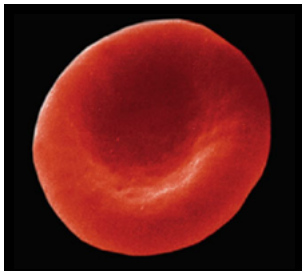
Amino acid change: Glutamic acid → Valine (Glu → Val)

Consequences of Sickle Cell Anemia:

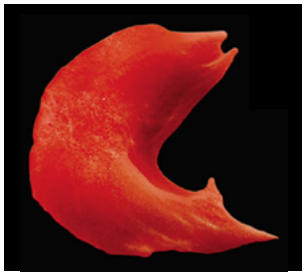
- Alters haemoglobin structure (forms insoluble strands)
- Cannot transport oxygen effectively (causing fatigue)
- Red blood cells adopt a sickle shape (may form clots)
- Sickle cells are destroyed at a higher rate (causes anemia)

Heterozygous Advantage:

- Sickle cell anemia is a codominant trait and heterozygous individuals demonstrate an increased resistance to malaria



Normal Blood Cell



Sickle Blood Cell

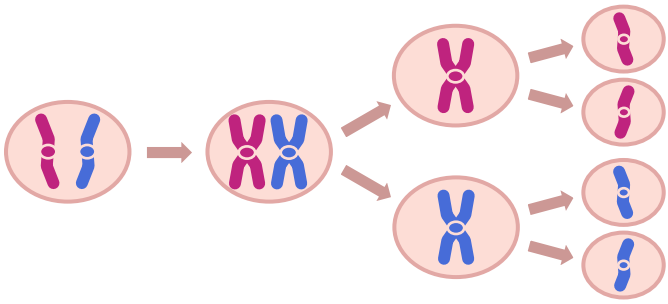
TOPIC 3.3: MEIOSIS

Meiosis

Meiosis is the reduction division of a diploid cell to produce four haploid cells (gametes) that are genetically distinct

It involves two divisions:

- Meiosis I separates homologous chromosomes
- Meiosis II separates sister chromatids



Interphase | Meiosis I | Meiosis II

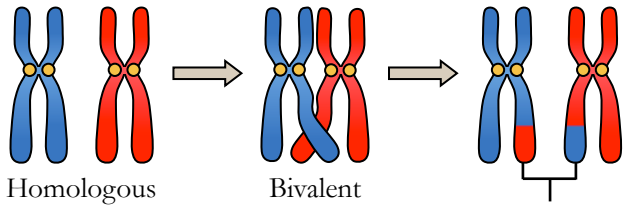
Mitosis versus Meiosis

Hint: Disco Pug	Mitosis	Meiosis
***D**ivisions*	One	Two
***I**ndependent Assortment*	No	Yes *(Metaphase I)*
***S**ynapsis*	No	Yes *(bivalents / tetrads)*
***C**rossing Over*	No	Yes *(Prophase I)*
***O**utcome*	Two cells	Four cells
***P**loidy*	Diploid → Diploid	Diploid → Haploid
***U**se*	Body cells	Sex cells (gametes)
***G**enetics*	Identical (clones)	Genetic variation

Genetic Variation

Crossing Over

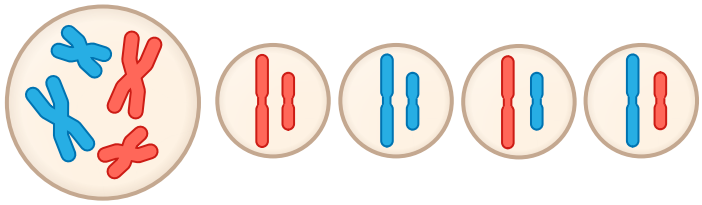
- Crossing over occurs via synapsis in Prophase I
- Homologous chromosomes form bivalents (or tetrads)
- Chiasmata represent the points where genetic information has been exchanged between the homologous pair
- The non-sister chromatids that have exchanged DNA are called recombinants



Homologous chromosomes | Bivalent (+ chiasma) | Recombinants

Random Assortment

- The homologous pairs orient randomly in Metaphase I
- This means there is an equal chance of a resulting gamete containing either the maternal or paternal chromosome
- As humans have a haploid number of 23, consequently there are 2^{23} potential gamete combinations (>8 million)

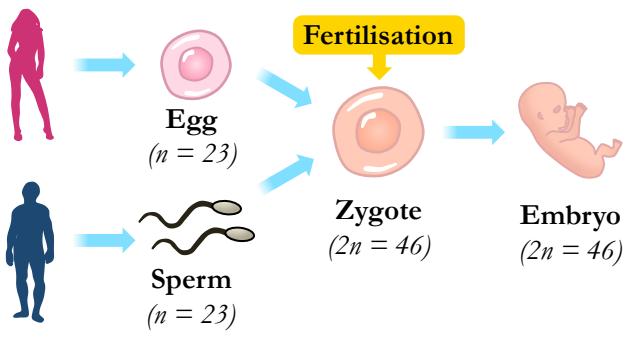


Parent Cell | Potential Gamete Combinations

Sexual Life Cycle

The halving of chromosome number by meiosis allows for a sexual life cycle with the fusion of gametes

- This acts as a further source of genetic variation



Non-Disjunction

Non-disjunction refers to chromosomes failing to separate, resulting in gametes with extra or missing chromosomes

The failure to separate may involve the homologous pairs in Anaphase I or the sister chromatids in Anaphase II

If a gamete with an extra chromosome fuses with a normal gamete, the resulting zygote will have three copies

- E.g. Trisomy 21 (Down Syndrome)

Studies show parental age influences chances of non-disjunction

- Older parents are at a higher risk of non-disjunction events

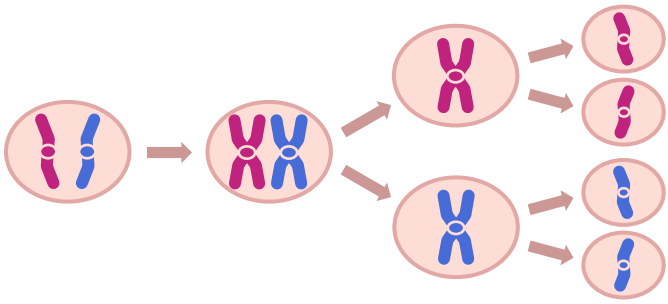
TOPIC 3.3: MEIOSIS

Meiosis

Meiosis is the reduction division of a diploid cell to produce four haploid cells (gametes) that are genetically distinct

It involves two divisions:

- Meiosis I separates homologous chromosomes
- Meiosis II separates sister chromatids



Interphase | Meiosis I | Meiosis II

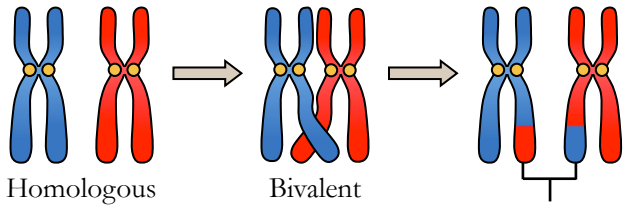
Mitosis versus Meiosis

Hint: Disco Pug	Mitosis	Meiosis
***D**ivisions*	One	Two
***I**ndependent Assortment*	No	Yes *(Metaphase I)*
***S**ynapsis*	No	Yes *(bivalents / tetrads)*
***C**rossing Over*	No	Yes *(Prophase I)*
***O**utcome*	Two cells	Four cells
***P**loidy*	Diploid → Diploid	Diploid → Haploid
***U**se*	Body cells	Sex cells (gametes)
***G**enetics*	Identical (clones)	Genetic variation

Genetic Variation

Crossing Over

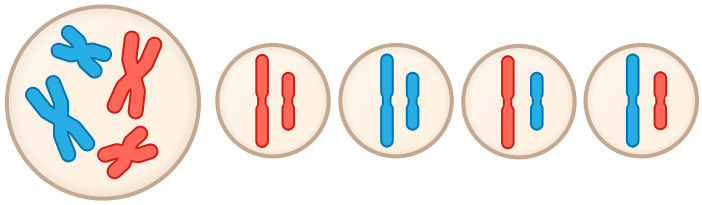
- Crossing over occurs via synapsis in Prophase I
- Homologous chromosomes form bivalents (or tetrads)
- Chiasmata represent the points where genetic information has been exchanged between the homologous pair
- The non-sister chromatids that have exchanged DNA are called recombinants



Homologous chromosomes | Bivalent (+ chiasma) | Recombinants

Random Assortment

- The homologous pairs orient randomly in Metaphase I
- This means there is an equal chance of a resulting gamete containing either the maternal or paternal chromosome
- As humans have a haploid number of 23, consequently there are 2^{23} potential gamete combinations (>8 million)

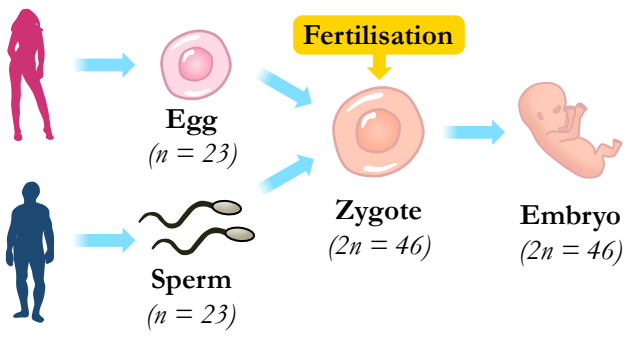


Parent Cell | Potential Gamete Combinations

Sexual Life Cycle

The halving of chromosome number by meiosis allows for a sexual life cycle with the fusion of gametes

- This acts as a further source of genetic variation



Non-Disjunction

Non-disjunction refers to chromosomes failing to separate, resulting in gametes with extra or missing chromosomes

The failure to separate may involve the homologous pairs in Anaphase I or the sister chromatids in Anaphase II

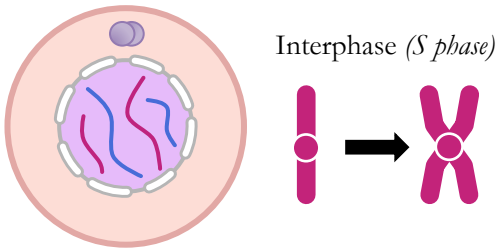
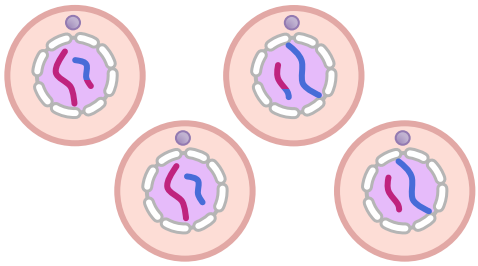
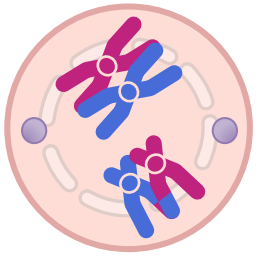
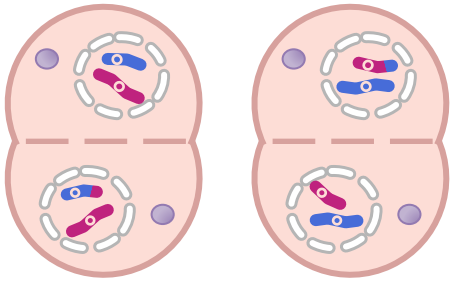
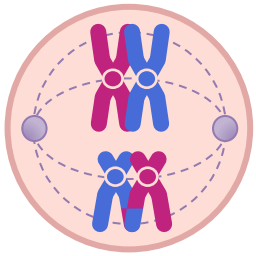
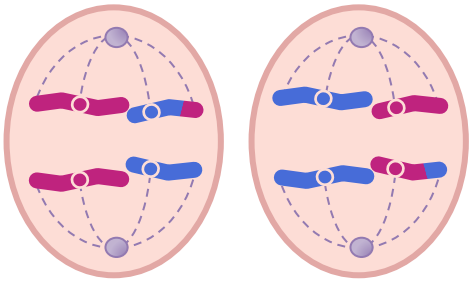
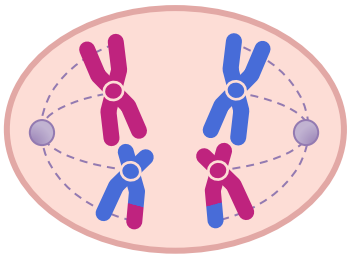
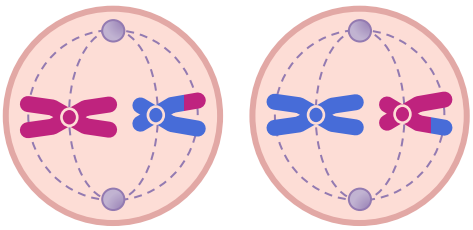
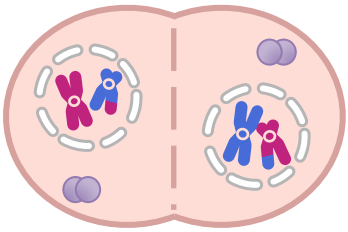
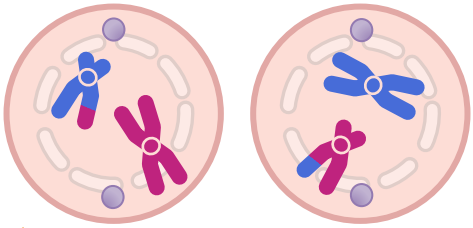
If a gamete with an extra chromosome fuses with a normal gamete, the resulting zygote will have three copies

- E.g. Trisomy 21 (Down Syndrome)

Studies show parental age influences chances of non-disjunction

- Older parents are at a higher risk of non-disjunction events

TOPIC 3.3: STAGES OF MEIOSIS

Stage	Diagram	Diagram	Stage
Before (1 × 2n)			**After** (4 × n)
Prophase I (2n)			**Cytokinesis** (2n → n) × 4 **Telophase II** (2n) × 2
Metaphase I (2n)			**Anaphase II** (n → 2n) × 2
Anaphase I (2n)			**Metaphase II** (n) × 2
Telophase I (2n) **Cytokinesis** (2n → n) × 2			**Prophase II** (n) × 2

Meiosis I Summary	Meiosis II Summary
• Is a reduction division (diploid → haploid) • Separates the homologous chromosomes • Crossing over may occur during Prophase I to create genetically divergent sister chromatids	• Is akin to a mitotic division (but of haploid cells) • Separates the sister chromatids • Occurs because DNA is replicated in interphase to create chromosomes with sister chromatids

TOPIC 3.4: INHERITANCE PATTERNS

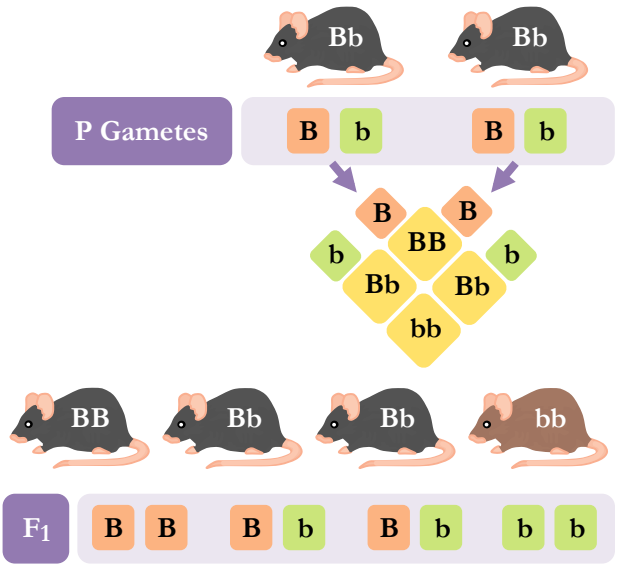
Monohybrid Crosses

A monohybrid cross determines the allele combinations for potential offspring for **one** gene only

- Crosses can be represented via the use of Punnett grids

Monohybrid crosses are calculated via the following steps:

- Designate letters to represent alleles (e.g. A, a)
- Identify genotype / phenotype of parents (P generation)
- Determine genotype of gametes (haploid)
- Work out gamete combinations with a Punnett grid
- Identify ratios of offspring (F_1 generation)



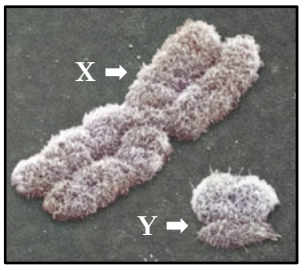
Sex Linkage

Sex linkage refers to when a gene is on a sex chromosome

- **I.e.** X or Y (all other chromosomes are autosomal)

Sex chromosomes (X/Y)

- **Y** chromosome is short and has few genes (<100)
- **X** chromosome is large with many genes (~2000)



Sex-Linked Traits

Sex-linked traits have altered inheritance patterns:

- Males have a higher rate of X-linked recessive conditions as they cannot mask the recessive allele (are hemizygous)
- Females can be **carriers** for X-linked recessive conditions (heterozygotes can carry the allele but not express it)

For X-linked conditions:

- *Recessive:* Affected mothers must have affected sons
- *Dominant:* Affected fathers must have affected daughters

Examples of X-linked recessive traits include:

- Haemophilia (cannot clot blood properly)
- Red-green colour blindness

Modes of Inheritance

A pedigree is a chart of genetic history over several generations

In a typical pedigree chart:

- Males are represented as squares, while females as circles
- Shaded symbols denote individual has a specified condition
- A horizontal line between man and woman represents mating
- Offspring numbered from left to right according to age

Autosomal Dominance:

- If both parents are affected by a trait and any offspring is not, the trait must be dominant (parents must be heterozygous)

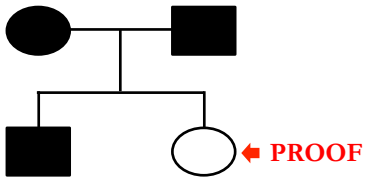
Autosomal Recessive:

- If neither parents is affected by a trait but any offspring is, the trait must be recessive (parents must be heterozygous)

Sex-Linked Traits:

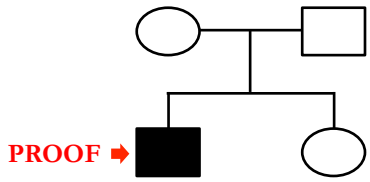
- No way to conclusively prove sex-linkage with a pedigree chart, but certain patterns may suggest the possibility

AUTOSOMAL DOMINANT



Not recessive as two affected parents could *not* have an unaffected offspring

AUTOSOMAL RECESSIVE



Not dominant as two unaffected parents could *not* have an affected offspring

TOPIC 3.4: MODES OF INHERITANCE

Principles of Inheritance

Gregor Mendel established the principles of inheritance via experimentation (he crossed large numbers of pea plants)

His findings pioneered current scientific understanding:

- Organisms have heritable factors (genes)
- Parents contribute equally to inheritance by supplying one version of the gene each (alleles)
- Gametes contain only one allele of each gene (haploid)
- Fusion of gametes results in zygotes with two alleles of each gene (diploid)

It is now known that the separation of the two alleles of each gene into separate haploid gametes occurs via meiosis

Genotype versus Phenotype

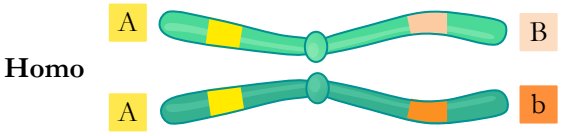
A **genotype** is the allele combination for a specific trait

There are three possible types of allele combinations:

- *Homozygous* – Both alleles are the same (e.g. AA)
- *Heterozygous* – Alleles are different (e.g. Aa)
- *Hemizygous* – Only one allele (e.g. X/Y genes in males)

A **phenotype** is the physical expression of a specific trait

- It is determined by genotype *and* environmental factors



Modes of Inheritance

Complete Dominance

One allele is expressed over another

- Dominant allele is expressed in heterozygote (capital letter)
- Recessive allele is masked in heterozygote (lower case letter)

A recessive phenotype can only be expressed in homozygotes

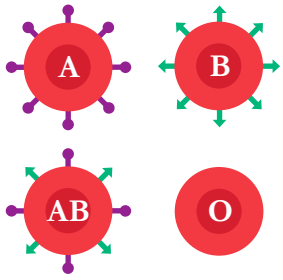
- Heterozygotes will display the dominant phenotype

Phenotype	Black	Black	Brown
Genotype	BB	Bb	bb

Codominance

Both alleles are equally expressed in the phenotype

- Heterozygotes have a distinct phenotype (superscript letter)
- An example of codominance is the ABO blood system

Blood Type	Genotype	Phenotypes
A	$I^A I^A$ *or* $I^A i$	
B	$I^B I^B$ *or* $I^B i$	
AB	$I^A I^B$	
O	i i	

Genetic Diseases

Genetic diseases can be due to recessive, dominant or codominant alleles

- Recessive conditions are most common, as heterozygotes are carriers

Autosomal Recessive

- Cystic fibrosis is caused by a mutated CFTR gene (chromosome 7)
- Produces thick mucus that clogs airways and causes respiratory issues

Autosomal Dominant

- Huntington's disease is caused by a mutated HTT gene (chromosome 4)
- An amplification of CAG repeats (>40) leads to neurodegeneration

Autosomal Codominant

- Sickle cell anemia is caused by a mutated HBB gene (chromosome 11)
- Sickling of blood cells leads to anemia and other complications

Radiation Exposure

Radiation and mutagenic chemicals increase mutation rates and can cause genetic diseases

- Most genetic diseases in humans are rare

Two examples of radiation exposure are:

- Nuclear bombing of Hiroshima (1945)
- Accident / meltdown in Chernobyl (1986)

Some long-term consequences included:

- An increased incidence of cancer
- Reduced immunity (⬇ T cell count)
- Congenital abnormalities (Chernobyl only)
- A variety of organ-specific health effects (e.g. liver cirrhosis, cataract induction, etc)

TOPIC 3.5: CLONING

Clones

Clones are groups of genetically identical organisms, derived from a single original parent cell

- Various methods of cloning exists for animals and plants, while humans can also clone organisms or tissues artificially

Animal Cloning

Binary Fission

- The parental organism divides equally into two clones
- Occurs in flatworms (also used by bacteria and protists)

Budding

- Cells split off from parent, generating smaller clones
- Occurs in Hydra, but is also common to yeast

Fragmentation

- New organisms grow from separated fragment of parent
- Common to starfish and some species of annelid worm

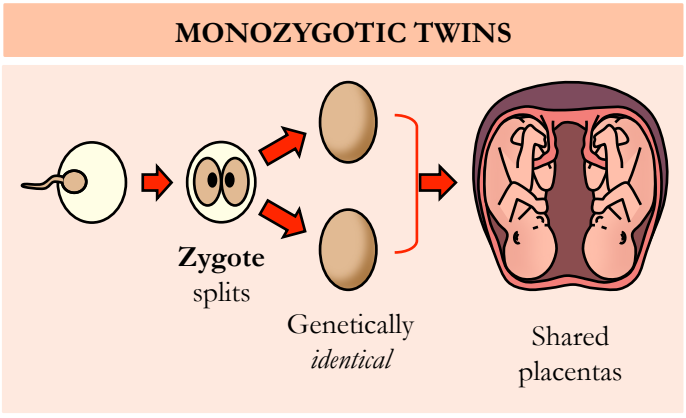
Parthenogenesis

- Embryos formed from an unfertilised (diploid) ova
- Occurs in some species of fish, insect, reptile, amphibian

Human Cloning

Humans can also produce clones via natural mechanisms

- Identical twins (monozygotic) are created when fertilised eggs split in two, forming two identical embryos



Plant Cloning

Plants have the capacity for vegetative propagation, whereby small pieces of plant can be induced to grow independently

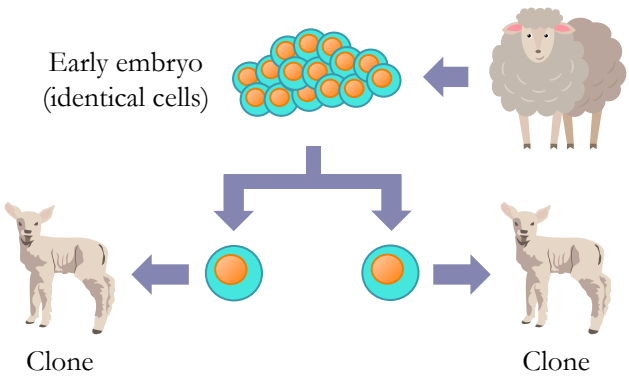
- This is because adult plants possess totipotent meristematic tissue capable of cellular differentiation

A **stem cutting** is a separated portion of a plant stem that is used to regrow a new clone via vegetative propagation

Artificial Cloning

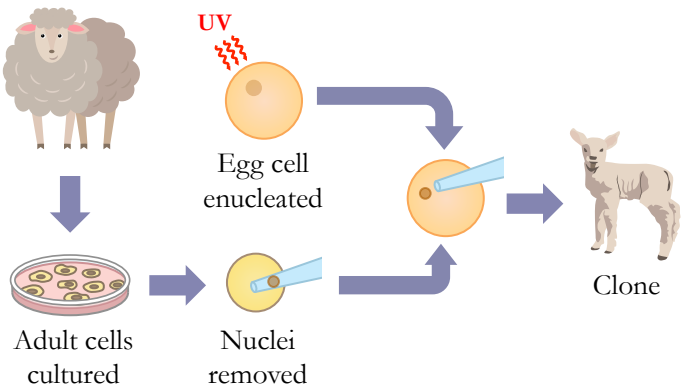
Embryo Cloning

- Animals can be cloned from an embryo by separating the embryonic cells into groups
- As embryonic stem cells are pluripotent, each cell can potentially form a cloned offspring
- As this method occurs after random fertilization, it is not possible to control the genetic features of potential clones



Adult Cloning

- Adults can be cloned via the process of somatic cell nuclear transfer (SCNT)
- The nucleus is removed from an adult body cell (diploid) and fused with an enucleated egg cell
- An electric shock stimulates division of the egg cell and the growing embryo is implanted into a surrogate



TOPIC 3.5: GENETIC MODIFICATION

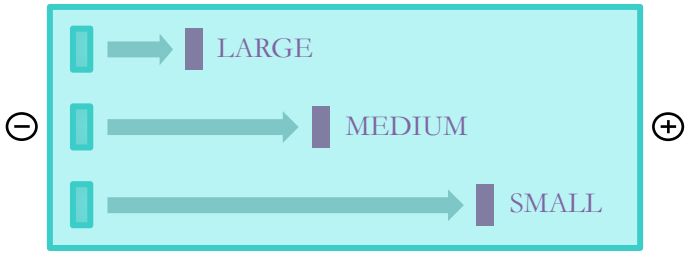
Gel Electrophoresis

Gel electrophoresis is a technique that separates proteins or fragments of DNA according to size

- Samples placed in a block of gel and current is applied
- Smaller samples move faster through the gel (⬇ resistance)

Samples will move towards the positive terminus (anode)

- DNA is negatively charged (due to phosphate group)
- Proteins are treated with an anionic detergent in order to impart a uniform negative charge on all molecules



Gene Transfer

Gene transfer can occur because the genetic code is *universal*

Step 1: DNA Extraction

- Gene of interest isolated from organism
- Gene is amplified using PCR (along with a plasmid)

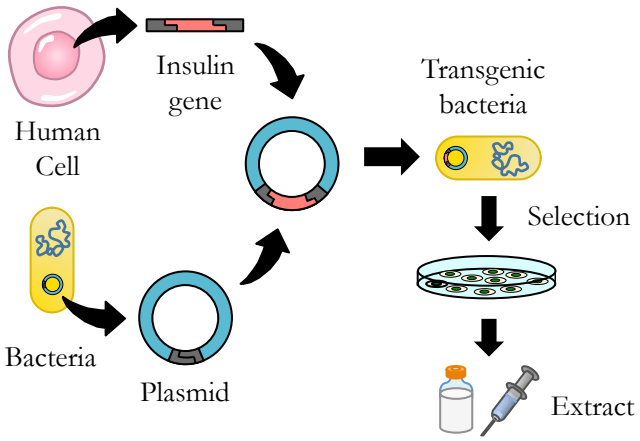
Step 2: Digestion and Ligation

- Plasmid and gene cut with a specific restriction enzyme
- Gene is spliced into plasmid vector by DNA ligase

Step 3: Transformation and Expression

- Recombinant plasmid is inserted into a host cell
- Antibiotic selection may be used to select for successful transgenic cells (if plasmid has an antibiotic resistance gene)
- Transgenic cells express new protein (for extraction / use)

Example: Production of Human Insulin in Bacteria



DNA Profiling

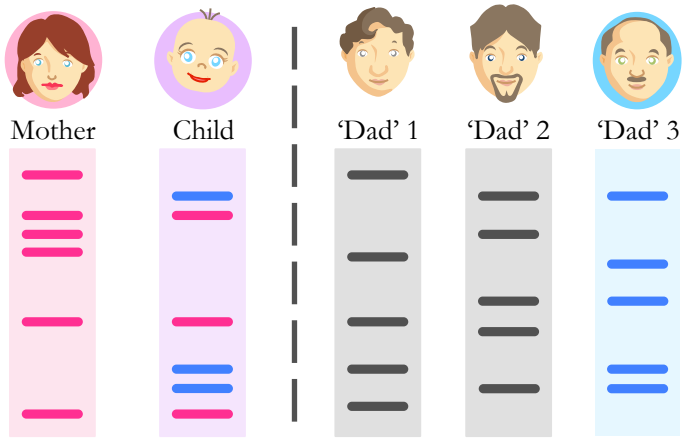
DNA profiling is a technique by which individuals can be identified and compared by their genetic sequences

- Individuals have different lengths of particular DNA segments called short tandem repeats (STR)
- These segments are amplified by PCR and then separated by gel electrophoresis for comparison
- Unique profiles appear when multiple loci are compared

DNA profiling is commonly used for:

- Forensic investigations (matching suspect to the crime scene)
- Paternity tests (offspring STRs are a combination of parents)

Sample Paternity Test



GMO Debate

Benefits of GM Crops:

- Could be used to improve nutritional standards
- Can grow in a wide range of environments (⬆ yields)
- Could reduce farming costs and associated deforestation
- Can be used to reduce spoilage (longer shelf life)

Risks of GM Crops:

- Could trigger unexpected health issues (e.g. allergies)
- Patent protections could restrict access (equity issues)
- Possible cross-pollination with weeds (hard to contain)
- Could compete with native plants (reduce biodiversity)

Example of GM Crop:

- Bt corn is a transgenic crop that produces an insecticide (*B. thuringiensis* toxin kills European corn borer insect)
- Bt corn may be impacting survival of monarch butterflies
- In lab conditions, butterfly mortality is higher when fed plants dusted with Bt pollen, however there is insufficient field evidence to support this (diet not naturally restricted)

TOPIC 4.1: CHI-SQUARED TEST

Worked Example

A chi-squared test can be applied to quadrat sampling data to determine if there is a statistically significant association between the distribution of two species

Case Study: Scallops on a Rocky Shore

The presence / absence of two scallop species is recorded in 50 quadrats ($1m^2$)

The following distribution was found:

- 6 quadrats = both species
- 20 quadrats = queen scallop only
- 15 quadrats = king scallop only
- 9 quadrats = neither species

		QUEEN		
		Present	Absent	Total
KING	Present	6	15	**21**
	Absent	20	9	**29**
	Total	**26**	**24**	50

Step 1: Identify Expected Frequencies

There are two distinct possibilities regarding associations between the two species:

- *Null Hypothesis (H_0)* – There is **no** association (i.e. distribution is random)
- *Alternative Hypothesis (H_1)* – There **is** an association (positive or negative)

A table must be constructed that identifies *expected* frequencies of distribution

- This data will be compared against the *observed* values previously identified

The expected frequencies can be calculated using the following formula:

- Expected frequency = (Row total × Column total) ÷ Grand total

		QUEEN		
		Present	Absent	Total
KING	Present	$\frac{21 \times 26}{50}$	$\frac{21 \times 24}{50}$	**21**
	Absent	$\frac{29 \times 26}{50}$	$\frac{29 \times 24}{50}$	29
	Total	**26**	24	**50**

Step 2: Apply the Chi-Squared Formula

The chi-squared (χ^2) formula calculates a value based on a comparison of the observed frequencies (O) and the expected frequencies (E)

$$\chi^2 = \sum \frac{(O - E)^2}{E}$$

Based on the worked example, the value calculated by the chi-squared test is:

- $\chi^2 = 2.20 + 2.38 + 1.59 + 1.73 =$ **7.90**

A degree of freedom *(df)* will also be required to determine statistical significance

- **df** = (number of rows – 1) × (number of columns – 1)

Raw data table had two rows and two columns, so degree of freedom equals **one**

			QUEEN	
			Present	Absent
KING	Present	O	6	15
		E	10.9	10.1
		$\frac{(O - E)^2}{E}$	2.20	2.38
	Absent	O	20	9
		E	15.1	13.9
		$\frac{(O - E)^2}{E}$	1.59	1.73

Step 3: Determine Significance

The chi-squared value is used to determine statistical significance (p value)

- $p<0.05$ is considered significant (less than 5% likelihood results due to chance)

Based on the worked example, a value of 7.90 lies above a p value of 0.01

- This means results are significant (less than 1% probability it is due to chance)

The null hypothesis can be rejected and the alternative hypothesis accepted

Because the species do not tend to co-exist, we might infer a negative association

		df
		1
p value	0.01	6.635
	0.05	3.841
	0.1	2.706

Values that are greater than this are statistically significant

TOPIC 4.1: SPECIES → ECOSYSTEMS

Ecological Organisation

Species:
A group of organisms that can interbreed and produce fertile, viable offspring

Population:
Group of organisms of the same species, living in the same area at the same time

Community:
A group of different populations living together and interacting in a given area

Habitat:
The environment in which a species lives or the normal location of an organism

Ecosystem:
A community and also its environment (all biotic and abiotic factors)

Modes of Nutrition

Living organisms can obtain chemical energy by one of two methods of nutrition (a few species can use both methods):

Autotrophs

Autotrophs synthesise organic molecules from inorganic nutrients within the environment, using energy from either:

- Light (photoautotrophs)
- Oxidation reactions (chemoautotophs)

Heterotrophs

Heterotrophs obtain their organic molecules from other organisms via a variety of feeding methods and food sources

- Consumers ingest other living organisms
- Detritivores ingest detritus (decomposing matter and faeces)
- Saprotrophs externally digest dead organisms *(decomposers)*

Autotrophs are commonly referred to as **producers**, as they are responsible for the production of organic molecules

- Heterotrophs could not survive without autotrophs

Nutrient Cycling

Nutrients are materials required by organisms for survival

The supply of inorganic nutrients within the environment is finite and therefore must be constantly recycled:

- Autotrophs convert inorganic nutrients into organic molecules (i.e. they are producers)
- Heterotrophs ingest organic molecules and may release inorganic byproducts (e.g. carbon dioxide)
- Saprotrophs break down the nutrients in dead organisms and return them to the soil (i.e. they are decomposers)

Mesocosms

Ecosystems have the potential to be sustainable over long periods of time, however this requires three conditions:

- Energy availability (e.g. light source)
- Nutrient availability (e.g. decomposers)
- Waste recycling (e.g. detoxifying bacteria)

Mesocosms are enclosed environments with controlled conditions (e.g. terrariums)

- They can be used to study sustainability

Species Associations

The presence of species in a habitat may be dependent on the interactions between them (either positive or negative)

If species are always found in the same habitat, this suggests a **positive association** (such as):

- Predator / prey relationships
- Symbiotic interaction (mutualism, commensalism, parasitism)

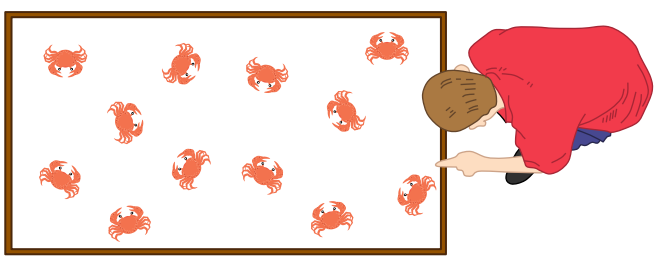
If species do not share the same habitat, this suggests there is a **negative association** (such as):

- Competition (niche partitioning or competitive exclusion)

Quadrat Sampling

The presence of a species in a given area can be determined via quadrat sampling (to assess sessile/non-motile species)

- Rectangular frame placed in an area (+ repeat sampling)
- Species numbers within the frame are counted/estimated



TOPIC 4.2: ENERGY FLOW

Energy Flow

Energy Source

Light is the initial energy source for *almost* all communities

- Some producers derive energy from chemical processes

Light energy is converted into chemical energy (i.e. organic compounds) via the process of **photosynthesis**

Energy Transfer

Heterotrophs obtain their chemical energy by feeding

- The energy stored in organic molecules is released via **cellular respiration** (in heterotrophs *and* autotrophs)

Trophic Levels

An organism's trophic level refers to the position it occupies within a feeding sequence

- Producers always occupy the first trophic level

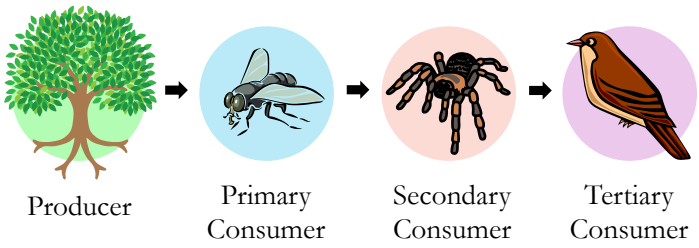
Trophic Level	Organism
1	Producer
2	Primary Consumer
3	Secondary Consumer
4	Tertiary Consumer

Feeding Patterns

Food Chains

Food chains show linear feeding patterns between the species in a community

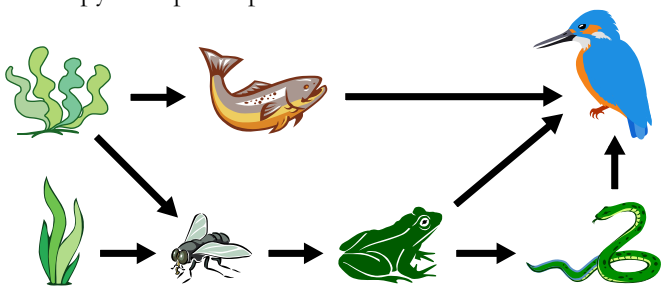
- Arrows indicate the direction of energy flow



Food Webs

Food webs show interrelated feeding patterns

- Most species have multiple food sources and hence will occupy multiple trophic levels



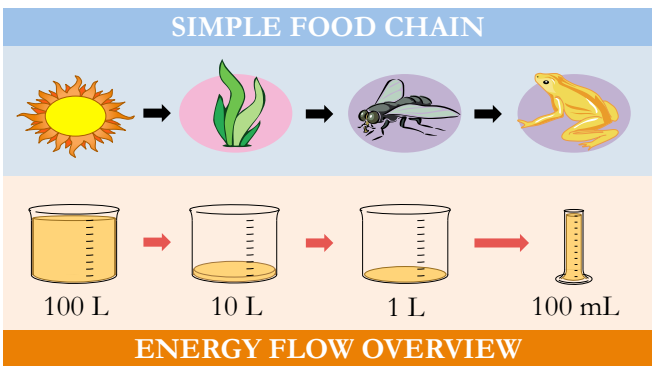
Energy Loss

Not all the stored energy is transferred upon feeding – most of the energy released via cell respiration is lost as **heat**

- Organisms cannot convert heat into other energy forms and hence the heat is lost from the ecosystem

Only ~10% of energy is transferred from one trophic level to the next (90% is lost as heat or is unconsumed)

- These energy losses restrict the length of food chains and limit the biomass of higher trophic levels



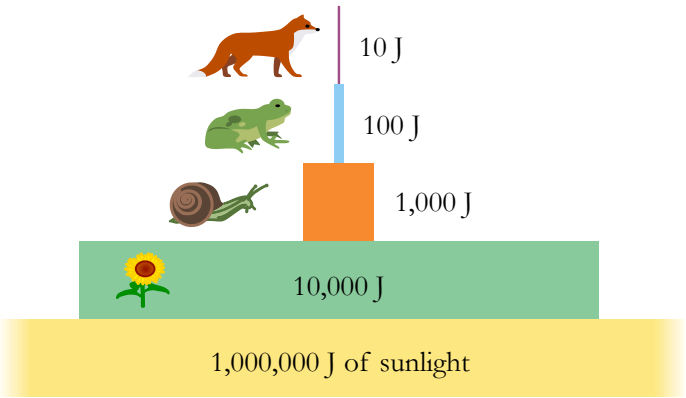
Pyramids of Energy

Pyramids of energy are representations of the amount of energy available at each trophic level

- Measured in energy units per area per time (kJ m^2 $year^{-1}$)

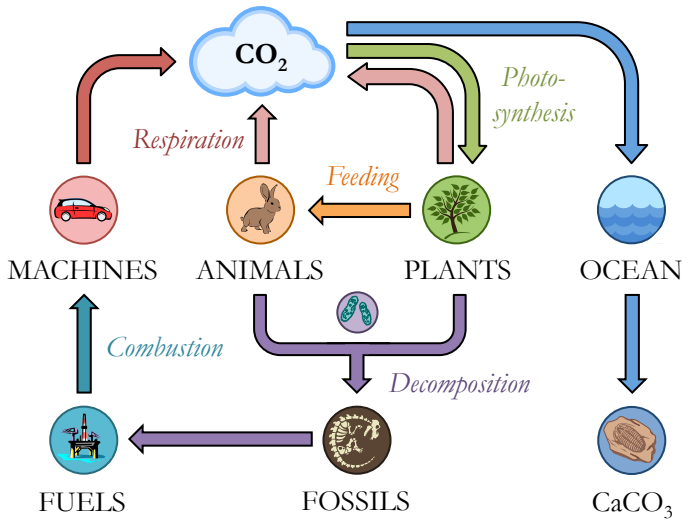
Pyramids of energy can never be inverted and their levels should differ by a factor of ~10

- Because energy transformations are ~10% efficient



TOPIC 4.3: CARBON CYCLING

Carbon Cycle



Fossil Fuels

In *aerobic conditions*, saprotrophic bacteria will break down organic material and return it to the soil (i.e. decomposition)

In *anaerobic conditions*, decomposition is prevented as the saprotrophic bacteria cannot function effectively

- Anaerobic respiration will produce organic acids (⬇ ph)

Peat / Coal

- Organic matter that is not fully decomposed in anoxic or acidic soils will become peat
- When peat is compressed under layers of sediment, heat and pressure remove moisture to transform it into coal

Oil / Natural Gas

- When marine organisms are buried under sediment on the ocean floor, compaction and anaerobic conditions transform the organic matter into oil and natural gas

Combustion

Hydrocarbons undergo combustion in the presence of O_2

- The reaction is exergonic and CO_2 and H_2O is produced

Sources of hydrocarbons include:

- Fossilised organic matter (i.e. coal, oil and gas)
- Biomass (e.g. bioethanol and biofuels)

The energy produced by combustion reactions is typically used to power industrial processes

- The combustion of fossil fuels is responsible for a significant increase in atmospheric CO_2 concentrations

Organic Conversions

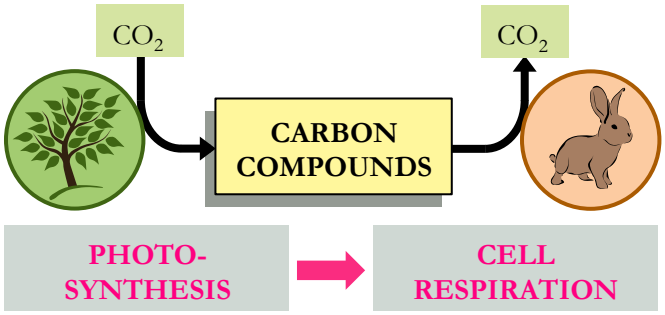
Autotrophs convert atmospheric carbon dioxide into organic compounds via the process of **photosynthesis**

- Equation *(balanced)*: $6CO_2 + 6H_2O \rightarrow C_6H_{12}O_6 + 6O_2$

Heterotrophs obtain organic compounds via **feeding**

The breakdown of organic compounds via **cell respiration** (to produce ATP) releases carbon dioxide as a by-product

- Equation *(balanced)*: $C_6H_{12}O_6 + 6O_2 \rightarrow 6CO_2 + 6H_2O$



Aquatic Conversions

In aquatic ecosystems, carbon dioxide may remain dissolved in water or alternatively form hydrogen carbonate ions

Animals may combine the carbonate ions with calcium to form hard shells (e.g. mollusca) and exoskeletons (e.g. coral)

Carbonate ions may also interact with rock and sediment to form limestone

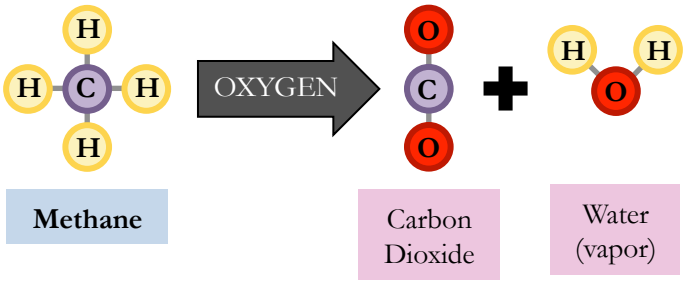
Methane Production

Methane (CH_4) is produced from organic compounds by methanogenic archaeans

This requires **anaerobic conditions** (commonly found in wetlands, marine sediments or digestive tract of ruminants)

Methane diffuses into the air or forms deposits underground

- In the air, methane is oxidised to form CO_2 and H_2O

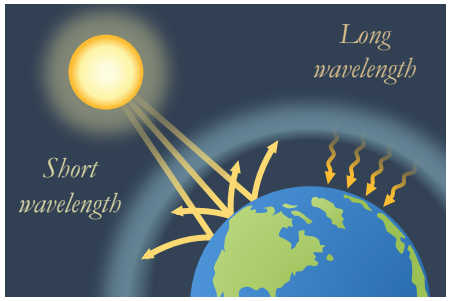


TOPIC 4.4: CLIMATE CHANGE

Greenhouse Effect

Greenhouse gases include carbon dioxide, water vapor, methane & nitrogen oxides
- Their impact depends on their concentration and ability to absorb IR radiation
- Water vapor and carbon dioxide are the most significant greenhouse gases

The greenhouse effect is a natural process that increases average temperatures:
- Incoming radiation from the sun includes short-wave ultraviolet (UV) radiation
- This radiation may be emitted by the Earth as long-wave infrared (IR) radiation
- Greenhouse gases absorb and re-emit this infrared radiation as heat

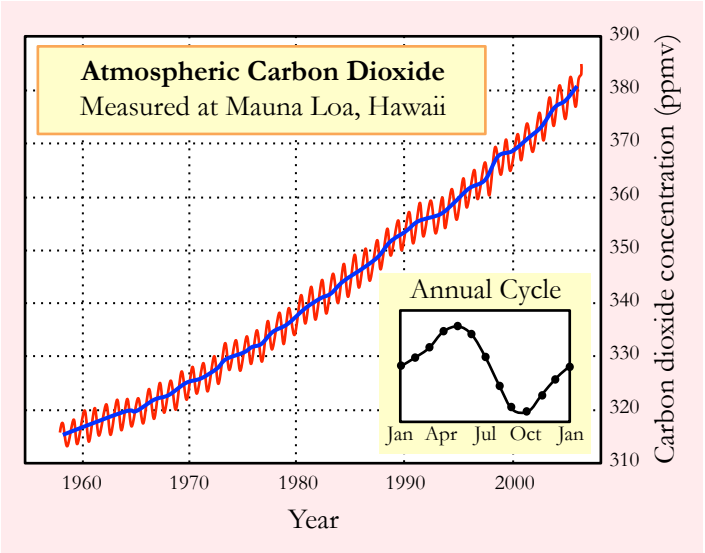


Carbon Dioxide Concentrations

Carbon fluxes describe the amount of carbon transferred between various carbon pools (e.g. lithosphere → atmosphere)

Carbon dioxide concentrations are increasing within the atmosphere due to a number of human-induced activities:
- Industrial practices (i.e. combustion of fossil fuels)
- Deforestation (less CO_2 transferred to the biosphere)
- Agriculture (land clearing and methane production)

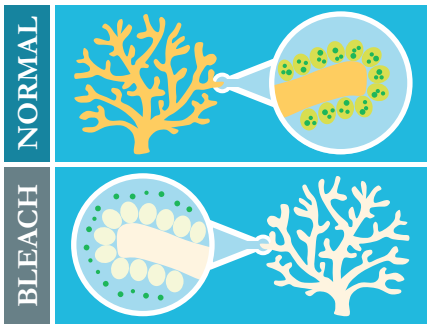
As global temperatures and climate patterns are influenced by greenhouse gases, increasing CO_2 concentrations may be causing global climate change (enhanced greenhouse effect)
- There is a positive correlation between rising CO_2 levels (since industrial revolution) and average global temperature



Ocean Acidification

The oceans are a major carbon sink (i.e. stores CO_2 from the atmosphere)
- Some of the CO_2 remains dissolved, but most of it is chemically converted
- CO_2 is converted into carbonic acid, which dissociates to release H^+ ions

This conversion impacts marine organisms (such as coral) in a number of ways:
- It increases ocean acidity, which can stress coral survival (⬆ H^+ = ⬇ pH)
- It lowers carbonate levels, which is required for shells and exoskeletons
- These conditions can cause coral to expel mutualistic algae (coral bleaching)



Climate Change Debate

Is current climate change natural?

Claim:
Historical data show temperature cycles

Counter:
Past changes were not as abrupt
Ocean levels are rising, pH decreasing

Are greenhouse gases the cause?

Claim:
Changes could be caused by sunspots

Counter:
Climate changes don't match sun activity
CO_2 levels are highest ever recorded

Are climate models reliable?

Claim:
Models may make varying predictions

Counter:
All the climate models are predicting a temperature increase by 2100 (~2–6°C)

TOPIC 5.1: EVIDENCE FOR EVOLUTION

Fossil Record

A fossil is the preserved remain or trace of a past organism

- The totality of all fossils is called the fossil record

Law of Fossil Succession

The fossil record shows that changes have occurred in organisms and these changes have occurred in a consistent sequence of development (the law of fossil succession)

- **Example:** Ferns always appear before flowering plants

Transitional Fossils

Transitional fossils represent intermediary forms within the evolution of a genus and demonstrate species connections

- **Example:** The archaeopteryx links the evolution of birds (wings and feathers) to dinosaurs (jaws and claws)

Selective Breeding

Selective breeding involves the mating of animals with desired characteristics (it is a form of artificial selection)

As human intervention drives selection, changes will occur over fewer generations as phenotype extremes are promoted

Examples of selective breeding include:

- Draft horses (power) versus racing horses (speed)
- Large variation in types of dog breeds

Molecular Evidence

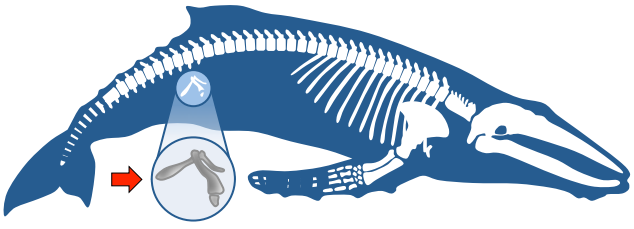
Closely related species share a greater degree of similarity in their DNA and protein sequences (due to common ancestry)

If a particular gene has a stable mutation rate, the time of evolutionary divergence can be estimated ('molecular clock')

Vestigial Structures

Some species show the presence of functionless or reduced remnants of organs that were once present in ancestors

- **E.g.** Whales have a *pelvic bone* (ancestors were terrestrial)



Comparative Anatomy

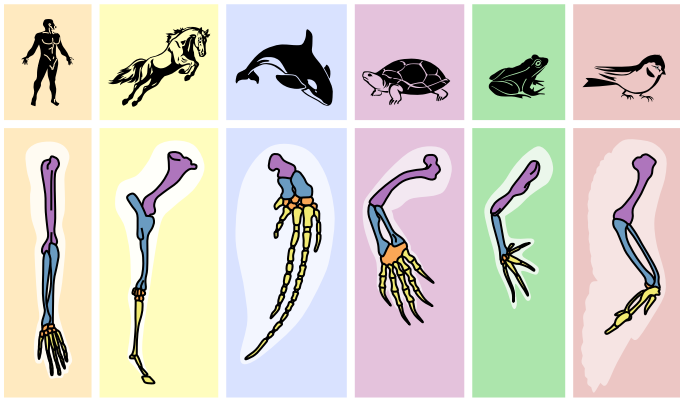
Homologous structures are anatomical features that share a common basic structure despite having distinct functions

The rapid diversification of an anatomical feature is a result of adaptive radiation (organisms adapt to different niches)

- Closely related species demonstrate greater homology

The pentadactyl limb is a prime example of a homologous structure (different appendages, yet same bone structure)

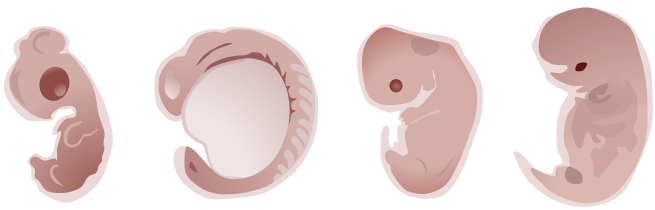
Homologous Structures – Pentadactyl Limb



Comparative Embryology

Comparing embryonic development in animals demonstrates similarities that suggest a common evolutionary pathway

- All terrestrial animals have non-functioning gill slits
- Many vertebrate have a primitive tail in early stages



Chicken Tuna fish Human Dolphin

Biogeography

Biogeography is the distribution of species across an area

- Related species will usually be found in close proximity
- **E.g.** Monotremes are exclusive to Australia/New Guinea

Exceptions may be explained via continental drift

- **E.g.** The ratites (flightless birds) are globally distributed over continents that were once part of a single land mass (Gwondanaland)

TOPIC 5.1: EVOLUTION

Evolution

Evolution is the cumulative change in the heritable characteristic of a population (i.e. biological change over time)

- These characteristics are encoded by genes and transferred between generations as alleles

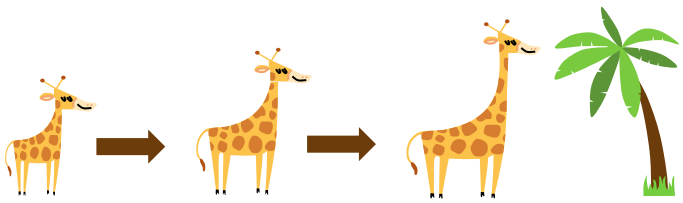
Hence, evolution is a change in the allele frequency of a population's gene pool over successive generations

Theories of Evolution

Lamarck

Proposed that species change via habitual use and disuse

- A giraffe stretches it neck to reach leaves in tall trees
- The giraffe's neck becomes extended from constant use
- The giraffe's offspring inherit its long neck

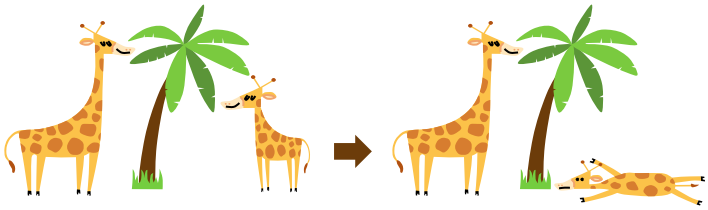


This theory has been **rejected** because these acquired traits do not have a genetic basis (and thus cannot be inherited)

Darwin (and Wallace)

Proposed that species change via natural selection

- A giraffe with a longer neck can reach leaves in tall trees
- The giraffe will get enough food to survive and reproduce
- The giraffe has more offspring (that inherit a long neck)



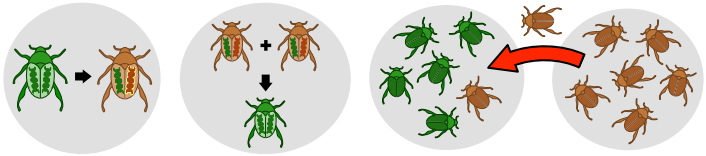
Darwin's theory has been **reinforced** by our understanding of modern genetics (incorporated as neo-Darwinism)

Mechanisms of Change

Fundamental to the process of evolution is the presence of variation within populations upon which selective forces act

There are three main mechanisms by which genetic variation within a population is maintained:

- Mutations – changes to the gene sequence
- Sexual reproduction – new gene combinations
- Gene flow – immigration and emigration

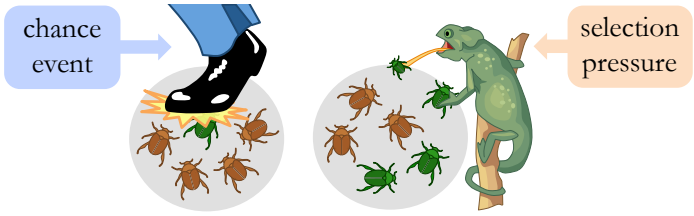


Mutation | Sex | Gene Flow

There are two mechanisms by which population variety can be altered (⬇ biodiversity):

- Random chance (genetic drift)
- Directed intervention (natural or artificial selection)

The impact of a change is greater if the population is small (this may occur via population bottlenecks or founder effect)



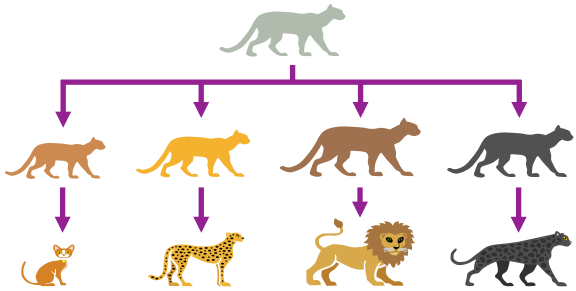
Genetic Drift | Natural Selection

Speciation

If populations become isolated, the level of genetic divergence gradually increases the longer the populations remain separated

- Continuous variation across a geographical range of related populations matches this concept of gradual divergence

Speciation will occur when populations diverge to the extent that they can no longer interbreed and produce fertile, viable offspring



TOPIC 5.3: BIODIVERSITY

Plant Phyla

Bryophyta *(e.g. liverworts and mosses)*
- No vascularisation (lacks xylem / phloem)
- Reproduce via spores released by stalks
- No 'true' leaves, roots or stems

Coniferophyta *(e.g. conifers)*
- Have vascularisation (xylem and phloem)
- Reproduce via seeds (found in cones)
- Narrow leaves with a thick, waxy cuticle

Filicinophyta *(e.g. ferns)*
- Have vascularisation (xylem and phloem)
- Reproduce via spores in sporangia
- Have large fronds divided into leaflets

Angiospermophyta *(e.g. flowering plants)*
- Have vascularisation (xylem and phloem)
- Reproduce via seeds (found in fruits)
- Have flowers as reproductive organs

Invertebrate Phyla

Porifera *(e.g. sponges)*
- Have an asymmetrical body plan
- Have no mouth or anus (have pores)
- May have spicules for structural support

Annelida *(e.g. earthworms and leeches)*
- Possess bilateral symmetry
- Have a separate mouth and anus
- Body composed of ringed segments

Cnidaria *(e.g. jellyfish and anemones)*
- Possess radial symmetry
- Have a mouth but no anus (single opening)
- Has tentacles and stinging cells (cnidocytes)

Mollusca *(e.g. squids, slugs, snails, bivalves)*
- Possess bilateral symmetry
- Have a separate mouth and anus
- Has non-visible segments (may have a shell)

Platyhelmintha *(e.g. flatworms, tapeworms)*
- Possess bilateral symmetry
- Have a mouth but no anus (single opening)
- Has a flattened body (increases SA:Vol ratio)

Arthropoda *(e.g. insects, spiders, crustaceans)*
- Possess bilateral symmetry
- Have a separate mouth and anus
- Have jointed appendages and exoskeleton

Vertebrate Classes

Phylum Chordata *(i.e. vertebrates)*
- Possess bilateral symmetry
- Have a separate mouth and anus
- Have a notochord (may form a backbone)

Reptiles
- Covered in scales (made of keratin)
- Have internal fertilisation (lays soft eggs)
- Breathe via lungs and are ectothermic

Fish
- Covered in scales (bony plates of skin)
- Reproduce via external fertilisation
- Breathe through gills and are ectothermic

Birds
- Covered in feathers (made of keratin)
- Have internal fertilisation (lays hard eggs)
- Breathe via lungs and are endothermic

Amphibians
- Have a moist skin (permeable to gases)
- Reproduce via external fertilisation
- Breathe through skin and are ectothermic

Mammals
- Covered in skin (and keratin hair follicles)
- Have internal fertilisation (and lactation)
- Breathe via lungs and are endothermic

TOPIC 5.4: CLADISTICS

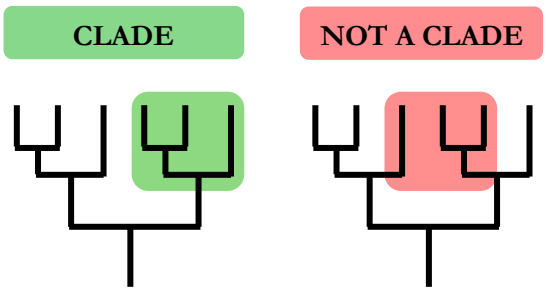
Clades

Cladistics involve classifying organisms into groups of species **(clades)**

- A clade consists of a single common ancestor and all descendants

Cladograms are tree diagrams where each branch point represent the splitting of two new species groups from a common ancestral species

- Each branch point (node) represents a speciation event
- The more nodes between groups, the less related the groups are



Structural Evidence

Historically, cladograms have been constructed based on structural characteristics, however this **not** always a reliable method for establishing evolutionary connections

- Related species may have distinctive *(homologous)* features
- Unrelated species may have similar *(analogous)* features

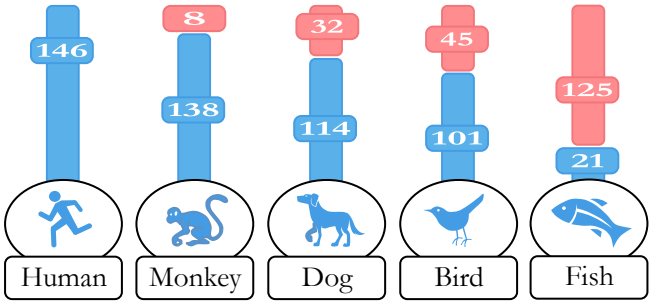
HOMOLOGOUS	ANALOGOUS
Structures look different	Structures look similar
Due to different selection pressures	Due to common selection pressures
Species **do** share a common ancestry	Species do **not** share a common ancestry
Evidence of *divergent* evolution	Evidence of *convergent* evolution
E.g. Pentadactyl limb	E.g. Fins (whale vs shark)

Molecular Evidence

Cladograms are now being generated via a comparison of biochemical evidence (i.e. DNA or amino acid sequences)

- Related species will have sequences with more similarities
- Amino acid sequences will accumulate differences at a slower rate to DNA sequences (due to degeneracy)

If a sequence accumulates mutations at a constant rate, the time of divergence can be calculated based on the number of mutations between the two species (molecular clock)



Haemoglobin β-chain: Similarities Differences

Cladograms

Structural Data: Compare characteristics via a table

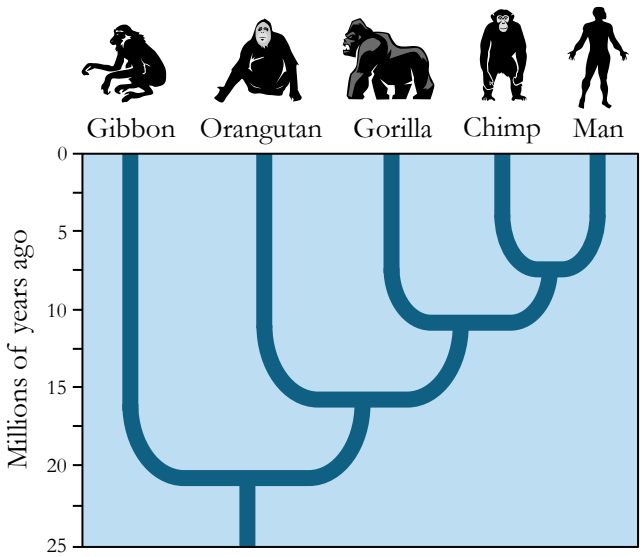
	Lungs	Endothermic	Hair / skin
Fish	–	–	–
Lizard	✔	–	–
Bird	✔	✔	–
Rodent	✔	✔	✔

Molecular Data: Compare sequences via multiple alignment

fish	F	A	A	A	A	F	Q	F	G	F	T	I	4
lizard	F	S	T	A	A	F	R	P	P	H	T	V	3
bird	F	S	T	A	A	F	R	G	G	H	T	I	1
rodent	F	S	T	A	A	F	R	F	G	H	T	I	0
Consensus	F	S	T	A	A	F	R	F	G	H	T	I	

Mutations

Example: Humans and Other Primates



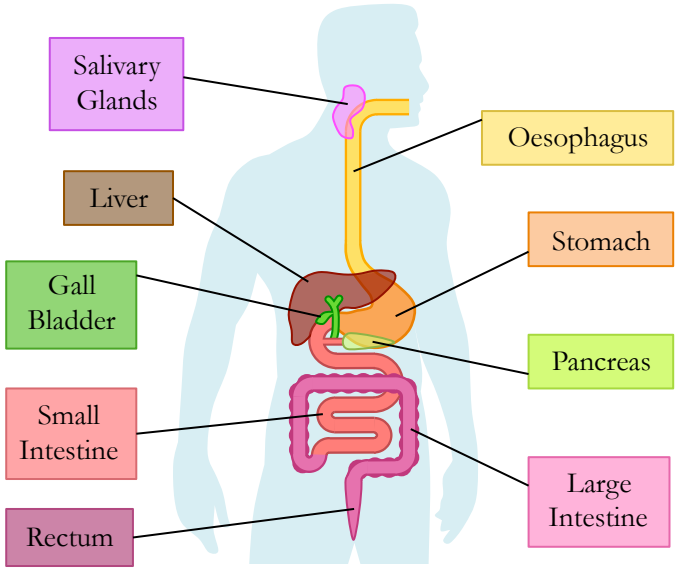
TOPIC 6.1: DIGESTION

Purpose of Digestion

The main purpose of the digestive system is to break large molecules down into smaller subunits due to the fact that:

- Large molecules are typically **chemically inert** and need to be broken down and reassembled into usable products
- Large molecules are typically **insoluble** and cannot be easily absorbed into cells, whereas smaller subunits are soluble

Digestive System Structure



Digestive System Components

The digestive system is composed of the alimentary canal and a variety of supporting accessory organs

Alimentary Canal *(directly transfers food)*

- Oesophagus – Food tract from mouth to stomach
- Stomach – Storage tank with low pH (protein digestion)
- Small intestine – Site of nutrient absorption
- Large intestine – Absorbs water and dissolved minerals

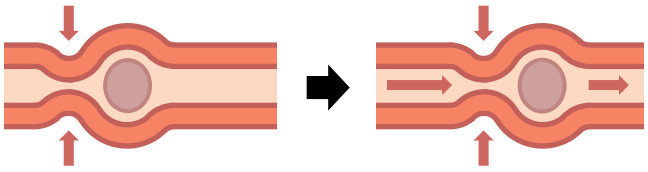
Accessory Organs *(supports digestive processes)*

- Salivary glands – Moistens food bolus (starch digestion)
- Pancreas – Secretes key enzymes into small intestine
- Liver – Metabolises absorbed nutrients (produces bile)
- Gall bladder – Stores and secretes bile (emulsifies fats)

Digestive Movement

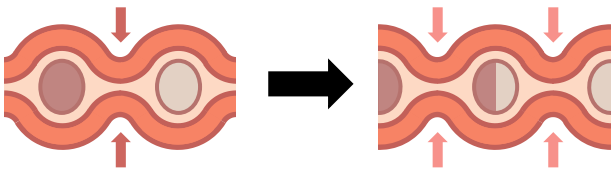
Peristalsis

- Unidirectional movement of food along alimentary canal
- Caused by contraction of sequential longitudinal muscles



Segmentation

- Bidirectional mixing of food within the small intestine
- Caused by contraction of non-sequential circular muscles



Types of Digestion

Food can be digested by one of two ways:

Mechanical Digestion

The breakdown of food via physical actions

- Chewing (grinding food using teeth)
- Churning (squeezing stomach contents)
- Segmentation (intestinal contractions)

Chemical Digestion

The breakdown of food via chemical agents

- Stomach acids (low pH environment)
- Bile (emulsification of fats into droplets)
- Enzymes (catalyse hydrolysis reactions)

Starch Hydrolysis

Starch is composed of glucose monomers

- Is linear *(amylose)* or branched *(amylopectin)*

Amylase (salivary or pancreatic) digests starch

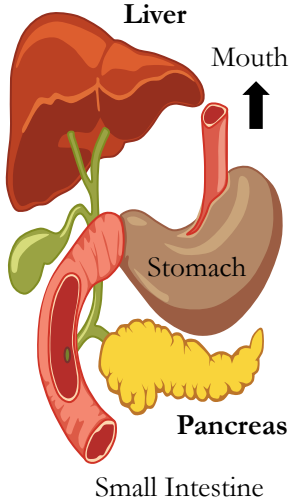
- It digests amylose into maltose disaccharides
- It digests amylopectin into dextrin chains

The **pancreas** regulates the uptake of glucose

- Insulin increases glucose uptake by cells
- Glucagon decreases glucose uptake by cells

The **liver** is responsible for glucose storage

- Glucose is stored as glycogen *(polysaccharide)*



TOPIC 6.2: THE BLOOD SYSTEM

Circulation

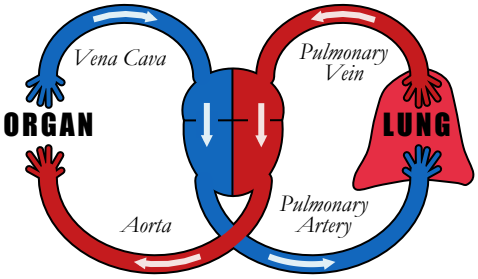
William Harvey proposed the modern understanding of the circulatory system

According to Harvey:

- The major blood vessels (arteries & veins) are connected by a single network
- Blood flow is unidirectional (due to the presence of one-way valves)
- The heart is a central pump (arteries = from heart ; veins = to heart)
- Blood flows continuously and is not consumed by the body

It has further been dicovered that:

- Arteries and veins are connected by capillaries (via arterioles & venules)
- There is a separate circulation for the lungs (pulmonary versus systemic)



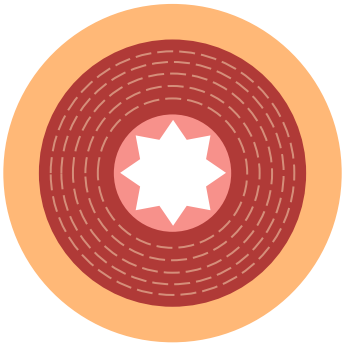
RIGHT SIDE
Body → Lungs
(Deoxygenated)

LEFT SIDE
Lungs → Body
(Oxygenated)

Blood Vessels

Arteries

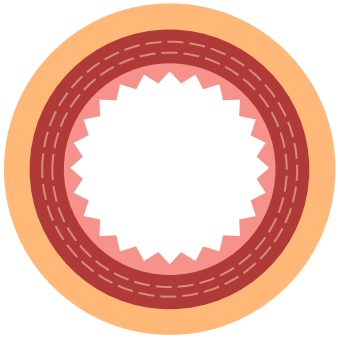
- Transport blood from the heart
- Blood at high pressure *(80-120 mmHg)*
- Walls are thick (muscle and elastin)
- Walls stretch or contract with pulse



collagen muscle/elastic fibres

Veins

- Transport blood to the heart
- Blood at low pressure *(<15 mmHg)*
- Walls are thin (with wider lumen)
- Have valves to prevent pooling



collagen muscle/elastic fibres

Capillaries

- Facilitate material exchange
- Blood at low pressure *(~10 mmHg)*
- Walls made of single layer of cells
- Extremely narrow lumen *(~10 μm)*

Capillaries may be categorised as:

- Continuous *(intact basement membrane)*
- Fenestrated *(have endothelial pores)*
- Sinusoidal *(discontinuous membrane)*

endothelium (single layer) basement membrane

Blood

Blood contains three main elements:

- Red blood cells (transport oxygen)
- White blood cells (fight infections)
- Platelets (responsible for clotting)

The blood fluid (plasma) transports:

- **N**utrients (e.g. glucose)
- **A**ntibodies
- **C**arbon dioxide
- **H**ormones
- **O**xygen
- **U**rea
- **H**eat

NACHO-UH!

Blood Flow

A heart pumps blood around the body via two distinct circulatory pathways

Right Side (of heart):

- Deoxygenated blood (from tissues) enters right atrium via the vena cava
- Blood in the right ventricle is pumped to lungs via the pulmonary artery
- Gas exchange at the lungs (capillaries ↔ alveoli) oxygenates the blood

Left Side (of heart):

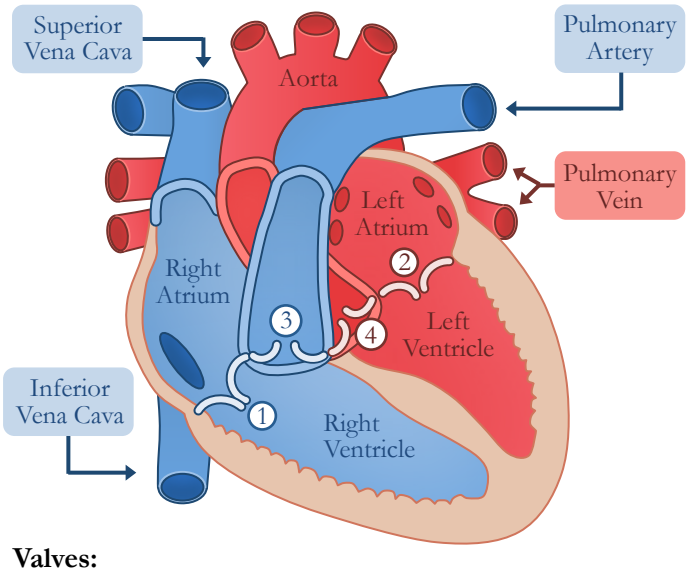
- Oxygenated blood (from lungs) enters left atrium via the pulmonary vein
- Blood in the left ventricle is pumped to the body tissues via the aorta
- Material exchange occurs at the respiring tissue (deoxygenates the blood)

Valves in veins ensure proper circulation by preventing backflow of blood

- Contraction of skeletal muscles may compress veins to aid blood flow

TOPIC 6.2: THE HEART

Heart Structure



Valves:

1. Tricuspid valve *(right)*
2. Bicuspid valve *(left)*
3. Pulmonary valve *(right)*
4. Aortic valve *(left)*

Mechanism of Heart Beat

A heart beat is **myogenic** (contraction initiated by the heart)

- Electrical signals are initiated by a sinoatrial (SA) node
- This pacemaker stimulates the atria to contract and also relays signals to an atrioventricular (AV) node
- The AV node sends signals to ventricular Purkinje fibres (via a Bundle of His within the wall of the septum)
- The Purkinje fibres cause the ventricular walls to contract

The SA node maintains a normal sinus rhythm *(60-100 bpm)*

- The pacemaker is regulated by the medulla oblongata
- Sympathetic nerves release noradrenaline *(⬆ heart rate)*
- Parasympathetic nerves release acetylcholine *(⬇ heart rate)*
- Heart rate may also be increased via hormonal action (via the release of adrenaline / epinephrine)
- Adrenaline will cause a more sustained elevation in heart rate than that achieved by the action of the brainstem

Cardiac Cycle

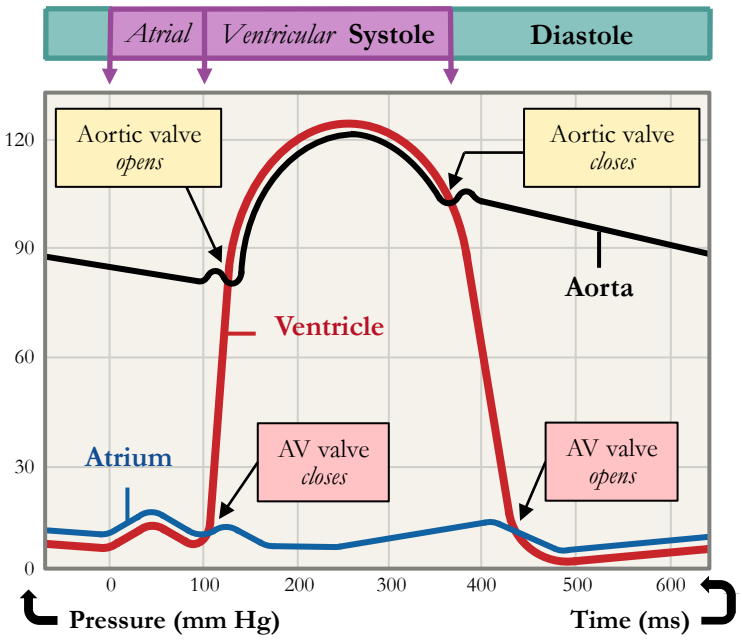
The cardiac cycle describes the events of a heart beat

Systole (contraction)

- As atria contract, atrial pressure exceeds ventricular pressure (AV valves open → blood flows to ventricles)
- As ventricles contract, ventricular pressure exceeds atrial pressure (AV valves close → 1st heart sound)
- Pressure builds (isovolumetric contraction) until the ventricular pressure exceeds the arterial pressure
- Semilunar valves open and blood flows into arteries

Diastole (relaxation)

- As blood flows into arteries, ventricular pressure drops
- Backflow closes semilunar valves → 2nd heart sound
- When ventricular pressure drops below atrial pressure, the AV valves will open and cardiac cycle is repeated



Coronary Heart Disease

Coronary thrombosis is caused by clots within the coronary arteries

- Vessels are damaged by cholesterol deposition (atherosclerosis)
- The deposits reduce vessel diameter and increase blood pressure
- The stress damages arterial walls (and is repaired with fibrous tissue)
- The vessel wall loses elasticity and forms atherosclerotic plaques
- If a plaque ruptures, blood clotting is triggered, forming a thrombus
- If the thrombus blocks blood flow, a myocardial infarction results
- These events are collectively described as coronary heart disease

Risk Factors

Risk factors for CHD include:

- **G**enetics (e.g. hypertension)
- **O**besity (overweight = risk)
- **D**iseases (e.g. diabetes)
- **D**iet (e.g. ⬆ *trans* fats)
- **E**xercise (inactivity = risk)
- **S**moking (⬆ blood pressure)
- **S**ex (males = higher risk)

TOPIC 6.3: ADAPTIVE IMMUNITY

Adaptive Immunity

The adaptive immune responses share two key characteristics:

- They are **specific** (i.e. they can differentiate between different types of pathogens and respond accordingly)
- They are **adaptive** (i.e. they produce a heightened response upon re-exposure – there is immunological memory)

Antigen Recognition

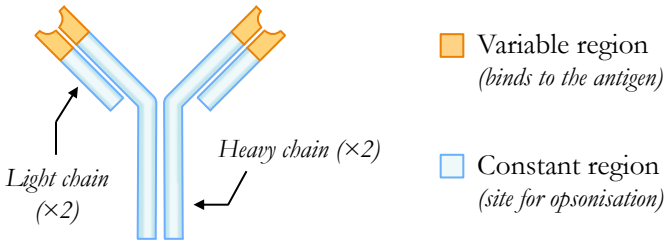
Antigens are substances that the body recognise as foreign and that can elicit an immune response

Antigens are presented to lymphocytes via identification markers on the surface of native cells (MHC molecules)

- MHC I markers are found on all body cells *(except RBCs)* and present endogenous antigens (cell-mediated response)
- MHC II markers are on innate immune cells *(macrophages)* and present exogenous antigens (humoral response)

Antibodies

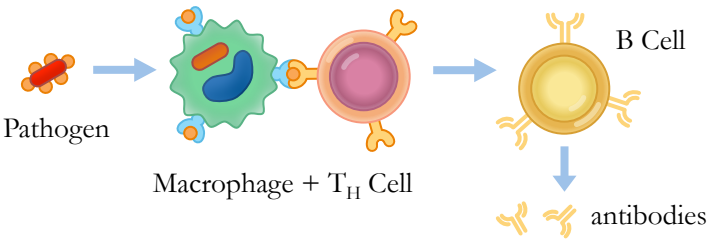
Antibodies are proteins produced by B lymphocytes that are **specific** to a given antigen (they are also called *immunoglobulins*)



Role of Lymphocytes

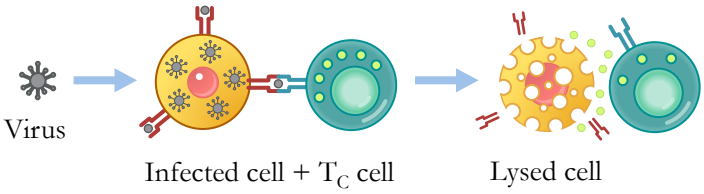
Humoral Immunity (targets 'non-self')

- B cells each produce one specific type of antibody
- Macrophages or dendritic cells present antigen fragments (via MHC II markers) to helper T lymphocytes (T_H cells)
- T_H cells release cytokines and activate the antigen-specific B cells (which rapidly divide to form many plasma cells)
- The plasma cells make antibodies specific to the antigen
- A small proportion of B cell clones differentiate into long-lasting memory B cells (for long-term immunity)



Cell Mediated Immunity (targets 'self')

- Infected cells present antigens on their MHC I markers
- Antigens are recognised by cytotoxic T cells (and T_H cells)
- Cytotoxic T lymphocytes (T_C cells) bind to the infected cell and trigger its destruction (via perforating enzymes)
- T_H cells stimulate the formation of memory T_C cells
- T_C cells can target virus-infected cells **and** tumor cells
- Suppressor T cells regulate the action of T_C cells in order to prevent sustained T cell activation (i.e. autoreactivity)



Immune System Disorders

Immunodeficiency

- HIV is a retrovirus that infects helper T cells (T_H cells)
- It is usually transmitted via the exchange of bodily fluids (e.g. sex, breastfeeding, transfusions, injections, etc.)
- HIV is integrated into the genome of infected T_H cells
- After a prolonged period of inactivity, it becomes active and lyses the T_H cell as it begins to spread
- This results in an inability to produce antibodies and a general loss of immunity (disease is called AIDS)

Hypersensitivity

- Allergens are substances that trigger an immune response despite not being inherently harmful (e.g. peanut allergy)
- When a B cell is activated by an allergen, it makes large quantities of allergen-specific antibodies (IgE)
- These IgE antibodies bind to mast cells and 'prime' them
- Upon re-exposure to the allergen, the sensitised mast cells release large quantities of histamine (causes inflammation)
- This inflammatory response is called an allergic reaction

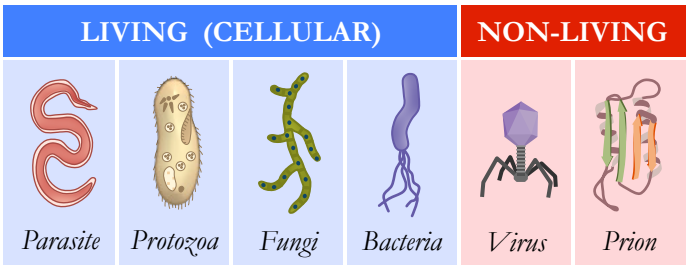
TOPIC 6.3: DEFENCE AGAINST DISEASE

Pathogens

Pathogens are disease-causing agent that disrupt the normal physiology of infected organisms (i.e. homeostatic imbalance)

Pathogens may be species-specific or cross species barriers

- Diseases that can be naturally transmitted between animals and humans are called **zoonotic** diseases



Lines of Defense

Immune system can be divided into three lines of defense:

- 1st line of defense – Surface barriers (skin / mucus)
- 2nd line of defense – Innate immunity (non-specific)
- 3rd line of defense – Adaptive immunity (specific)

Antibiotics

Antibiotics are compounds that target prokaryotic features but don't harm eukaryotic cells (i.e. don't affect host organism)

- May target structures (e.g. cell wall) or metabolic processes

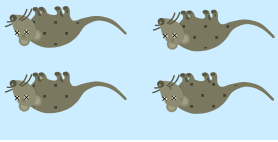
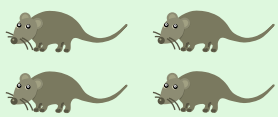
Some strains of bacteria have evolved with genes that confer resistance to antibiotics (some even have multiple resistance)

- Antibiotics can't be used to treat viruses (no metabolism)

The first antibiotic identified was penicillin (Fleming – 1928)

- Its treatment use was demonstrated by Florey and Chain

Experiment: Mice infected with pathogenic bacteria

Control: No treatment	**Treatment:** Penicillin
	
Result: All mice died	**Result:** All survived

Conclusion: Penicillin has antibiotic properties

Surface Barriers

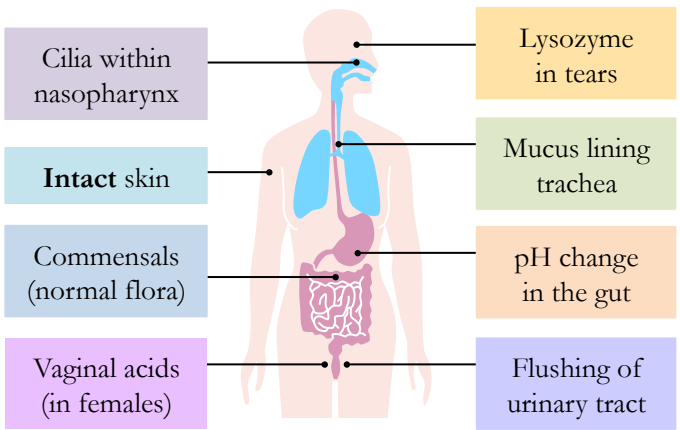
The first line of defense against infectious disease is the surface barriers that function to prevent pathogenic entry

Skin

- Protects external structures (i.e. outside the body)
- Thick, dry and composed predominantly of dead cells
- Glands secrete chemicals to restrict bacterial growth

Mucous Membranes

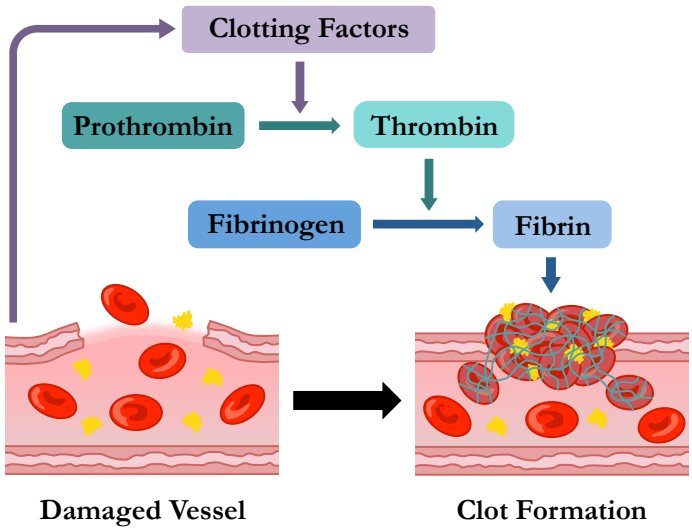
- Protects internal structures and cavities (inside body)
- Thin region composed of living cells that secrete fluid (mucus) to trap pathogens (which may then be removed)



Clotting

Clotting seals damaged vessels to prevent pathogenic entry

- Injured cells and platelets release clotting factors
- These factors convert prothrombin into thrombin
- Thrombin converts fibrinogen *(soluble)* into fibrin *(insoluble)*
- Fibrin forms a mesh of fibres that block the injured site
- Clotting factors also cause platelets to become sticky and form a solid plug (called a clot), sealing the wound
- This process of events is called a coagulation cascade
- Clot formation in coronary arteries lead to heart attacks



TOPIC 6.3: INNATE IMMUNITY

Innate Immunity

The innate immune responses share two key characteristics:

- They are **non-specific** (i.e. they do not differentiate between different types of pathogens)
- They are **non-adaptive** (i.e. they produce the same response to every infection – there is no immunological memory)

Lymphatic System

The lymphatic system is a secondary transport system that protects the body by producing and filtering lymph

- Lymph is a clear fluid rich in white blood cells that arises from the drainage of interstitial fluid from the tissues
- Lymph is filtered at lymph nodes, whereby pathogens are removed and the fluid is returned to venous circulation

Inflammation

Tissue damage causes mast cells to release histamine, which triggers vasodilation and increased capillary permeability

- This improves the recruitment of white blood cells

An inflammatory response, while necessary, has side effects:

- Vasodilation = localised redness & heat *(⬆ blood flow)*
- Capillary permeability = swelling & tenderness *(⬆ fluid)*

Inflammation can be short-term *(acute)* or long-term *(chronic)*

Fever

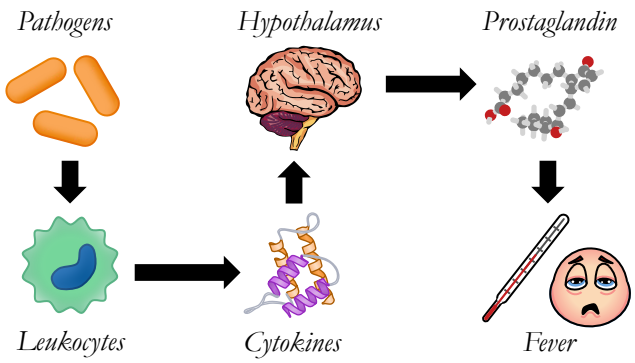
Fever is an abnormally high body temperature *(due to infection)*

- It increases metabolism and activates heat shock proteins
- It reduces the growth rate of infectious pathogens

Fever occurs when white blood cells release cytokines

- This causes the hypothalamus to produce prostaglandin
- Prostaglandin increases the temperature of the body

While a fever may initially strengthen an immune response, beyond tolerable limits it will cause damage to the body



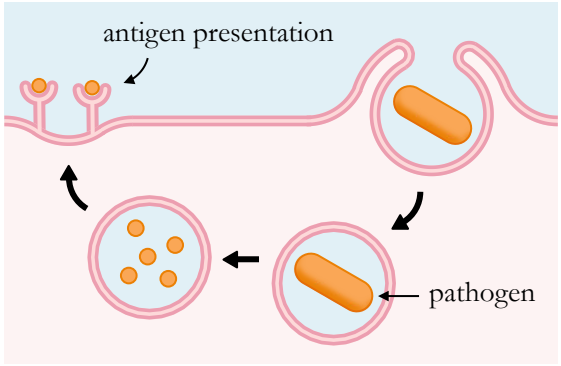
Phagocytosis

Macrophages and dendritic cells migrate via the blood to sites of infection (damaged cells release chemotactic agents)

The pathogens are surrounded by extensions (pseudopodia) and are then internalised within a vesicle (via phagocytosis)

The vesicle may fuse with a lysosome to digest the pathogen

- Fragments (antigens) are presented on the surface of the cell in order to activate the third line of defense *(adaptive)*



Complement System

Inactive complement proteins are produced by white blood cells and certain body cells (particularly the liver)

In response to immune activation, they trigger a cascade of reactions that help protect the body from infection:

- Opsonisation (increase pathogen recognition by phagocytes)
- Chemotaxis (recruitment of phagocytes to the infection site)
- Membrane attack (forms a complex that ruptures cell walls)

Natural Killer Cells

Natural killer cells are a class of non-specific lymphocytes that can target and destroy infected body cells or tumor cells

- Infected cells release chemicals called interferons, which function to promote the activation of natural killer cell
- Natural killer cells induce apoptosis in the infected cell

Natural killer cells are part of the innate immune response because they do not rely on antigen recognition to function

TOPIC 6.4: GAS EXCHANGE

Ventilation

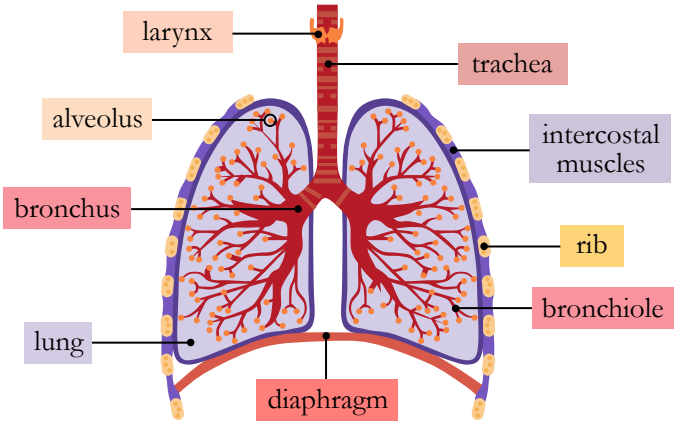
Ventilation is the exchange of gases between the lungs and the atmosphere (achieved by the physical act of breathing)

These gases are integral to the process of cell respiration
- Oxygen is an input, carbon dioxide is a by-product

Ventilation maintains the concentration gradient necessary for passive diffusion (O_2 = into lungs, CO_2 = out of lungs)

Ventilation rates will change with exercise and can be measured via **spirometry** (measures amount / rate of air)

Lung Structure

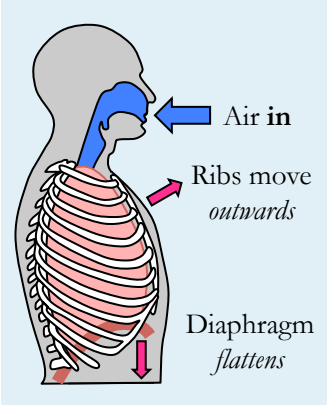


Mechanism of Breathing

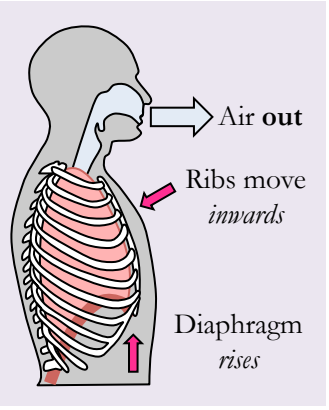
Breathing utilises antagonistic sets of respiratory muscles in order to facilitate the passage of air (inhalation / exhalation)
- Muscles change lung volume to create negative pressure
- Negative pressure is equalised by air from atmosphere
- Air flows in / out according to the volume of the thorax

Inhalation
- Diaphragm muscles contract (diaphragm flattens)
- External intercostal muscles pull ribs up (outwards)
- This increases the volume of the thoracic cavity
- Pressure in lungs decreases below atmospheric pressure
- Air flows into the lungs in order to equalise the pressure

Exhalation
- Diaphragm muscles relax (diaphragm curves upwards)
- Internal intercostal muscles pull the ribs down (inwards)
- Abdominal muscles contract to push diaphragm upwards
- This decreases the volume of the thoracic cavity
- Pressure in lungs increases above atmospheric pressure
- Air flows out of the lungs to equalise the pressure



INHALATION



EXHALATION

Pneumocytes

Pneumocytes (alveolar cells) line the alveoli and comprise the majority of the inner surface of the lungs

Type I pneumocytes:
- Involved in gas exchange between alveoli and capillaries
- Are extremely thin (minimises gas diffusion distances)

Type II pneumocytes:
- Responsible for the secretion of pulmonary surfactant
- This creates a moist surface that reduces surface tension (prevents sides of alveoli from adhering to each other)

Lung Disorders

Lung Cancer

Cancer is uncontrolled cell proliferation, leading to tumors
- Lungs possess a rich blood supply (for gas exchange), increasing the chances of metastasis (spread of cancer)

There are many factors that contribute to lung cancer:
- **Intrinsic:** Genetics, age, certain diseases / infections
- **Extrinsic:** Smoking, asbestos, radiation exposure

Emphysema

Emphysema is the abnormal enlargement of the alveoli
- These form air spaces and lower the overall surface area

Emphysema is most commonly caused by smoking
- Chemicals in the cigarettes damage the alveoli
- Phagocytes release elastase as part of immune response
- Elastase destroys the elastic fibres in the alveolar walls
- Huge air spaces (pulmonary bullae) develop in the lungs

TOPIC 6.5: NEURONS & SYNAPSES

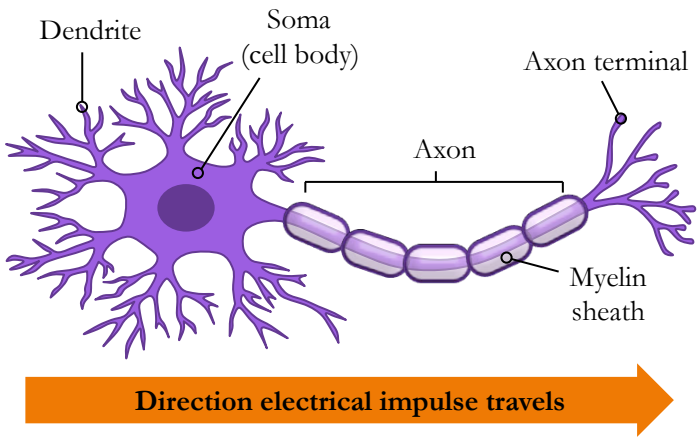
Nervous System

The nervous system consists of two main divisions:
- Central nervous system (CNS) = brain and spinal cord
- Peripheral nervous system (PNS) = peripheral nerves

The nervous system is composed of specialised cells called **neurons** that function to transmit electrical signals

The CNS coordinates sensory & motor signals from the PNS
- Sensory neurons send signals to the CNS *(afferent pathway)*
- Motor neurons send signals from the CNS *(efferent pathway)*
- Relay neurons (interneurons) send signals within the CNS

Structure of a Motor Neuron



Membrane Potentials

Neurons have a difference in charge across their membranes due to the distribution of positively-charged ions (Na^+ / K^+)

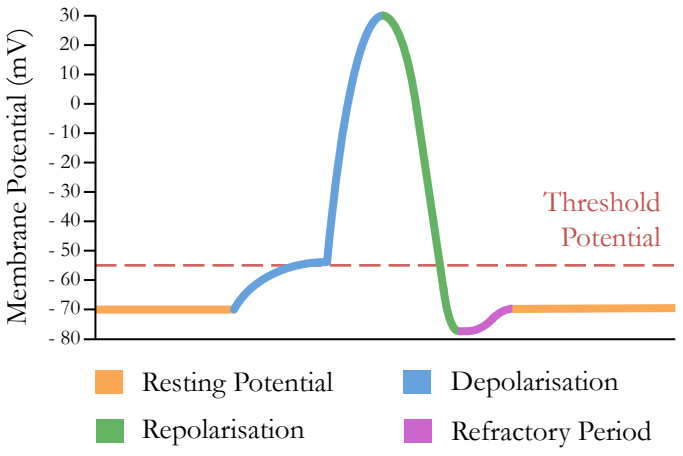
Electrical signals are created by changing membrane polarity
- Polarity of a neuron at rest is the *resting potential* (-70mV)
- Polarity of a firing neuron is the *action potential* (+30mV)

Nerve Impulses

The **resting potential** is maintained by a Na^+/K^+ pump
- It exchange sodium ions (3 out) and potassium ions (2 in) so that the membrane potential becomes slightly negative

An **action potential** changes the resting membrane potential
- The opening of sodium channels causes a sodium influx
- This creates a positive membrane potential *(depolarisation)*
- Opening potassium channels causes a potassium efflux
- This restores a negative membrane potential *(repolarisation)*

The ion distribution must be restored to original conditions before a neuron can fire again (this is the **refractory period**)



Myelination

Nerve impulses are action potentials propagated via axons
- Action potentials are *'all or none'* and are only propagated if a certain threshold potential is reached (~ -55mV)

In certain neurons, the axon is covered by a **myelin sheath**
- This enables saltatory conduction *(⬆ transmission speed)*
- The action potential 'hops' between gaps in the myelin sheath (called nodes of Ranvier) for faster transmission

Synaptic Transfer

Synapses are the physical junctions between two neurons
- Electrical impulses cannot cross these physical gaps

Neurons release **neurotransmitters** into the synapse cleft
- Depolarisation in axon terminals opens Ca^{2+} channels
- Ca^{2+} influx causes vesicles containing neurotransmitters to release their contents into the synapse (via *exocytosis*)
- Neurotransmitters bind receptors on post-synaptic cells and generate graded potentials (excitatory or inhibitory)
- The summation of these graded potentials determines if the post-synaptic neuron (or effector cell) is activated

Neonicotinoid Pesticides

Acetylcholine is a neurotransmitter used in CNS and PNS
- It is broken down in synapses by acetylcholinesterase
- This prevents the overstimulation of the receptors

Neonicotinoid pesticides irreversibly bind to acetylcholine receptors and cannot be digested by acetylcholinesterase
- Insects have higher levels of these types of receptors
- This makes neonicotinoids highly effective pesticides

TOPIC 6.6: HORMONES & HOMEOSTASIS

Homeostasis

Homeostasis is the maintenance of a constant internal environment within physiological tolerance limits

- A disease ensues if a factor deviates from its normal range

Physiological processes are regulated by **negative feedback**

- An effect is antagonistic (opposite) to the stimulus
- This means the detected change is reversed

Endocrine System

The endocrine system releases chemical messengers called hormones into the blood to act on distant target cells

- Hormones only act on the cells with a *specific* receptor

The endocrine system works in tandem with the nervous system to maintain physiological balance (homeostasis)

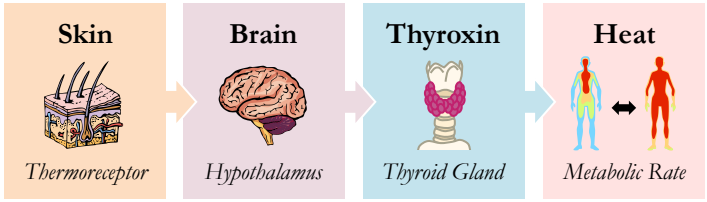
- Hormones initiate slower responses (longer durations)

Thermoregulation

Body temperature is regulated by the hormone **thyroxin**

- Thermoreceptors (skin) send signals to the hypothalamus
- Thyroxin is released from the thyroid gland when body temperature is low and increases metabolism *(generates heat)*

Thyroxin production requires iodine and a deficiency will result in **goitre** (enlargement of the thyroid gland)



Blood Glucose Regulation

Blood sugar levels are regulated by **insulin** and **glucagon**

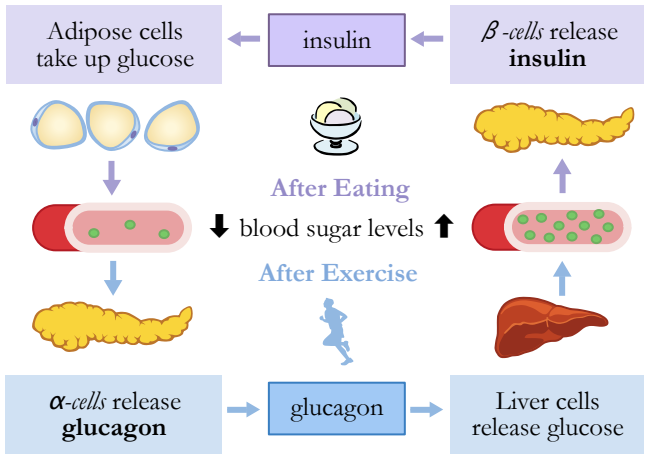
- These hormones are secreted by cells in the pancreas

Insulin is secreted by β-cells to <u>lower</u> blood sugar levels

- Stimulates glucose uptake by the liver and adipose cells
- Increases the rate of glucose metabolism *(⬆ respiration)*

Glucagon is secreted by α-cells to <u>raise</u> blood sugar levels

- Stimulates glycogen breakdown within the liver
- Decreases the rate of glucose metabolism *(⬇ respiration)*



Circadian Rhythms

Circadian rhythms are regulated by the hormone **melatonin**

- Photoreceptors (eyes) send signals to the hypothalamus
- Melatonin is secreted by the pineal gland (in the brain)
- Melatonin release is inhibited by light (levels high at night)
- High levels of melatonin promote sleep in diurnal animals

Changing time zones can disrupt melatonin release (**jet lag**)

- Melatonin supplements can recalibrate sleep patterns

Appetite Control

Appetite suppression is regulated by the hormone **leptin**

- Adipose cells secrete leptin to suppress appetite *(⬇ hunger)*
- Leptin binds to receptors located in the hypothalamus

Over-eating causes more fat cells to be produced (**obesity**)

- Over time, obese people become desensitized to leptin and therefore are more likely to continue to over-eat
- Hence, leptin treatments for obese people are ineffective (obesity linked to leptin *unresponsiveness* – not a deficiency)

Diabetes

Diabetes is a disorder that prevents blood sugar regulation

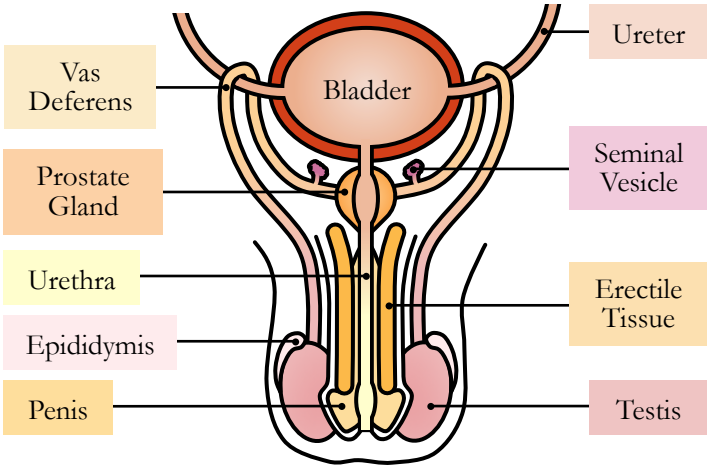
- It can be either type I (IDDM) or type II (NIDDM)

	Type I	Type II
Onset	Early (childhood)	Late (adulthood)
Effect	Body does not *produce* insulin	Body does not *respond* to insulin
Cause	β-cells destroyed (autoimmune?)	Insulin receptors down-regulated
Treatment	Insulin injections	Diet management

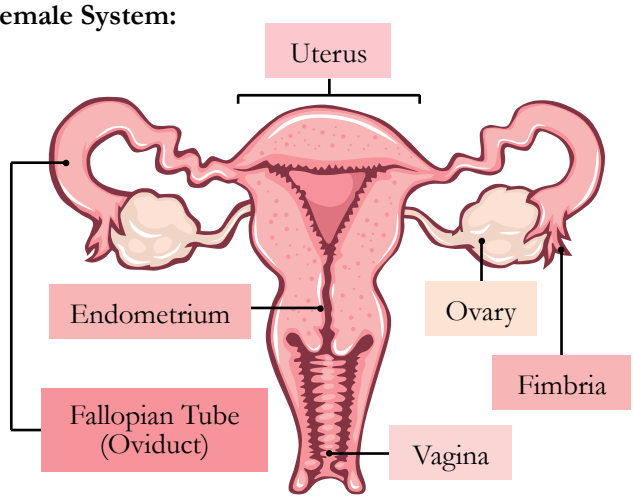
TOPIC 6.6: REPRODUCTIVE SYSTEMS

Human Reproductive Systems

Male System:



Female System:



Menstrual Cycle

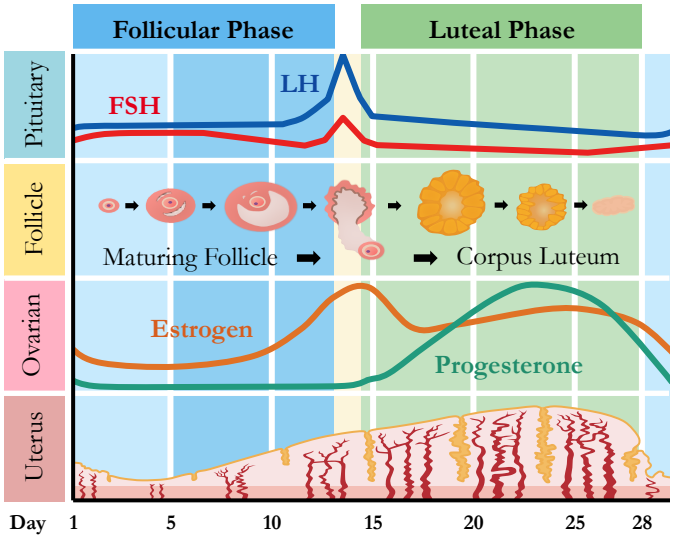
The menstrual cycle involves four key hormones and describes the recurring changes that occur to enable pregnancy

Pituitary Hormones (FSH and LH):

- Stimulate follicular growth within the ovaries
- Stimulate estrogen secretion (from the ovarian follicles)
- Stimulate progesterone secretion (from corpus luteum)
- A mid-cycle surge in LH triggers ovulation (egg release)

Ovarian Hormones (estrogen and progesterone):

- Promote development / thickening of the endometrium
- Promote FSH / LH secretion during the follicular phase
- Inhibit FSH / LH secretion during the luteal phase



Reproductive Theories

One of the earliest theories involving how human reproduction occurs was the 'soil and seed' theory proposed by Aristotle

- Males provide all the information for life in a 'seed', which forms an egg when mixed with menstrual blood (the 'soil')

William Harvey dissected deer after the mating season and was unable to identify embryos until several months after mating

- He concluded that the 'soil and seed' theory was incorrect and that menstrual blood did **not** contribute to fetal growth

Sex Development

Fertilisation requires a combination of male **and** female 'seeds'

Male sex is determined by a gene on the Y chromosome which causes gonads to develop as testes and secrete testosterone

- Testosterone produces sperm and male sex characteristics

Female reproductive organs develop in the absence of this gene

- Estrogen and progesterone develop female sex characteristics

In Vitro Fertilisation

- **S**top normal menstrual cycle with drugs
- **H**ormone treatments to induce ovulation
- **E**xtract multiple eggs from female
- **S**perm sample is collected from male
- **F**ertilisation occurs externally (in vitro)
- **I**mplantation of embryos into surrogate
- **T**est for pregnancy to determine success

TOPIC 7.1: DNA REPLICATION

Replication Enzymes

Helicase:
- Helicase separates the DNA strands to form a replication fork (breaks the hydrogen bonds between complementary base pairs)
- Single stranded binding proteins prevent strands re-annealing

DNA Gyrase:
- DNA gyrase reduces the torsional strain created by helicase
- It prevents the DNA from supercoiling as it is being unwound

DNA Primase:
- DNA primase generates a short RNA primer on each strand
- Primers provide an initiation point for DNA polymerase III (DNA pol III can only add nucleotides to 3'-end of a primer)

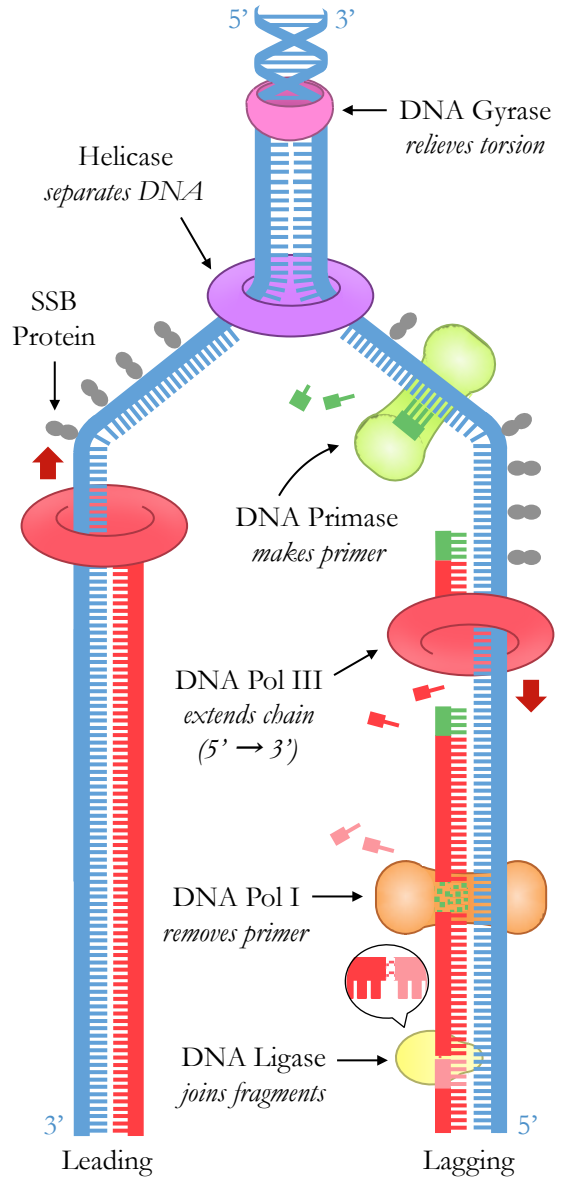
DNA Polymerase III:
- Free nucleotides (dNTPs) line up opposite complementary bases
- DNA polymerase III covalently joins free nucleotides together

Okazaki Fragments:
- DNA strands are *antiparallel*, so replication occurs bidirectionally (replication always occurs in a 5' → 3' direction on each strand)
- Synthesis is continuous on the leading strand *(towards fork)* and is discontinuous on the lagging strand *(away from fork)*
- Discontinuous segments are called Okazaki fragments

DNA Polymerase I:
- DNA pol I removes RNA primers and replaces them with DNA

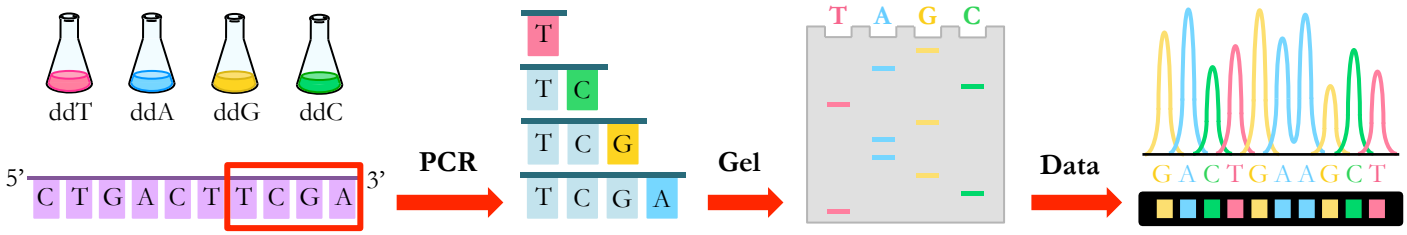
DNA Ligase:
- DNA ligase covalently joins the Okazaki fragments together

Replication Process



DNA Sequencing

Sequencing is a technique by which the nucleotide base order of a DNA sequence is elucidated (typically via Sanger method)
- Dideoxynucleotides (ddNTPs) lack the 3'-hydroxyl group needed to form covalent bonds (they terminate replication)
- Four PCR mixtures are prepared – each with stocks of normal bases **and** <u>one</u> dideoxynucleotide (ddA, ddT, ddG, ddC)
- Whenever the dideoxynucleotide is randomly incorporated, the DNA sequence is terminated at that base position
- Because a complete PCR cycle generates millions of sequences, every base position is likely to have been terminated
- These sequences are separated by gel electrophoresis to determine base sequence (according to ascending sequence length)
- Automated machines can determine the sequence quickly if fluorescent labeling of the dideoxynucleotides has occurred



TOPIC 7.2: TRANSCRIPTION

Sections of a Gene

A gene is a sequence of DNA which is transcribed into RNA
- Most genes encode proteins, but some do not (e.g. tRNA)

A gene sequence has three main sections:
- **Promoter** (transcription initiation site)
- **Coding sequence** (the region transcribed)
- **Terminator** (transcription termination site)

As DNA is double stranded, only one strand is transcribed
- The *antisense* strand **is** transcribed into RNA
- The *sense* strand is **not** transcribed into RNA

Transcription

RNA polymerase binds to a promoter and unwinds DNA
- It breaks the H bonds between complementary bases

Nucleoside triphosphates bind to complementary bases
- In RNA, uracil pairs with adenine instead of thymine

RNA polymerase covalently joins the nucleotides together
- The two extra phosphates are released (provides energy)

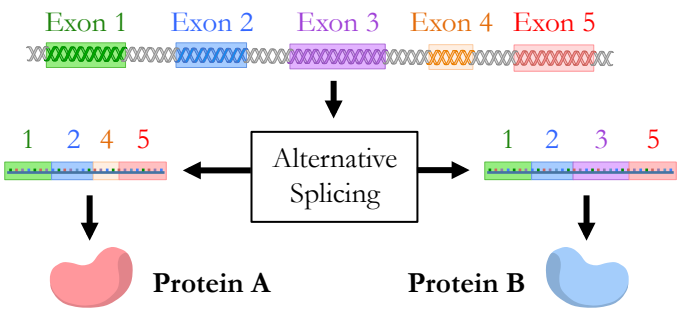
Transcription occurs in a 5' → 3' direction *(antisense strand)*
- At the terminator site, RNA polymerase is detached and the RNA sequence is released (and the DNA rewinds)

Splicing

Eukaryotic cells modify RNA after transcription has occurred
- Modifications must occur to produce mature mRNA

Non-coding regions within genes are removed (**splicing**)
- Introns are non-coding regions in genes (intruding)
- Exons are the coding regions of genes (expressing)

Exons can be selectively removed to form different proteins from the same gene (this is called **alternative splicing**)

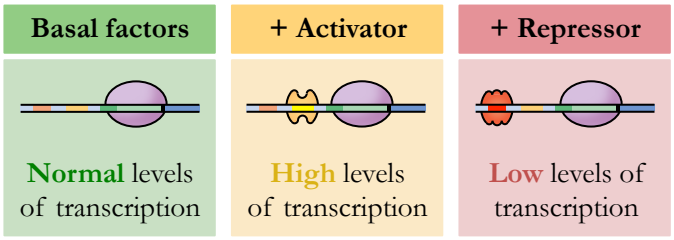


Gene Expression

Transcription Factors

Gene expression is regulated by proteins *(transcription factors)* that bind to specific sequences associated with a promoter
- Activators bind enhancer sites *(⬆ rate of transcription)*
- Repressors bind silencer sites *(⬇ rate of transcription)*

The presence of regulatory proteins may be tissue-specific or may be influenced by chemical signals (e.g. hormones)



Nucleosomes

Nucleosomes also help regulate transcription in eukaryotes
- Histones proteins have protruding tails that determine how tightly the DNA is packaged within nucleosomes

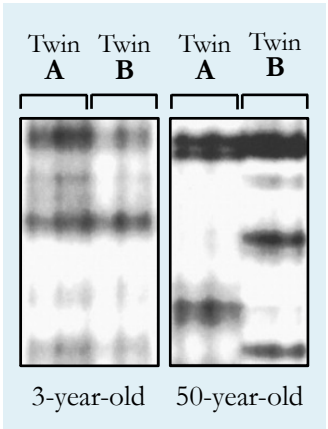
Modifications to these tails alters the DNA packaging:
- Acetylation makes DNA **less** tightly packed
- Methylation makes DNA **more** tightly packed

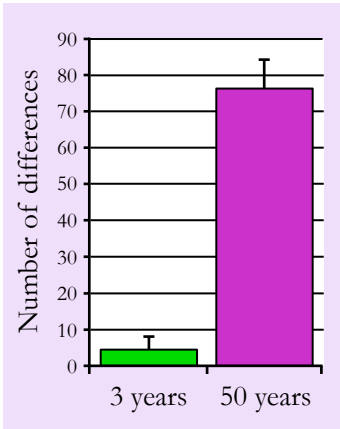
Cells package DNA differently according to genetic needs
- Active genes remain unpackaged as euchromatin
- Inactive genes are tightly packed as heterochromatin

DNA Methylation

DNA can also be directly methylated to change expression patterns of genes over time in response to external stimuli
- Increased methylation = decreased transcription

Methylation Patterns in Twins Over Time





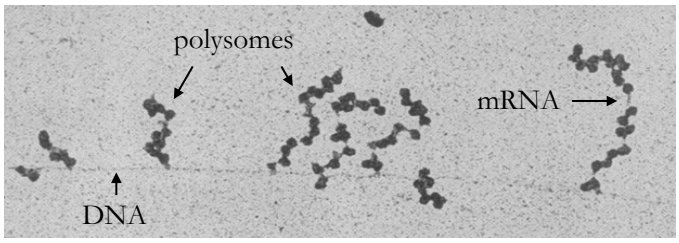
TOPIC 7.3: TRANSLATION

Ribosomes

Ribosomes are the site of polypeptide synthesis (translation)
- They are composed of ribosomal RNA and protein

Ribosomes consist of two subunits:
- Small subunit contains an mRNA binding site
- Large subunit contains three tRNA binding sites (E, P, A)

Multiple ribosomes can translate a single mRNA sequence simultaneously (these are collectively called a **polysome**)



Transfer RNA

Transfer RNA (tRNA) carries amino acids to the ribosome
- Amino acids are attached by tRNA-activating enzymes

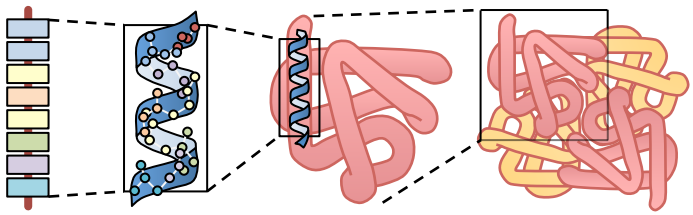
The tRNA-activating enzyme functions in two steps:
- The enzyme joins ATP to an amino acid ('charging')
- 'Charged' amino acid is linked to tRNA (AMP is released)

The purpose of 'charging' the amino acid is to create a high energy bond that can be be used during translation
- Ribosomes use this energy to synthesise peptide bonds

Each tRNA-activating enzyme is specific to a particular amino acid, but may bind multiple tRNA (due to degeneracy)

Protein Structure

Proteins have four levels of structural organisation:
- 1° structure = sequence and number of amino acids
- 2° structure = folding into α-helix or β-pleated sheet
- 3° structure = three-dimensional shape of a polypeptide
- 4° structure = presence of multiple polypeptide chains



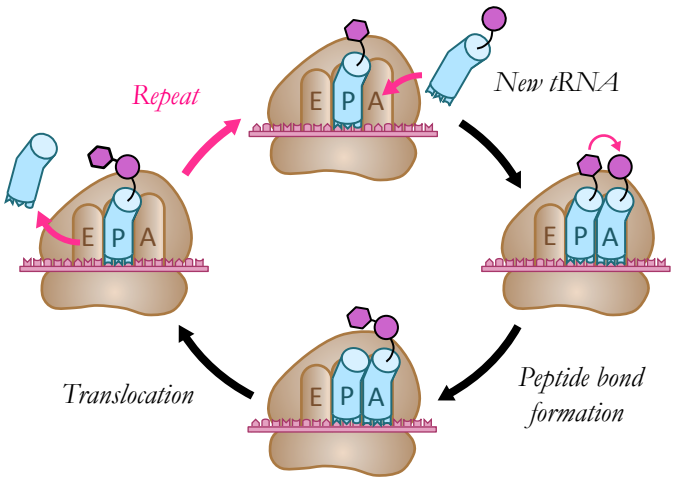
Translation

Translation is the process of polypeptide synthesis and this process involves a repeated cycle of four key events

Initiation *(component assembly)*
- The small ribosomal subunit binds to mRNA and moves in a 5' → 3' direction to the START codon (AUG)
- The complementary tRNA molecule binds to the START codon via its anticodon
- The large subunit aligns itself to the tRNA molecule at its P-site and forms a complex with the small subunit

Elongation / Translocation *(polypeptide synthesis)*
- A tRNA molecule pairs with the next codon (via A-site)
- The ribosome covalently attaches the amino acid in the P-site to the amino acid in the A-site (via peptide bond)
- The ribosome moves along one codon position and the deacylated tRNA molecule is released (from the E-site)
- The elongation and translocation processes continue along the mRNA coding sequence in a 5' → 3' direction

Termination *(component disassembly)*
- When a ribosome reaches a STOP codon, a polypeptide is released and the ribosome disassembles into subunits



Protein Destinations

In prokaryotes, the absence of a nuclear membrane allows translation to occur immediately after transcription

In eukaryotes, translation will occur at one of two locations:
- Free ribosomes *(cytosolic)* synthesise intracellular proteins
- Bound ribosomes *(rER)* synthesise proteins destined for secretion from the cell or for use in lysosomes

TOPIC 8.1: METABOLISM

Metabolic Pathways

Metabolism describes the sum total of all chemical reactions that occur within an organism in order to maintain life

- Metabolic processes are controlled and coordinated by a series of enzyme-catalysed reactions
- Metabolic pathways are typically organised into chains (e.g. glycolysis) or cycles (e.g. Krebs cycle, Calvin cycle)

Enzyme Action

Every chemical reaction requires a certain level of energy in order to proceed – this is called the **activation energy (E_A)**

Enzymes speed up reaction rates by *lowering* the activation energy threshold (destabilise substrate bonds = ⬆ product conversion)

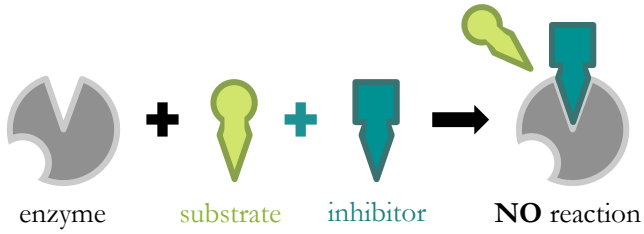
- If reactants contain *more* energy than the products, the reaction is **exergonic** as energy is released (e.g. catabolic reactions)
- If reactants contain *less* energy than the products, the reaction is **endergonic** as energy is absorbed (e.g. anabolic reactions)

Enzyme Inhibition

Competitive Inhibition

- Inhibitor is structurally similar to the substrate
- It directly blocks the active site of the enzyme
- Increasing substrate concentration will reduce inhibition

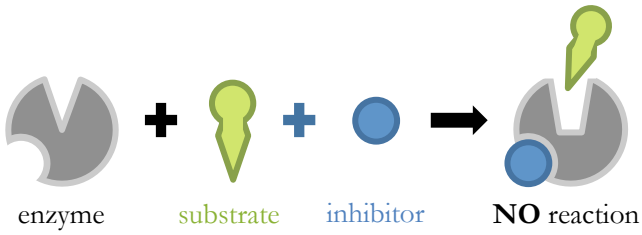
Example: Treating influenza with a neuraminidase inhibitor



Non-Competitive Inhibition

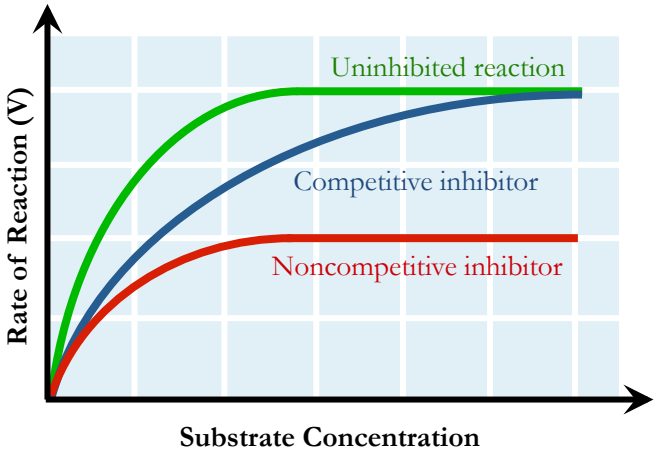
- Inhibitor is not structurally similar to the substrate
- It binds to an allosteric site (not the active site)
- It induces a conformational change in the active site

Example: Cyanide as an inhibitor of cytochrome oxidase



Enzyme Kinetics

Enzyme inhibitors lower reaction rates by reducing levels of uninhibited enzymes *(reaction rate = 1 / time taken)*



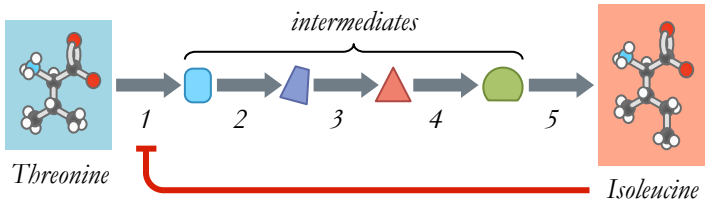
Feedback Inhibition

Metabolic pathways can be controlled by feedback inhibition *(end product inhibition)*, where a product inhibits an earlier step

- This ensures product levels are always tightly regulated

Example: Isoleucine Synthesis

- Threonine deaminase convert threonine into isoleucine
- Isoleucine inhibits the enzyme's activity *(non-competitive)*
- Thus, isoleucine synthesis inhibits further formation



Rational Drug Design

Inhibitors can be used to treat infectious diseases by targeting the enzymes involved in pathogenesis (e.g. anti-malaria drugs)

- Inhibitors can be identified by database mining (bioinformatics) or constructed via combinatorial chemistry techniques

TOPIC 8.2: AEROBIC RESPIRATION

Redox Reactions

Biological energy can be stored or released by *redox reactions*

- **O**xidation **i**s the **L**oss of electrons / hydrogen (OIL)
- **R**eduction **i**s the **G**ain of electrons / hydrogen (RIG)

	Oxidation	*Reduction*
Electrons	Loss	Gain
Hydrogen	Loss	Gain
Oxygen	Gain	Loss

OIL RIG

Electron carriers transfer chemical energy via *redox reactions*

- Organic molecules are oxidised to form reduced carriers
- The reduced carriers may then be oxidised to form ATP

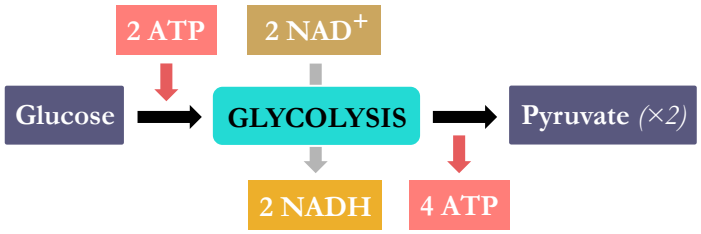
Glycolysis

Aerobic respiration is preceded by glycolysis (anaerobic)

- Glucose is broken down to form two pyruvate molecules

The process of glycolysis involves four basic stages:

- Glucose is *phosphorylated* by ATP (becomes less stable)
- The 6C sugar splits *(lysis)* into two triose phosphates (3C)
- 3C sugars are *oxidised* to form reduced carriers (NADH)
- A small amount of ATP is produced (net gain = 2 ATP)



Aerobic Respiration

Link Reaction:

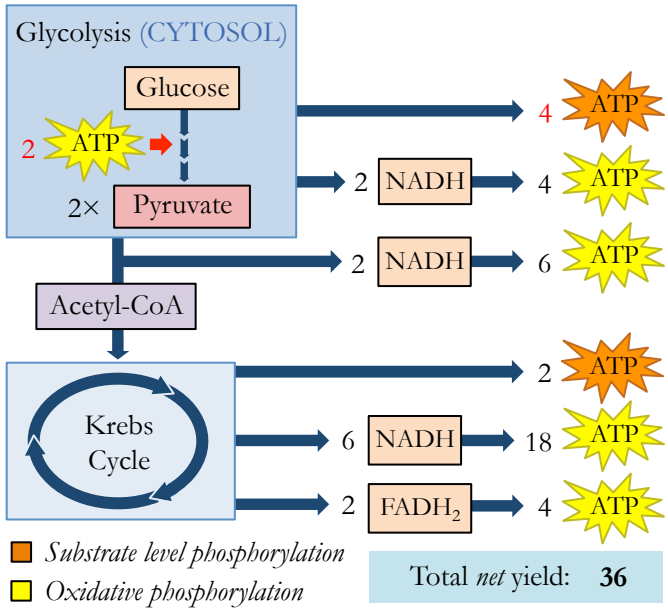
- Pyruvate transported from cytosol to mitochondrial matrix
- Pyruvate oxidised to produce a reduced carrier *(NADH)*
- Pyruvate decarboxylated to form acetyl CoA *(CO_2 produced)*

Krebs Cycle:

- Acetyl CoA is combined with a 4C compound *(forms 6C)*
- 6C compound broken down into original 4C *(CO_2 produced)*
- This involves oxidation reactions *(NADH / $FADH_2$ formed)*
- There is also a small yield of ATP *(one per cycle)*

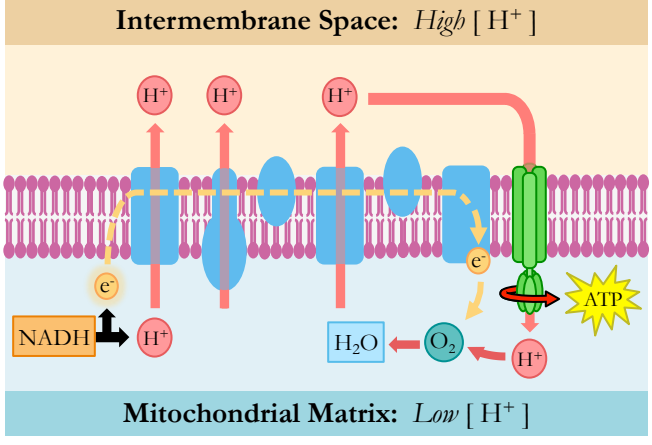
Electron Transport Chain:

- Reduced carriers are oxidised at the electron transport chain
- The energy is used to make ATP *(via oxidative phosphorylation)*
- 32 ATP molecules are made from the reduced carriers



Oxidative Phosphorylation

- Carrier molecules donate electrons *(oxidation)* to an electron transport chain located on the mitochondrial cristae
- The electrons lose energy as they are passed along the chain, which is used to pump protons (H^+ ions) from the matrix
- The build up of protons in the intermembrane space creates an electrochemical gradient *(proton motive force)*
- Protons return to the matrix via a transmembrane enzyme *(ATP synthase)*, which uses the translocation to make ATP
- The de-energised electrons are removed from the chain by oxygen *(final electron acceptor)*, forming water as a by-product



TOPIC 8.3: PHOTOSYNTHESIS

Stages of Photosynthesis

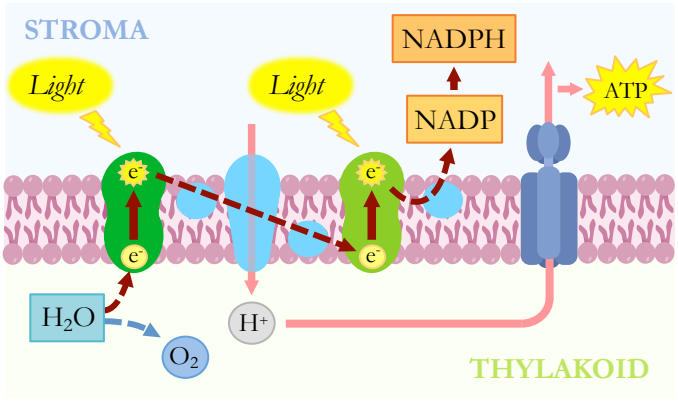
Photosynthesis is a two-step process:

- The light dependent reactions occur in the thylakoids and convert light energy into chemical energy (ATP + NADPH)
- The light independent reactions occur in the stroma and use this chemical energy to make organic compounds

Light Dependent Reactions

Non-Cyclic Photophosphorylation

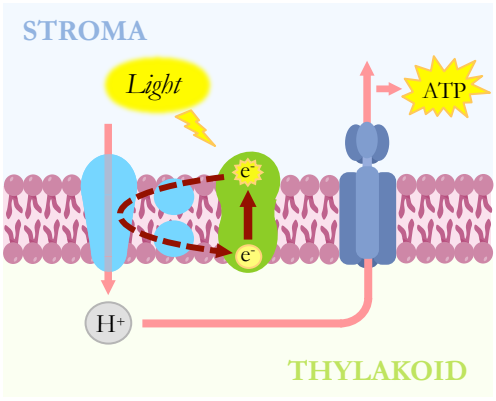
- Chlorophyll in Photosystems I and II absorb light, which triggers the release of energised electrons *(photoactivation)*
- The electrons from PS I reduce NADP (forms NADPH)
- The electrons from PS II move through an electron transport chain before replacing the electrons from PS I
- The transport chain produces ATP *(photophosphorylation)*
- Electrons lost from PS II are replaced by water *(photolysis)*



Photosystem II (P680) Photosystem I (P700)

Cyclic Photophosphorylation

- Only chlorophyll in Photosystem I are activated by light
- The electrons move through an electron transport chain before returning to their original location (i.e. cyclic)
- The transport chain produces ATP *(photophosphorylation)*
- Cyclic photophosphorylation does not produce NADPH
- Hence, while cyclic photophosphorylation can produce usable energy (ATP), it cannot produce organic molecules



Photosystem I (P700)

Light Independent Reactions

Step 1: Carbon Fixation

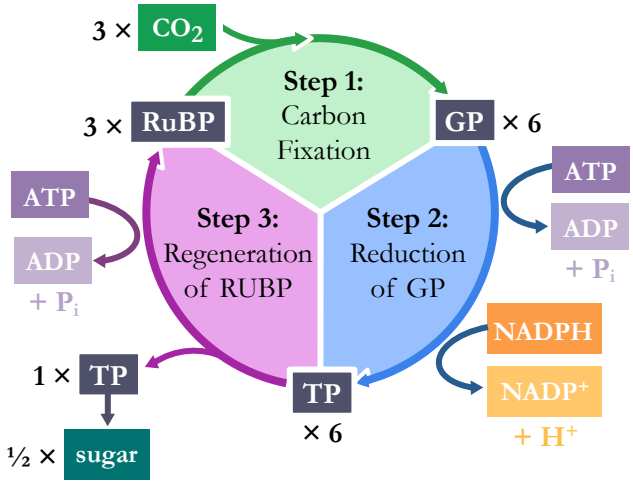
- *Rubisco* catalyses the carboxylation of RuBP (requires CO_2)
- This forms two 3C compounds called GP

Step 2: Reduction of GP

- GP is phosphorylated by ATP and reduced by NADPH
- This converts each GP molecule into a TP molecule

Step 3: Regeneration of RuBP

- One molecule of TP is used to form half a sugar *(two complete cycles are needed to form a glucose molecule)*
- The remaining TP molecules are used to reform RuBP



Lollipop Experiment

The light independent reactions were elucidated by Melvin Calvin (i.e. Calvin cycle) using a 'lollipop'-shaped apparatus

- Radioactive CO_2 was incorporated to identify the different carbon compounds *(involves chromatography and autoradiography)*

TOPIC 9.2: PHLOEM TRANSPORT

Active Translocation

Plants transport organic molecules from source to sink

- **Source:** Photosynthetic tissues (e.g. leaves)
- **Sink:** Storage organs (e.g. fruits, seeds, roots)

Organic molecules are transported via vessels called **phloem**

- Organic molecules are loaded and unloaded into the phloem by companion cells at the source and sink

The active loading of solutes at the source creates high solute concentrations within the viscous phloem fluid (sap)

- Water is drawn into the phloem from the xylem (osmosis)

The incompressibility of water causes the sap volume to be increased, creating a pressure gradient (i.e. mass flow)

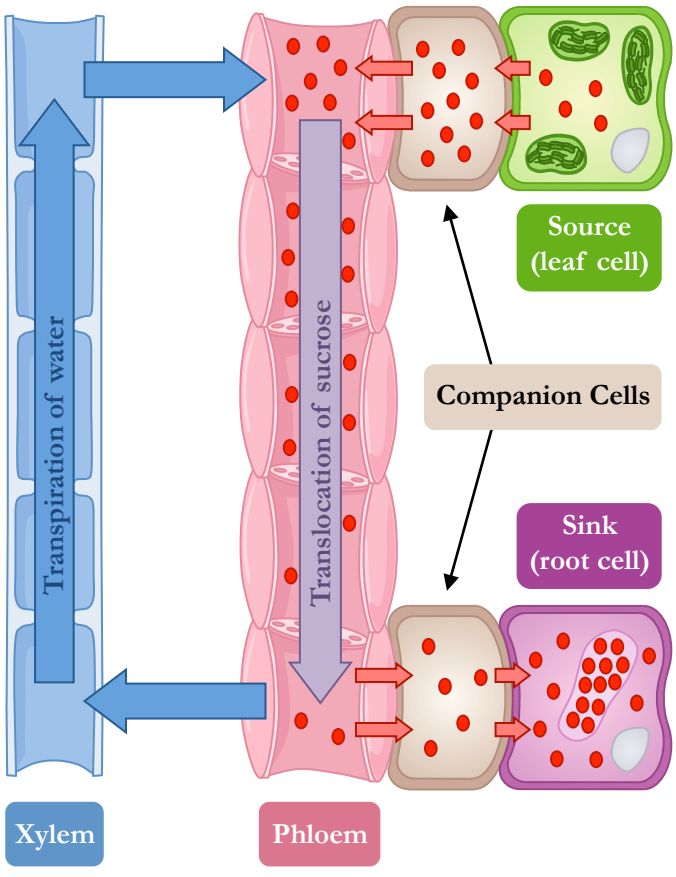
- Mass flow drives sap along the phloem (source to sink)

Organic molecules are actively unloaded at the sink, which lowers solute concentrations (and water returns to the xylem)

- Loss of water lowers the hydrostatic pressure at the sink, maintaining the pressure gradient (and mass flow)

Carbohydrates are usually transported in the phloem as sucrose, but are typically stored within the sink as starch

Active Translocation Within the Phloem



Xylem versus Phloem

Xylem:

- Composed of a perforated inner layer of dead cells that are fused into a continuous tube (vessel element)
- The cell walls have thickened cellulose are reinforced with lignin (spiral or annular arrangement)

Phloem:

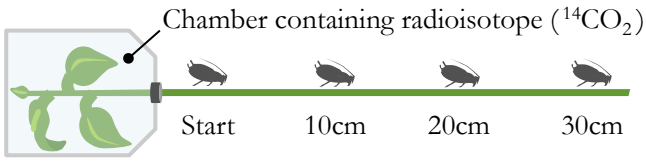
- Composed of living cells connected by porous plates at their transverse ends (sieve elements)
- Are supported by companion cells that are connected via plasmodesmata to mediate material exchange

	XYLEM	PHLOEM
Process	Transpiration	Translocation
Materials	Water, minerals	Organic nutrients
Transport	Unidirectional	Bidirectional
Composition	Vessel element and tracheid	Sieve element and companion cell
Structure	Dead cells form a hollow tube	Living cells form a tube with plates
Location	Inner or central region of bundle	Outer region of vascular bundle

Translocation Rate

Translocation rates can be measured using aphid stylets

- Aphids are insects that feed on the sap in phloem via a protruding mouthpiece called a stylet
- If the stylet is severed, the sap will continue to flow from the plant and can be collected and measured
- Plants exposed to radioactive carbon dioxide will produce radioactively labelled sugars within the phloem
- The rate of translocation can be identified by the time taken for radioisotopes to be detected along the phloem



Distance from start	10 cm	20 cm	30 cm
Time ^{14}C detected	1.25 hr	2.5 hr	5.0 hr
Translocation Rate	8 cm/hr	8 cm/hr	6 cm/hr

TOPIC 9.3: PLANT GROWTH

Meristems

Meristems are undifferentiated cells in plants that are capable of indeterminate growth *(analogous to totipotent stem cells)*

- They have specific regions of growth or development and allow for regrowth and vegetative propagation

Meristematic tissue can be characterised as either:

- **Apical** – Occurs in shoots and roots and is responsible for primary growth (i.e. lengthening) and leaf development
- **Lateral** – Occurs at the cambium and is responsible for secondary growth (i.e. widening) and the production of bark

Auxin

Plant hormones (specifically auxins) control growth in the shoot apex by stimulating or inhibiting cell division (mitosis)

- Auxin efflux pumps can set up concentration gradients of auxin in plant tissues to allow for differentiated growth rates

Auxin is released by the shoot apical meristem and coordinates both apical growth and directional growth (tropism)

- Auxin influences cell growth rates by changing the pattern of gene expression within the plant tissue

Apical Growth

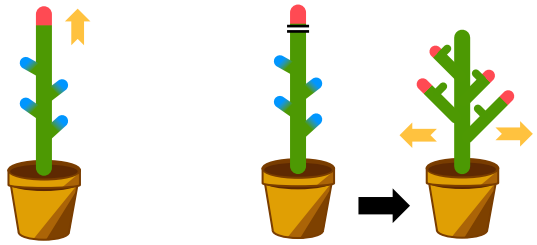
Growth in the shoot apex allows for the extension of the stem and the development of leaves (primary growth)

In the stem, growth occurs in sections called nodes, with the remaining meristem tissue forming inactive axillary buds

- Axillary buds have the potential to form new shoots

Auxins promote growth in apex but inhibit growth in buds

- This condition is known as **apical dominance**



Apical Dominance
vertical growth

Pruning Terminal Bud
lateral growth

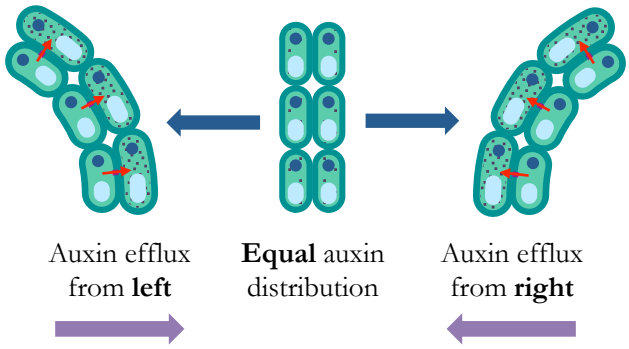
Tropisms

A tropism is the turning of an organism in response to a directional external stimulus (e.g. light = phototropism)

Plant tropisms are caused by the differential elongation of plant cells (plant turns *away* from side with cell elongation)

Tropisms may differ according to the type of plant tissue

- In plant **shoots**, auxin *promotes* cell elongation
- In plant **roots**, auxin *inhibits* cell elongation



Auxin efflux from **left**

Equal auxin distribution

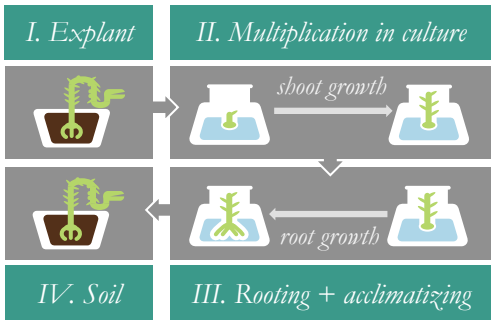
Auxin efflux from **right**

Micropropagation

Micropropagation is an in vitro technique used to produce large numbers of identical plants (i.e. clones) from a selected stock plant

- Tissue sample *(explant)* is grown in agar and treated with growth hormones
- Growing shoots are divided and transferred to soil to form new plants

Micropropagation can be used for the rapid bulking up of new plant varieties, the production of virus-free stains of existing varieties and the propagation of rare plant species (e.g. certain types of orchids)



TOPIC 9.4: PLANT REPRODUCTION

Flowering Plants

Flowers are the reproductive organs of certain types of plants and develop from changes to gene expression in the shoot apex

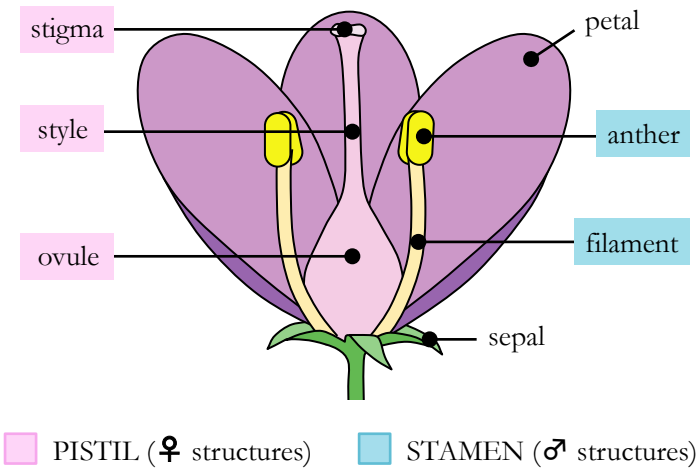
Sexual reproduction in flowering plants (angiosperms) involve three key stages:

- **Pollination** – The transfer of pollen from the anther to the stigma (usually occurs between different plants)
- **Fertilisation** – The fusion of the male gamete nuclei (in pollen) with the female gamete nuclei (in ovule)
- **Seed Dispersal** – The fertilised ovule (seed) moves away from the parent plant to reduce the competition for growth

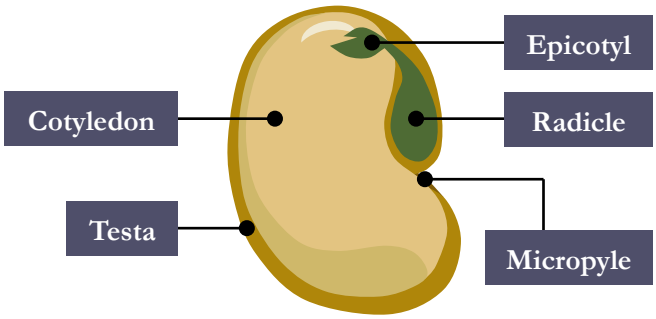
Most flowering plants will employ a mutualistic relationship with pollinators (e.g. birds, bees) in order to reproduce

- The plant gains a mechanism of pollen transfer, while the animal gains a source of nutrition (plant nectar)

Flower Structure



Seed Structure



Germination

Germination is the process by which a seed emerges from a period of dormancy and sprouts (forming a new plant)

Germinating seeds require the following conditions:

- Oxygen (to produce ATP via aerobic respiration)
- Water (to metabolically activate the cells)
- Suitable temperature and pH (for enzyme activity)

Photoperiodism

Flowering in plants is controlled by **photoperiodism**

- The response of a plant to the length of day or night

Flowering is regulated by *phytochrome* which exist in 2 forms:

- Inactive red form (P_r) absorbs red light (to become P_{fr})
- Active far red form (P_{fr}) absorbs far red light (forms P_r)

Sunlight contains more red light, so:

- The active far red form is predominant during the day
- Reverts to mainly the inactive red form at night

Flowering is triggered by the active form, but effects differ

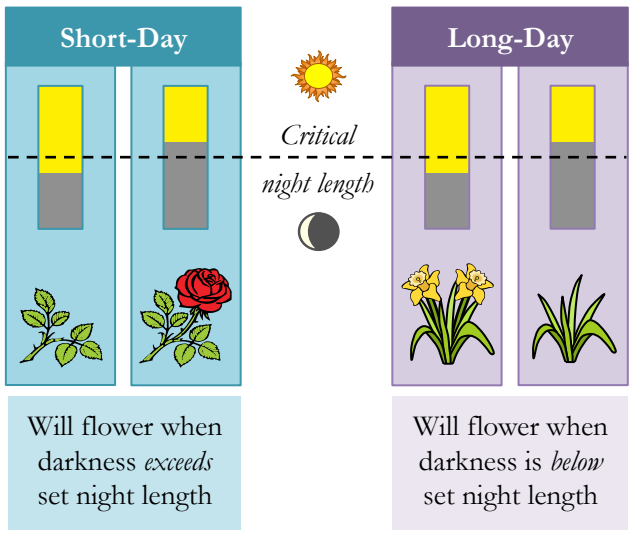
- Flowering requires a set length of *uninterrupted darkness*

Long Day Plants:

- P_{fr} **activates** flowering in long-day plants
- Flowering induced when night length is short (⬆ P_{fr})

Short Day Plants:

- P_{fr} **inhibits** flowering in short day plants
- Flowering induced when night length is long (⬇ P_{fr})



TOPIC 10.1: MEIOSIS

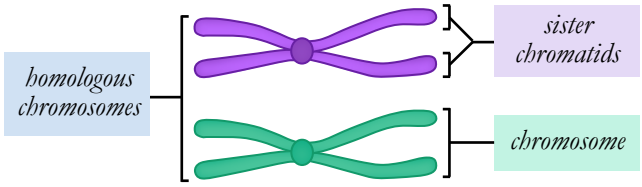
Homologous Pairs

The chromosomes of sexually reproducing organisms are **homologous** (i.e. they exist in pairs)

- There is a paternal copy and a maternal copy (sex chromosomes may not be homologous)

Chromosomes will replicate during interphase to form genetically identical sister chromatids

- These chromatids are separated during meiotic division to become autonomous chromosomes

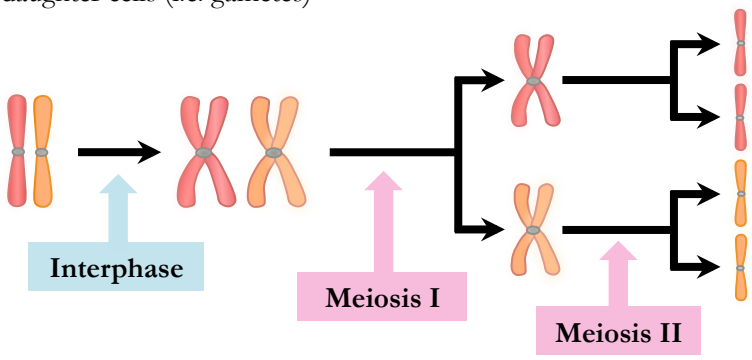


Meiotic Divisions

Meiosis produces haploid gametes via two nuclear divisions:

- Homologous pairs are separated during meiosis I
- Sister chromatids are separated during meiosis II

The final outcome of meiosis is four genetically distinct haploid daughter cells (i.e. gametes)



Random Assortment

During Metaphase I, homologous pairs of chromosomes line up in a random orientation along the equator

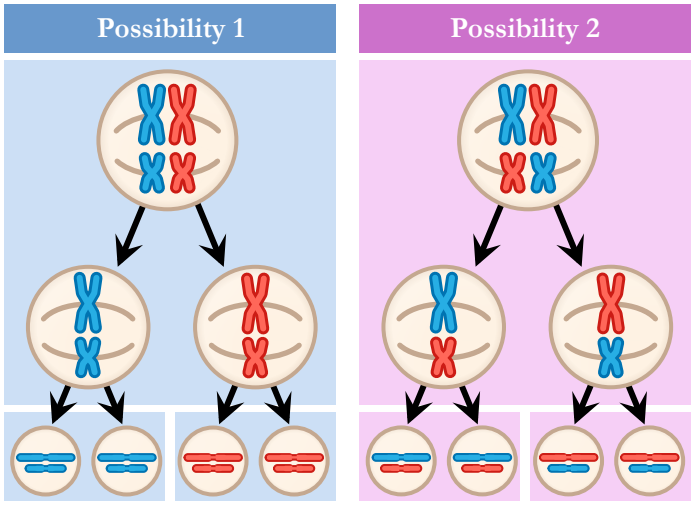
This means there is an equal chance of a gamete containing either the maternal or paternal copy of a given chromosome

The orientation of each homologous pair is independent to the orientation of any other homologous pair

The number of potential chromosome combinations can be determined by the formula: $\mathbf{2^n}$ *(where n = haploid number)*

As humans have a haploid number of 23, they can produce 2^{23} gamete combinations via random assortment

- $2^{23} > 8$ million different combinations



Four gamete combinations are possible (2^n)

Crossing Over

During Prophase I, homologous pairs of chromosomes form points of connection between non-sister chromatids

The connection points form via a process known as synapsis and the resulting complex is called a bivalent (or tetrad)

While in synapsis, non-sister chromatids may break and recombine with their homologous partner (crossing over)

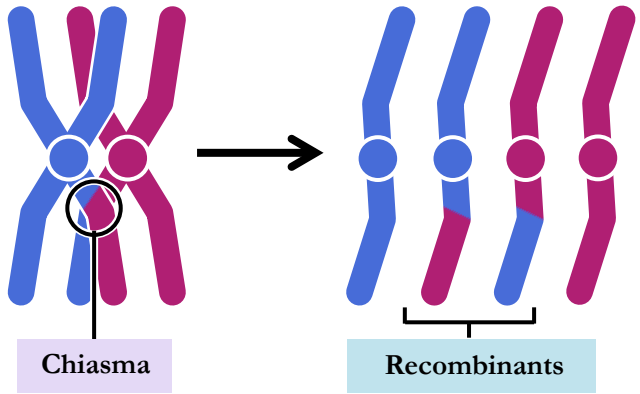
- Crossing over may result in the exchange of alleles

The non-sister chromatids remain physically connected at points of exchange (chiasmata) until separated by anaphase

Recombinants

The non-sister chromatids that have had genetic material exchanged are called recombinants

- Recombination may result in novel allele combinations



TOPIC 10.2: CHI-SQUARED TEST

Worked Example

A chi-squared test can be applied to phenotypic ratios to determine if there is a statistically significant likelihood that two particular genes are linked or unlinked

Case Study: Pea Plant Inheritance Patterns

Peas can be considered smooth (R) or wrinkled (r) **and** yellow (Y) or green (y)

Two heterozygous plants (RrYy) were crossed to give the following results:

- Smooth / yellow = 701 plants
- Smooth / green = 204 plants
- Wrinkled / yellow = 243 plants
- Wrinkled / green = 68 plants

Pea Phenotype	Observed
= smooth/yellow	701
= smooth/green	204
= wrinkled/yellow	243
= wrinkled/green	68
Total	**1216**

Step 1: Identify Expected Frequencies

There are two possibilities regarding the phenotypic ratios of the two genes:

- *Null Hypothesis (H_0)* – There is **no** association (i.e. genes are unlinked)
- *Alternative Hypothesis (H_1)* – There **is** an association (i.e. genes are linked)

A table is constructed to identify *expected* frequencies of distribution *(unlinked)*

- This data will be compared against the *observed* values previously identified

The expected ratios are calculated using a dihybrid cross (ratios = 9 : 3 : 3 : 1)

- The ratios are applied to total population to determine expected frequencies

Pea	Ratio	Expected
	9/16 × 1216	684
	3/16 × 1216	228
	3/16 × 1216	228
	1/16 × 1216	76
Total	9 : 3 : 3 : 1	1216

Step 2: Apply the Chi-Squared Formula

The chi-squared (χ^2) formula calculates a value based on a comparison of the observed frequencies (O) and the expected frequencies (E)

$$\chi^2 = \sum \frac{(O - E)^2}{E}$$

Based on the worked example, the value calculated by the chi-squared test is:

- $\chi^2 = 0.42 + 2.53 + 0.99 + 0.84 =$ **4.76**

A degree of freedom *(df)* will also be required to determine statistical significance

- **df** = (number of rows – 1) × (number of columns – 1)

Raw data table had 4 rows and 2 columns, so degree of freedom equals **three**

Pea	O	E	$\frac{(O-E)^2}{E}$
	701	684	0.42
	204	228	2.53
	243	228	0.99
	68	76	0.84

Step 3: Determine Significance

The chi-squared value is used to determine statistical significance (p value)

- $p<0.05$ is considered significant (less than 5% likelihood results due to chance)

Based on the worked example, a value of 4.76 lies below a p value of 0.05

- This means results are **not** significant (>5% probability it is due to chance)

The alternative hypothesis can be rejected and the null hypothesis accepted

- It is statistically unlikely that the genes are linked (they are likely unlinked)

		df
		3
p value	0.01	11.345
	0.05	7.815
	0.25	4.110

Values that are greater than this are statistically significant

TOPIC 10.2: INHERITANCE

Unlinked Genes

The inheritance of two different genes / traits will occur *independently* provided the genes are on separate chromosomes

- This is because unlinked genes segregate independently during meiosis (random assortment of homologous pairs)

Mendel's Law of Independent Assortment

- Separation of alleles for one gene occurs independently of the separation of alleles for another gene

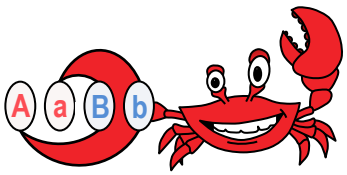
Dihybrid Crosses

Dihybrid crosses determine allele combinations of offspring for two genes that are **unlinked** (on different chromosomes)

- 2 genes × 2 alleles = 4 potential gamete combinations

Gamete combinations are calculated via the FOIL method:

- **F**irst (**A**a**B**b = AB)
- **O**utside (**A**aB**b** = Ab)
- **I**nside (A**a**B**b** = aB)
- **L**ast (A**a**B**b** = ab)



Once gamete combinations are identified, a punnett square is then used to calculate genotype and phenotype frequencies

Example:

Pea seed cross (heterozygous)

YyRr × YyRr

Y = yellow
y = green
R = round
r = wrinkled

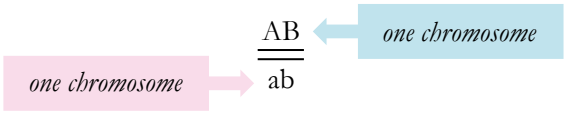
	YR	Yr	yR	yr
YR	YYRR	YYRr	YyRR	YyRr
Yr	YYRr	YYrr	YyRr	Yyrr
yR	YyRR	YyRr	yyRR	yyRr
yr	YyRr	Yyrr	yyRr	yyrr

Linked Genes

A linkage group describes a group of genes whose loci are on the same chromosome (i.e. linked genes)

- Linked genes will function as a single inheritable unit and will **not** follow the law of independent assortment

Linked genes are represented as pairs:



Linked genes can be separated (unlinked) by crossing over

- The novel allele combinations are called **recombinants**

Recombinant phenotypes will only be evident if crossing over has occurred and thus occur at **lower frequencies**

- Frequency increases the further apart the two genes are

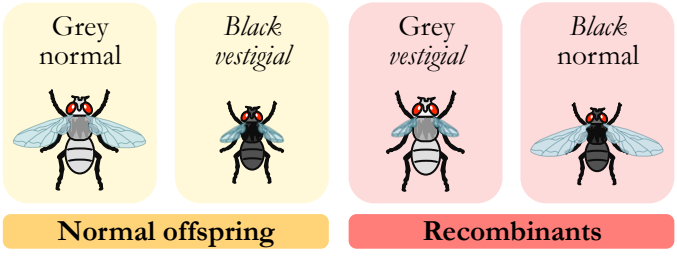
Linkage Studies

Thomas Morgan determined the concept of gene linkage via breeding experiments involving fruit flies *(Drosophila)*

Morgan identified a number of different traits that did not conform to Mendelian ratios and surmised the following:

- These traits represented linked genes *(on same chromosome)*
- Linked genes can be uncoupled via recombination, but such events are uncommon *(hence occur at low frequencies)*

Grey/normal wing (B.VG) × Black/vestigial wing (b.vg)



Polygenic Inheritance

Variation can be discrete (finite patterns) or continuous (normal distribution)

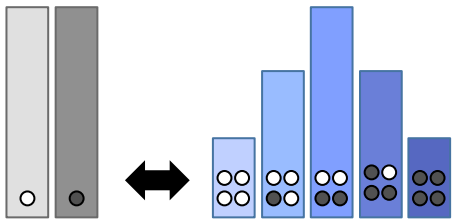
Monogenic traits are characteristics that are controlled by a single gene locus

- They therefore have a finite pattern of expression (discrete variation)

Polygenic traits are characteristics controlled by more than two gene loci

- They exhibit a bell-shaped distribution pattern (continuous variation)

Polygenic traits (e.g. human height) may also be influenced by environment



TOPIC 10.3: GENE POOLS

Gene Pools

Evolution is the change in the *allele frequency* within a *gene pool* over several successive generations

A **gene pool** is the sum total of all the genes (and the alleles) that are present within an interbreeding population

The **allele frequency** refers to the relative proportion of a particular allele within a population

Allele Frequencies

Genetic drift changes the composition of a gene pool due to random / chance events within the population

- There is higher drift in smaller populations *(faster change)*
- There is lower drift in larger populations *(greater stability)*

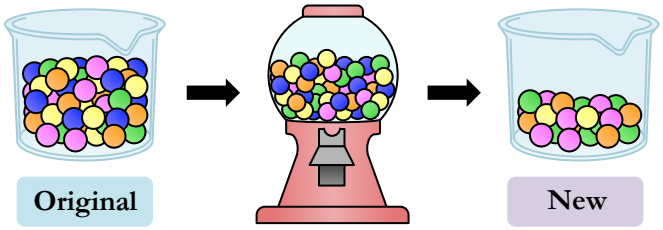
Natural selection changes the composition of a gene pool due to environmental selection pressures

- Selection may be stabilising, directional or disruptive

Genetic Drift

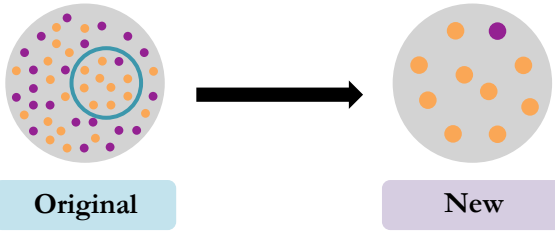
Population Bottlenecks

- Population bottlenecks occur when an event reduces the population size by an order of magnitude
- Surviving population has less genetic variability (⬆ drift)



Founder Effect

- The founder effect describes the establishment of a new population by a fraction of a larger existing population
- The new population has less genetic variability (⬆ drift)

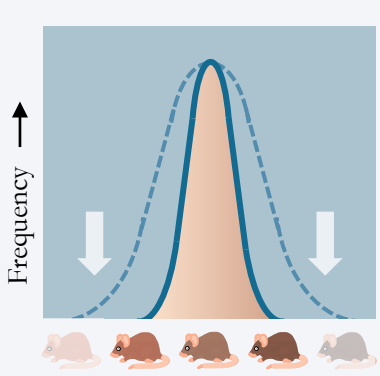


Types of Selection

Stabilising Selection

- When an intermediate phenotype is favored at the expense of extremes
- Operates when conditions are stable
- **Example:** Human birth weights
  - ⇨ Too large = birth complications
  - ⇨ Too small = high infant mortality

Stabilising Selection

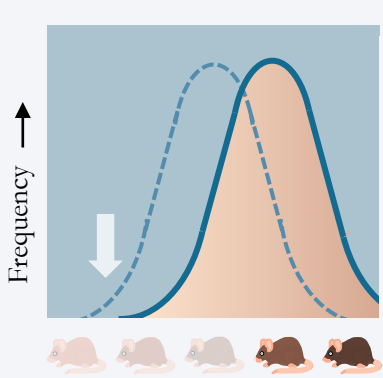


Culls extreme variations
Narrows width of distribution

Directional Selection

- When one phenotypic extreme is selected at the cost of the other
- Operates when conditions change
- **Example:** Antibiotic resistance
  - ⇨ Antibiotic = ⬆ resistance
  - ⇨ No antibiotic = ⬆ susceptibility

Directional Selection

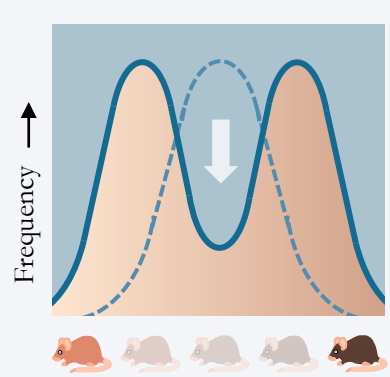


Favours one extreme
Shifts distribution left / right

Disruptive Selection

- When both extremes are favored at the expense of the intermediate
- Operates when conditions fluctuate
- **Example:** Moth pigmentation
  - ⇨ Pigmentation = camouflage
  - ⇨ Benefit depends of conditions

Disruptive Selection



Favours both extremes
Creates bimodal distribution

TOPIC 11.1: ANTIBODY PRODUCTION

Antigens

All organisms have unique molecules on the surface of cells

- Molecules that trigger immune responses are **antigens**

Antigens act to trigger the production of *specific* antibodies

- **E.g.** Antigens on red blood cells will stimulate antibody production in a person with a different blood group

Antibodies

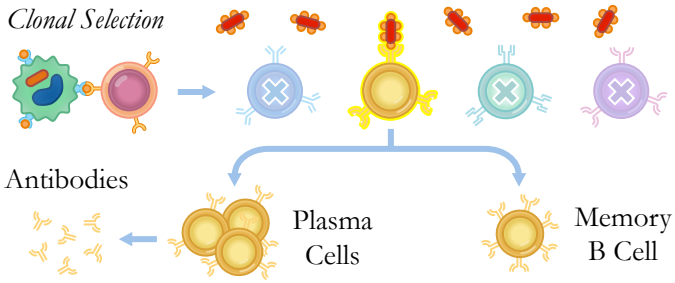
Antibodies aid in pathogen destruction by promoting:

- **P**hagocyte recruitment
- **A**gglutination
- **N**eutralization
- **I**nflammation
- **C**omplement activation

Clonal Selection

Immune systems must be *challenged* with specific antigens in order to initiate an appropriate *response* (antibody production)

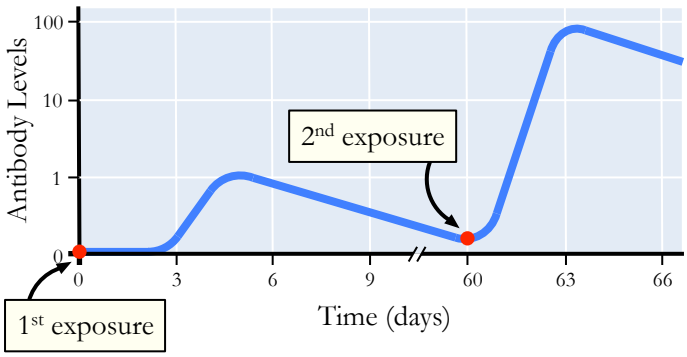
- Macrophages present antigen fragments to T_H cells
- T_H cells activate antigen-specific B cells (clonal selection)
- The B cells divide and differentiate into plasma cells that produce large quantities of specific antibodies
- A small proportion differentiate into B memory cells



Immunological Memory

The adaptive immune response includes the production of memory cells following an initial pathogenic infection

- Memory cells persist for years, secreting antibodies
- If re-infection with the same antigen occurs, memory cells can respond faster and with much greater potency
- As a result, disease symptoms do not develop (immunity)



Vaccination

Vaccines contain attenuated forms of a pathogen (cannot cause the disease, but can stimulate an immune response)

Vaccines induce active immunity by stimulating the presence of memory cells (confers long-term immunity)

When exposed to the actual pathogen, the memory cells will trigger a significantly faster and stronger immune response

- Periodic booster shots may still be required

Smallpox was the first disease eradicated by vaccination

Types of Immunity

Immunity can be **active** (able to produce own antibodies):

- Natural active immunity = normal response to infection
- Artificial active immunity = immunity via vaccination

Immunity can be **passive** (acquires antibodies externally):

- Natural passive immunity = via breastfeeding
- Artificial passive immunity = monoclonal antibodies

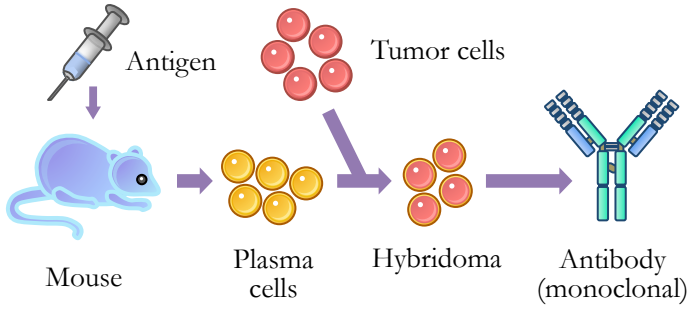
Monoclonal Antibodies

Monoclonal antibodies are antibodies that have been derived from a single B cell clone (i.e. identical specific antibodies)

- An animal (e.g. mouse) is injected with a pathogen to stimulate production of specific plasma cells
- The plasma cells are removed and fused with tumor cells capable of endless divisions
- The hybridoma formed will mass-produce the antibody

Monoclonal antibodies for hCG are used to test pregnancy

- Results detected via enzyme-linked immunosorbant assay



TOPIC 11.2: MOVEMENT

Movement Systems

Skeletons are a rigid framework (internal or external) that provide a surface for muscle attachment (i.e. act as levers)

- Bones are connected to other bones by *ligaments*
- Bones are connected to muscles by *tendons*

Synovial joints are capsules surrounding articulating bone surfaces that allow for certain movements but not others

Muscles provide the force required for movement of bones

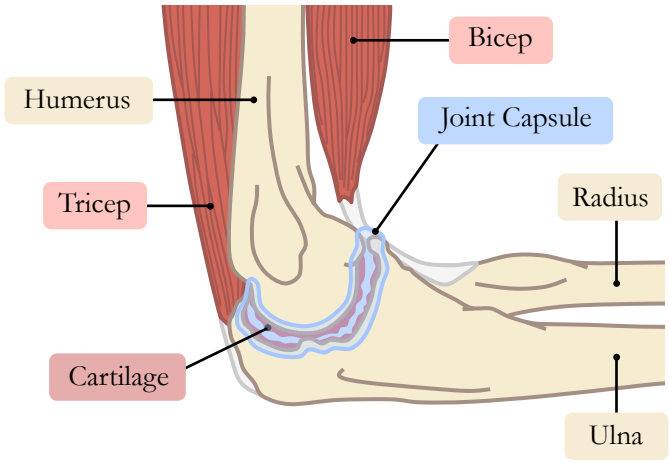
- Muscles work in antagonistic pairs *(one contracts, one relaxes)*
- **E.g.** Flexor and extensor muscles in insect hind leg

Motor neurons provide the stimulus for muscle movement and coordinate sets of antagonistic muscles

Human Elbow Joint

The human elbow joint is an example of a hinge joint

- It is capable of angular movement (flexion / extension)



Muscle Fibres

Skeletal muscles consist of bundles of fibres (formed from fused muscle cells) that have several specialised features:

- They are **multinucleated** (multiple nuclei per fibre)
- There is a large number of **mitochondria** (for ATP)
- Are surrounded by a *continuous* membrane (**sarcolemma**)
- Have a *specialised* ER network (**sarcoplasmic reticulum**)
- Contain many *striated* **myofibrils** (for contraction)

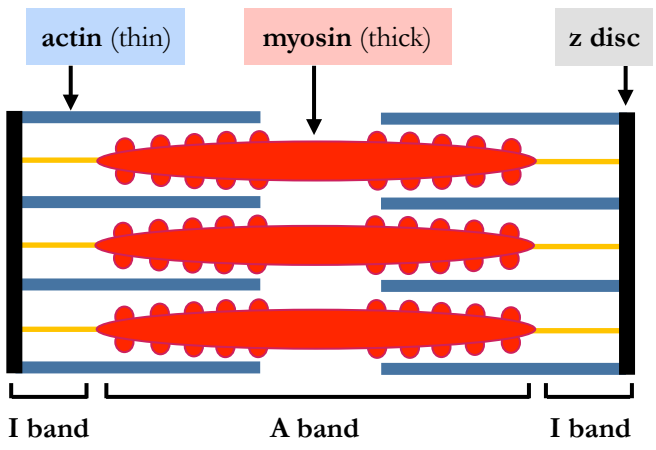
Sarcomeres

Myofibrils are made up of repeating contractile **sarcomeres**

- Sarcomeres contain two myofilaments (actin + myosin)

Myosin (thick) has protruding heads that bind to actin (thin)

- Overlapping of filaments creates a dark central **A** band
- Sarcomere peripheries form light **I** bands (actin only)



Muscle Contraction

Calcium Ion Release

- Motor neurons release acetylcholine (neurotransmitter)
- This triggers sarcolemma depolarisation, causing calcium ions to be released from the sarcoplasmic reticulum

Cross-Bridge Formation

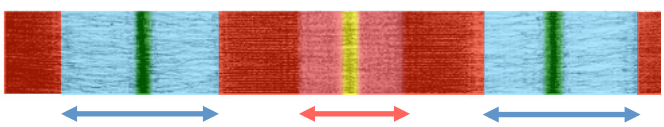
- Calcium ions bind to a complex (troponin/tropomyosin) that blocks actin from binding with the myosin heads
- Calcium ions displace this complex, allowing the actin and myosin heads to form a cross-bridge

Sliding Mechanism

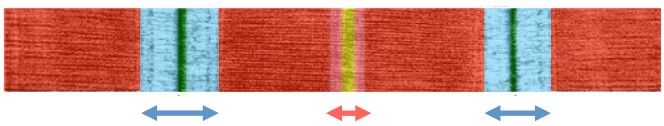
- ATP binds to myosin heads and breaks the cross-bridge
- ATP hydrolysis causes myosin heads to swivel and slide along the actin fibre – this shortens the sarcomere length
- Via repeated ATP hydrolysis, skeletal muscles contract

Muscle Contraction

Fully Relaxed: Wide I bands *(blue)* and wide H zone *(red)*



Fully Contracted: Narrow I bands *(blue)* and H zone *(red)*



TOPIC 11.3: OSMOREGULATION

Stages of Excretion

Nephrons are the functional units of the kidneys
- Are situated in the cortex but descend into the medulla

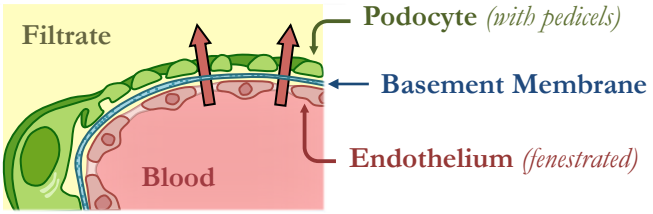
Nephrons mediate excretion via three main stages:
- **Ultrafiltration** – filters out all cells and proteins
- **Selective reabsorption** – retains nutrients / solutes
- **Osmoregulation** – controls water retention

Ultrafiltration

Ultrafiltration occurs at the Bowman's capsule / glomerulus
- Separates cells and proteins from blood to form filtrate

Structure of the Bowman's Capsule

- Glomerular capillaries are fenestrated (have pores), which allows blood to freely exit the glomerulus
- The capsule is lined with podocytes that have extensions (called pedicels) that the blood can freely pass between
- The **only** filtration barrier is the basement membrane that lies between the glomerulus and the capsule



Hydrostatic Pressure (ULTRAfiltration)

- Blood is forced into a Bowman's capsule at high pressure
- Wide afferent arterioles (entry) lead into narrow efferent arterioles (exit), increasing the pressure in the capsule
- Also, the extensive narrow branching of the arterioles increases glomerular surface area available for filtration

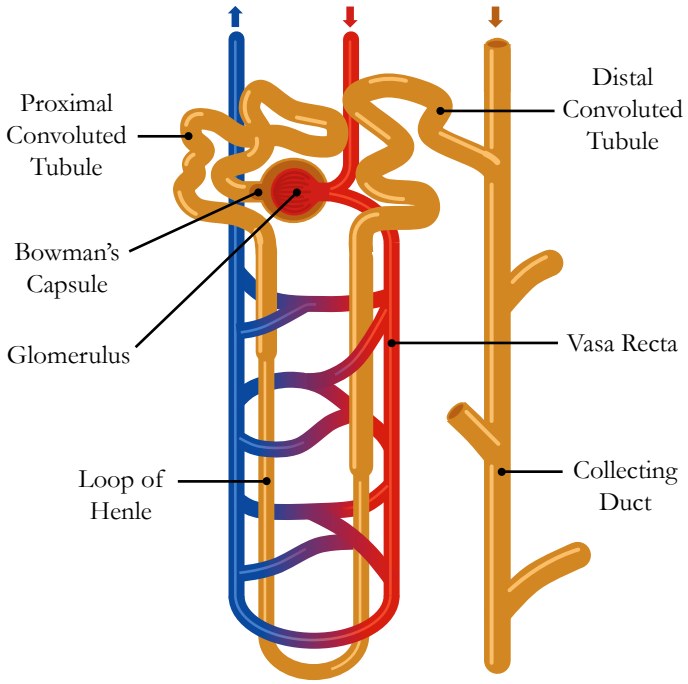
Selective Reabsorption

Selective reabsorption occurs in the convoluted tubules
- Involves the reuptake of usable substances from filtrate

Materials are **actively** transported across the tubule's apical membrane before diffusing across the basolateral membrane
- Tubules are lined with microvilli to increase surface area

Materials reabsorbed by the convoluted tubules include:
- Glucose and amino acids (via symport with sodium ions)
- Mineral ions and vitamins (via protein pumps)
- Water (follows ions and solutes via osmosis)

Nephron



Osmoregulation

Osmoregulation is the control of water balance in the body
- Involves the loop of Henle and collecting ducts

Establishing a Salt Gradient

- The loop of Henle creates a salt gradient in the medulla
- The descending limb is permeable to water but not salt
- The ascending limb is permeable to salts but not water
- This means that as the loop descends into the medulla, the interstitial fluid becomes increasingly hypertonic

Antidiuretic Hormone (ADH)

- As the collecting duct passes through the medulla, the salt gradient draws water **out** of the duct (into blood)
- The amount of water drawn from the ducts is controlled by ADH (released from the posterior pituitary gland)
- ADH produces water channels (aquaporins) to faciliate water reabsorption by the collecting duct
- Levels are high when dehydrated and low when hydrated

Water Conservation

Maintaining water balance is critical to survival *(homeostasis)*
- Dehydration causes blood pressure to drop *(⬆ heart rate)*
- Overhydration causes cells to swell *(leads to organ damage)*

Desert animals will have longer loops of Henle to maximise water conservation *(⬆ salt gradient = ⬆ water reabsorption)*

TOPIC 11.3: THE KIDNEY

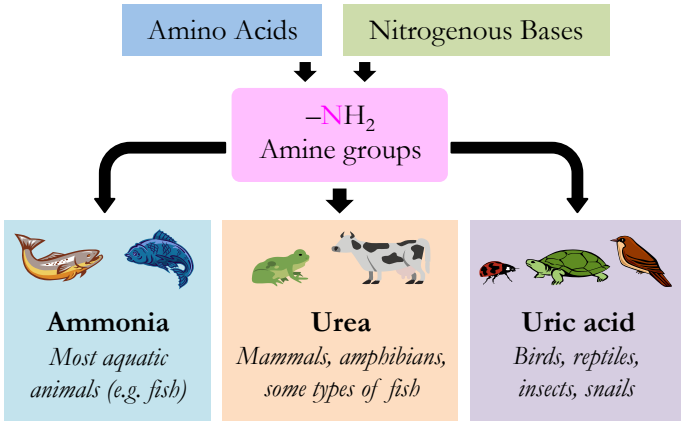
Excretion

Excretion is the removal of waste products from the body
- Wastes are produced as a consequence of metabolism

Excretory systems perform two functions:
- Removes nitrogenous wastes (toxic) from the body
- Removes excess water (maintains osmolarity)

Nitrogenous Wastes

The type of nitrogenous waste produced differs according to an animal's evolutionary history and predominant habitat
- Aquatic animals excrete **ammonia** *(toxic but water soluble)*
- Birds and reptiles excrete **uric acid** *(requires minimal water)*
- Mammals excrete **urea** *(can store at high concentrations)*



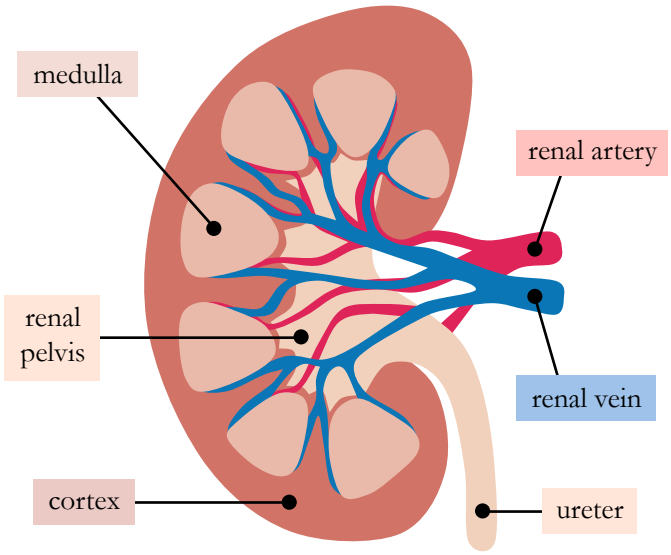
Osmotic Conditions

Animals maintain internal osmotic conditions in two ways:
- *Osmoconformers* match their osmolarity to the environment
- *Osmoregulators* maintain a constant internal osmolarity

Osmoregulation is a more energy intensive process, but it also provides independence from environmental conditions

Animals possess certain structures to enable osmoregulation:
- Insects use a Malpighian tubule system for water balance
- Mammals (e.g. humans) possess kidneys for water balance

Human Kidney



Blood Composition

Blood composition in the renal artery (*before* the kidneys) is different to that in the renal vein (*after* excretory processes)

The renal vein will have:
- Less urea (large amounts are excreted)
- Less water (variable amounts are excreted)
- Similar amounts of nutrients (mostly reabsorbed)
- The same amount of proteins (not filtered)

Urinary Analysis

Kidneys filter waste products from the bloodstream
- Hence, the presence of non-waste substances in the urine is a potential indicator of a disease condition

Urinary analysis can be used to test for:
- **Glucose:** Presence in urine may indicate diabetes
- **Protein:** Indicate certain diseases / hormonal conditions
- **Blood cells:** Suggestive of infectious diseases or cancers
- **Drugs:** Indicates illicit use (e.g. performance enhancers)

Kidney Disease

Kidney diseases incapacitate the ability of the kidney to filter waste products from the bloodstream (leading to toxic build up)

Kidney failure can be treated by **hemodialysis** (a patient's blood is pumped through an external machine to remove wastes)
- Hemodialysis treatments typically last several hours (~4 hrs) and must be performed multiple times in a week (~3×)

Kidney failure can alternatively be treated via **kidney transplant** with a compatible donor (donor *can* survive with one kidney)

TOPIC 11.4: EMBRYOGENESIS

Fertilisation

Fertilisation involves the fusion of male and female gametes
- Animal fertilisation can be internal or external

Human fertilisation is internal and involves key three stages:

Capacitation
- Uterine chemicals dissolve the sperm's cholesterol coat, improving its mobility

Acrosome Reaction
- The acrosome releases hydrolytic enzymes which soften the glycoprotein matrix of the jelly coat *(enables penetration)*

Cortical Reaction
- Cortical granules release enzymes to destroy the sperm binding sites on the jelly coat (prevents polyspermy)

Implantation

After fertilisation, the **zygote** undergoes several mitotic divisions to form a bundle of cells (called a **morula**)

Unequal division of a morula results in a **blastocyst**, with:
- An inner cell mass (develops into an *embryo*)
- An outer layer called the trophoblast (forms the *placenta*)
- A fluid-filled cavity (blastocoele)

These developments occur in the *oviduct* – when a blastocyst reaches the uterus, it becomes embedded in the *endometrium*

Zygote Morula Blastocyst

Pregnancy

When a blastocyst implants within the endometrium, it begins to secrete hCG (human chorionic gonadotropin)

hCG prevents the degeneration of the corpus luteum in the ovary (which continues to produce estrogen + progesterone)

Progesterone maintains the endometrium until the placenta develops (at which point, levels of hCG will begin to drop)

Placenta

The placenta functions to provide support to the fetus:
- It is disc-shaped and connected via an umbilical cord

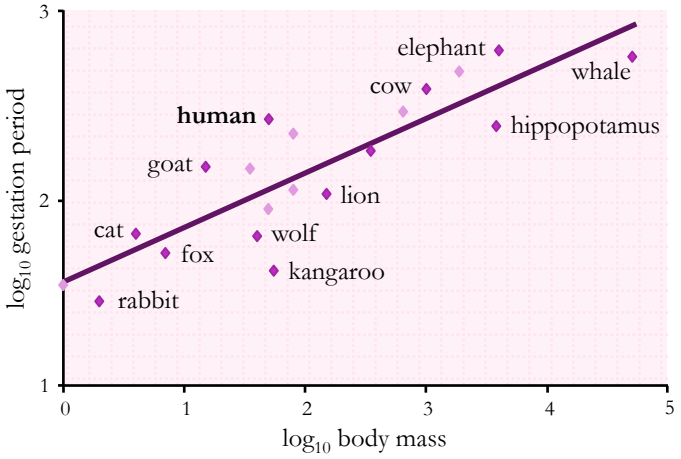
The placenta exchanges materials between mother and fetus
- Maternal blood pools via *open-ended arterioles* into **lacunae**
- Fetal *chorionic villi* extend into lacunae to transfer material
  - ⇨ Nutrients/oxygen/antibodies are transferred to fetus
  - ⇨ Carbon dioxide/waste (urea) is transferred to mother

The placenta produces hormones required for pregnancy
- *Progesterone:* Develops endometrium / stops contractions
- *Estrogen:* Develops myometrium and mammary glands

Gestation Periods

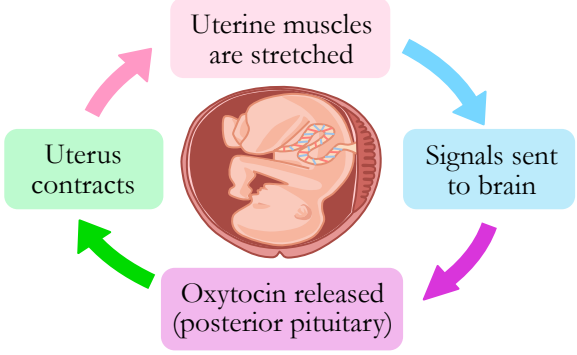
A gestation period is the time taken for a fetus to develop
- Altricial animals are born helpless *(need extensive rearing)*
- Precocial animals are born developed *(no rearing needed)*

While other factors contribute, there is a positive correlation between animal size and development of young at birth



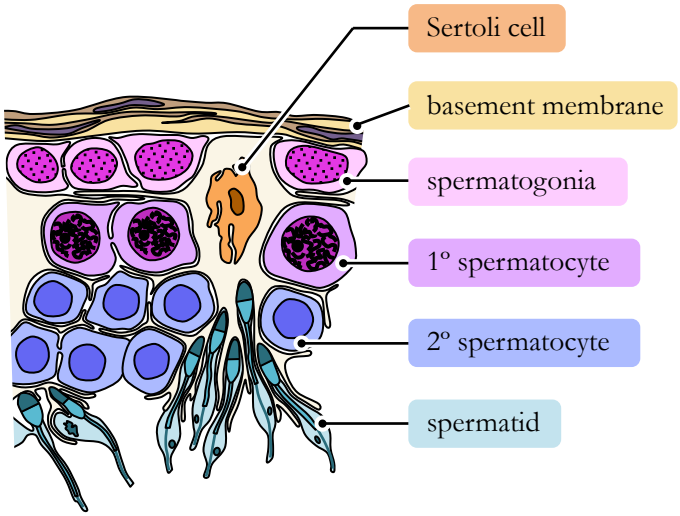
Birth

Birth involves **positive feedback** *(response reinforces change)*
- Stretching of the uterus triggers hormonal release
- Oxytocin stimulates uterine contractions
- Estrogen inhibits progesterone *(was blocking contractions)*

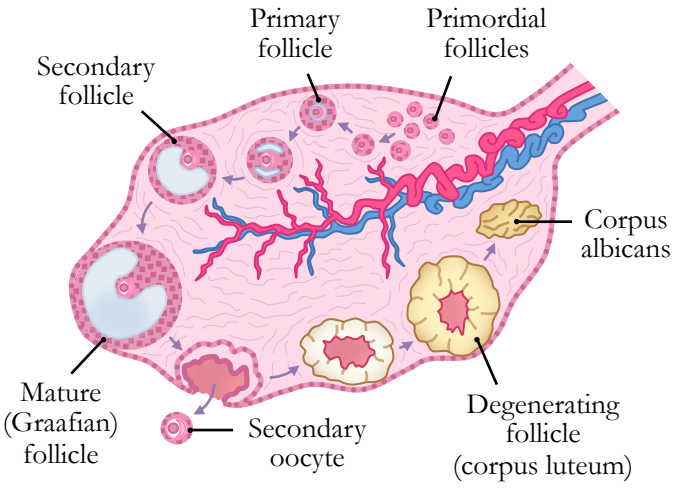


TOPIC 11.4: GAMETOGENESIS

Male Reproductive Tissue



Female Reproductive Tissue



Spermatogenesis

Spermatogenesis occurs in seminiferous tubules and involves mitosis, cell growth, two meiotic divisions and differentiation

- Four gametes are produced per germ cell
- Each gamete differentiates into a spermatozoa
- Gametes are produced continuously from puberty

This process is induced by **testosterone** (from Leydig cells)

- Sertoli cells nourish the developing spermatozoa

Oogenesis

Oogenesis occurs in the ovaries and involves mitosis, cell growth, two (unequal) meiotic divisions and differentiation

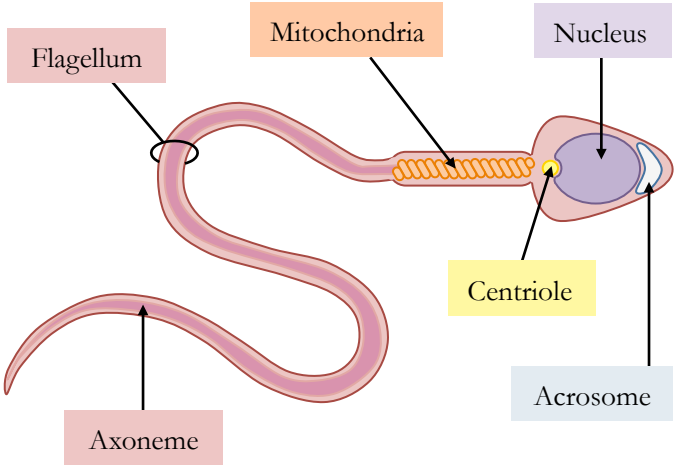
- Only one gamete is produced per germ cell due to the unequal division of cytoplasm (polar bodies degenerate)
- The process occurs in staggered stages:
  - ⇨ Begins in foetal development *(arrested in Prophase I)*
  - ⇨ Continues via menstrual cycle *(arrested in Metaphase II)*
  - ⇨ Only completed following fertilisation by sperm

Sperm

A human spermatozoa consists of three main sections:

- **Head** – contains nucleus, acrosome and centriole
- **Midpiece** – contains mitochondria (ATP source)
- **Tail** – Flagellum bends to facilitate movement

Structure of a Human Sperm

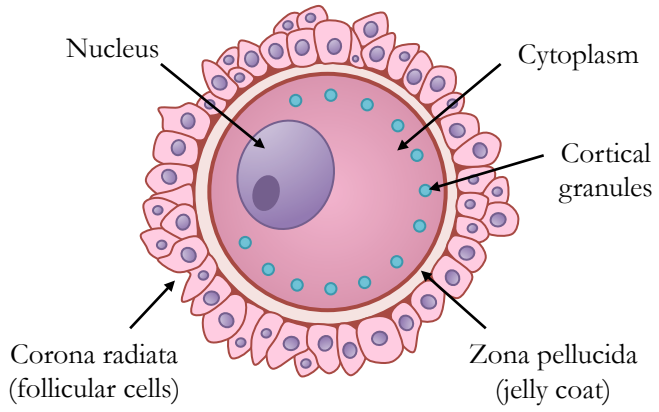


Egg

A human egg cell (ovum) is surrounded by two layers:

- **Zona pellucida** – a jelly coat that mediates sperm entry
- **Corona radiata** – follicular cells that nourish the egg (meiosis only completed when sperm provides centriole)

Structure of a Human Egg



N.B. Egg cells are arrested in metaphase II until fertilisation and do **not** have a condensed nucleus – drawings include this structure to indicate the haploid DNA