QCE Biology — Units 3 & 4

Detailed Process Notes

Comprehensive step-by-step revision notes for major biological processes across Units 3 & 4

Water, carbon and nitrogen cycles

Syllabus: *Describe the transfer and transformation of matter (water, carbon, nitrogen) as it cycles through ecosystems.*

Water cycle

- Evaporation — the sun heats water on the surface of oceans, rivers and lakes, converting it to water vapour.
- Transpiration — water vapour released from plant leaves (via stomata) as part of the transport of water from roots to leaves.
- Condensation — water vapour cools in the atmosphere and forms clouds.
- Precipitation — water falls back to Earth as rain, snow or hail.
- Run-off / infiltration — water flows over land into waterways (run-off) or soaks into the ground (infiltration), replenishing groundwater and eventually returning to oceans, restarting the cycle.

Carbon cycle

- Photosynthesis — producers remove CO_2 from the atmosphere and fix carbon into organic molecules (glucose).
- Respiration — organisms (producers, consumers, decomposers) break down glucose for energy, releasing CO_2 back to the atmosphere.
- Feeding — carbon is transferred between organisms as biomass moves along food chains.
- Decomposition — decomposers break down dead organic matter and waste, releasing carbon as CO_2 (or forming fossil fuels over geological time).
- Combustion — burning of biomass or fossil fuels releases stored carbon rapidly back into the atmosphere as CO_2.
- Ocean exchange — CO_2 dissolves into and is released from oceans, which act as a major carbon reservoir/sink.

Nitrogen cycle

- Nitrogen fixation — atmospheric N_2 gas is converted into ammonia (NH_3)/ammonium by nitrogen-fixing bacteria (free-living or in root nodules of legumes) or by lightning.
- Nitrification — soil bacteria convert ammonium into nitrite (NO_2^-), then nitrite into nitrate (NO_3^- , a usable form for plants).
- Assimilation — plants absorb nitrate/ammonium through their roots and use it to build proteins and nucleic acids; this nitrogen passes to consumers when plants are eaten.
- Ammonification (decomposition) — decomposers break down dead organisms and waste products, converting organic nitrogen back into ammonium.
- Denitrification — denitrifying bacteria (usually in low-oxygen/waterlogged soils) convert nitrate back into N_2 gas, releasing it back to the atmosphere and completing the cycle.

Together these cycles describe how matter (unlike energy) is continually recycled between the biotic (living organisms) and abiotic (atmosphere, soil, water) components of an ecosystem, rather than being lost.

Competitive exclusion principle

Syllabus: *Explain the competitive exclusion principle.*

The competitive exclusion principle (Gause's principle) states that two species competing for exactly the same limiting resource within the same ecological niche cannot coexist indefinitely in the same habitat — over time, one species will out-compete and locally eliminate the other.

Why it happens

- Even a very slight competitive advantage (e.g. slightly faster resource acquisition or higher reproductive rate) compounds over generations.
- The less efficient competitor experiences reduced access to the resource, leading to lower survival and reproduction, and eventual local extinction or emigration.

Possible outcomes

- Competitive exclusion — the weaker competitor is eliminated from the habitat entirely.
- Resource/niche partitioning (character displacement) — the two species evolve to use the resource differently (e.g. different feeding times, food size, or microhabitat), reducing niche overlap and allowing coexistence with each species now occupying a distinct realised niche.

A classic example is Gause's experiments with two species of Paramecium grown in the same test tube with a fixed food supply — when grown together, one species always drove the other to extinction, but when grown separately both survived, demonstrating that resource overlap (not the species themselves) caused exclusion.

Ecological succession (primary and secondary)

Syllabus: *Describe the process of ecological succession; distinguish between primary and secondary succession; and identify the features of pioneer species that make them effective colonisers.*

Ecological succession is the predictable, directional and gradual change in the species composition of a community over time, following the formation of new, unoccupied habitat or a disturbance to an existing community. Succession proceeds through a series of seral stages (seres) towards a relatively stable, self-sustaining climax community.

Primary succession

- Begins on bare substrate that has never previously supported life and contains no soil (e.g. new volcanic rock/lava flow, exposed rock after glacial retreat, new sand dune).
- Pioneer species (e.g. lichens, mosses) colonise first — they can tolerate harsh conditions (extreme temperature, no soil, little water) and begin to break down rock and add organic matter, gradually forming basic soil.
- As soil develops, small plants (e.g. grasses, herbs) can establish, followed by shrubs, then fast-growing trees, and eventually larger, slower-growing climax trees — biodiversity and biomass generally increase and stabilise as succession approaches the climax community.
- This process is very slow, often taking hundreds to thousands of years, because soil must be built up from scratch.

Secondary succession

- Begins after a disturbance (e.g. fire, flood, farming, logging, storm) that removes some or all of the existing community, but where soil and often a seed bank/root systems remain intact.
- Because soil and nutrients are already present, colonisation and succession proceed much faster than primary succession — pioneer species (often fast-growing grasses and weeds) establish quickly, followed by shrubs and trees, progressing back towards a climax community over decades rather than centuries.

Features of effective pioneer species

- Rapid dispersal and colonisation ability (e.g. wind-blown spores/seeds produced in large numbers).
- Fast growth rate and short life cycle, allowing quick establishment and reproduction.
- High tolerance of harsh, exposed abiotic conditions (e.g. intense sunlight, temperature extremes, low nutrients, low water availability).
- Ability to modify/improve the environment for later species, e.g. nitrogen-fixing ability adding nutrients to the soil, or trapping wind-blown organic matter.

Over successive seral stages, r-selected pioneer species are progressively replaced by more competitive K-selected species as conditions become more stable and resource-rich.

DNA replication

Syllabus: *Describe the process of DNA replication with reference to helicase, DNA polymerase and the joining of Okazaki fragments.*

DNA replication is semi-conservative — each new double helix contains one original (parental) strand and one newly synthesised strand. It always proceeds in the 5' → 3' direction on the newly forming strand, because DNA polymerase can only add new nucleotides to the free 3'-OH end of an existing strand.

Key steps and enzymes

1. Initiation — the double helix is unwound and the hydrogen bonds between complementary base pairs are broken by helicase, forming a 'replication fork'. Single-strand binding proteins attach to the separated strands to keep them apart and prevent them re-annealing. Topoisomerase (gyrase) relieves the twisting/supercoiling strain ahead of the fork.
2. Priming — because DNA polymerase cannot start a new strand from scratch, the enzyme primase lays down a short complementary RNA primer to provide a free 3'-OH group for DNA polymerase to extend from.
3. Elongation — DNA polymerase III adds new complementary nucleotides to the exposed template strands, always synthesising in the 5' → 3' direction:

- Leading strand — synthesised continuously in the same direction as the replication fork is opening (since its template runs 3' → 5', matching the required 5' → 3' synthesis direction).
- Lagging strand — its template runs in the opposite orientation (5' → 3'), so this new strand must be synthesised discontinuously, in short fragments called Okazaki fragments, each still built 5' → 3' but working back away from the fork.

4. Primer removal and joining — RNA primers are removed and replaced with DNA nucleotides (DNA polymerase I), and DNA ligase seals the remaining gaps (the sugar-phosphate backbone nicks) between Okazaki fragments and between the leading strand and its final primer site, forming one continuous new strand.
5. Termination — replication continues until the entire molecule has been copied, producing two identical double-stranded DNA molecules, each with one old and one new strand.

Meiosis

Syllabus: *Describe the process of meiosis and explain how crossing over, independent assortment and random fertilisation produce variation in the genotypes of offspring.*

Meiosis is a type of cell division that produces four genetically variable, haploid (n) daughter cells (gametes) from a single diploid (2n) parent cell, through two successive rounds of division (Meiosis I and Meiosis II) following one round of DNA replication.

Meiosis I (reductional division — homologous pairs separate)

- Prophase I — chromosomes condense; homologous chromosomes pair up to form a bivalent/tetrad (synapsis); crossing over occurs at chiasmata, exchanging segments of DNA between non-sister chromatids of homologous chromosomes.
- Metaphase I — homologous chromosome pairs (bivalents) line up along the metaphase plate; the orientation of each pair is random (independent assortment).
- Anaphase I — homologous chromosomes (each still made of two sister chromatids) are pulled to opposite poles of the cell; sister chromatids remain joined.
- Telophase I / cytokinesis — the cell divides into two haploid cells, each with chromosomes still consisting of two sister chromatids.

Meiosis II (equational division — sister chromatids separate, similar to mitosis)

- Prophase II — chromosomes condense again in both haploid cells.
- Metaphase II — chromosomes line up individually along the metaphase plate in each cell.
- Anaphase II — sister chromatids are finally separated and pulled to opposite poles.
- Telophase II / cytokinesis — both cells divide, producing a total of four genetically unique haploid daughter cells (gametes).

Sources of genetic variation generated

- Crossing over (Prophase I) — swaps DNA segments between homologous chromosomes, creating new combinations of alleles on a single chromosome.
- Independent assortment (Metaphase I) — the random orientation of each homologous pair means maternal and paternal chromosomes are distributed into gametes in random combinations (2^n possible arrangements).
- Random fertilisation — which two gametes (from the huge range produced by two parents) combine at fertilisation is random, multiplying the possible genetic combinations in offspring.

Spermatogenesis and oogenesis

Syllabus: *Compare spermatogenesis and oogenesis.*

Spermatogenesis (in the testes)

- A diploid germ cell (spermatogonium) grows into a primary spermatocyte.
- The primary spermatocyte undergoes Meiosis I to form two secondary spermatocytes.
- Each secondary spermatocyte undergoes Meiosis II, producing a total of four haploid spermatids.
- Spermatids mature (spermiogenesis) into four equally sized, small, motile sperm cells, each with roughly equal cytoplasm.
- This process occurs continuously (not cyclically) from puberty onwards, producing very large numbers of sperm throughout adult life.

Oogenesis (in the ovaries)

- A diploid germ cell (oogonium) grows into a primary oocyte, which begins meiosis but is arrested in prophase I, often for many years (from before birth until ovulation).
- At ovulation, the primary oocyte completes Meiosis I, dividing the cytoplasm very unequally to form one large secondary oocyte and one small first polar body (which usually degenerates).
- The secondary oocyte begins Meiosis II but is arrested again at metaphase II, and is released from the ovary in this state — it will only complete Meiosis II if fertilised by a sperm.
- If fertilisation occurs, Meiosis II is completed, producing one large ovum and a second polar body; the polar bodies degenerate.
- This process is cyclical (tied to the menstrual cycle) and produces only one viable ovum per cycle, ceasing at menopause.

Key comparison

- Spermatogenesis produces 4 equal, functional gametes per meiotic event; oogenesis produces only 1 functional gamete (plus non-functional polar bodies), because unequal cytoplasm division concentrates nutrients/organelles into a single large ovum to support a future embryo.
- Spermatogenesis is continuous from puberty; oogenesis is cyclical and involves long periods of meiotic arrest.

Protein synthesis

Syllabus: *Explain the process of protein synthesis in terms of transcription of a gene into messenger RNA in the nucleus, RNA processing (5' cap, RNA splicing, poly-A tail), and translation of mRNA into an amino acid sequence at the ribosome, referring to transfer RNA, codons and anticodons.*

Transcription (in the nucleus)

1. RNA polymerase binds to the promoter region of a gene on the DNA template strand and unwinds the double helix.
2. RNA polymerase moves along the template strand (3' → 5') synthesising a complementary strand of pre-mRNA in the 5' → 3' direction, using RNA nucleotides (with uracil replacing thymine).
3. Transcription ends when RNA polymerase reaches a termination sequence, releasing the pre-mRNA strand.

RNA processing (in the nucleus, before export)

- A 5' cap (modified guanine nucleotide) is added to the front of the pre-mRNA to protect it and assist ribosome binding during translation.
- A poly-A tail (a string of adenine nucleotides) is added to the 3' end, increasing stability and aiding export from the nucleus.
- RNA splicing removes non-coding introns and joins the coding exons together (carried out by the spliceosome), producing mature mRNA.

Translation (at the ribosome, in the cytoplasm)

4. Initiation — the mature mRNA binds to a ribosome; a transfer RNA (tRNA) carrying the first amino acid (usually methionine) pairs its anticodon with the start codon (AUG) on the mRNA.
5. Elongation — the ribosome moves along the mRNA one codon (a triplet of bases) at a time; for each codon, a tRNA with a complementary anticodon delivers the matching amino acid, which is joined to the growing polypeptide chain by a peptide bond.
6. Termination — when the ribosome reaches a stop codon (which does not code for an amino acid), no matching tRNA binds, and the completed polypeptide chain is released to fold into a functional protein.

Making recombinant DNA

Syllabus: *Describe the process of making recombinant DNA, including the role of restriction enzymes, plasmids and DNA ligase.*

Recombinant DNA technology combines DNA from two different sources (e.g. a gene of interest and a bacterial plasmid) into a single molecule.

1. A restriction enzyme (endonuclease) that recognises a specific DNA sequence is used to cut out the gene of interest from the source DNA, and the same restriction enzyme is used to cut open a plasmid vector — producing matching complementary 'sticky ends' (or blunt ends) on both pieces of DNA.
2. The cut gene of interest and the cut plasmid are mixed together; their complementary sticky ends base-pair, allowing the gene to insert into the opened plasmid.
3. DNA ligase seals the sugar-phosphate backbone at the join points, permanently joining the gene of interest into the plasmid to form a single recombinant DNA molecule.
4. The recombinant plasmid is inserted into a host cell (commonly a bacterium) through a process called transformation, often assisted by heat-shock or electroporation to make the host cell membrane temporarily permeable.
5. Host cells are grown on a selective medium (e.g. containing an antibiotic) so that only cells that took up the recombinant plasmid (which typically also carries an antibiotic-resistance marker gene) survive and multiply, each producing many identical copies (clones) of the inserted gene, which may then be expressed to produce a desired protein.

Natural selection (stabilising, directional, disruptive)

Syllabus: *Explain natural selection and identify the three main types of phenotypic selection: stabilising, directional and disruptive.*

Natural selection is the process by which individuals with heritable traits that increase their fitness (survival and reproductive success) in a given environment are more likely to survive and pass those traits to offspring, gradually changing the allele frequencies of a population over generations.

Stabilising selection

- Favours individuals with an intermediate phenotype, while both extremes are selected against.
- Reduces overall variation in the population and keeps the population's average trait value stable over time.
- Example: human birth weight — babies of average weight have the highest survival rate; both very low and very high birth weights are associated with increased risk.

Directional selection

- Favours one phenotypic extreme over the other, causing the population's average trait value to shift in that direction over time.
- Often occurs in response to a consistent environmental change or new selection pressure.
- Example: peppered moths — darker moths were favoured (better camouflage) as tree bark became sooty during industrialisation, shifting the population towards darker colouration.

Disruptive selection

- Favours both phenotypic extremes over the intermediate phenotype, increasing variation within the population.
- Can eventually split a population into two distinct phenotypic groups, potentially leading to speciation if the groups become reproductively isolated.
- Example: a bird population with a food supply of both small and large seeds may favour both small- and large-beaked birds, disadvantaging medium-beaked birds that struggle to efficiently eat either seed type.

Modes of speciation

Syllabus: *Explain how geographic, temporal and spatial isolation influence gene flow and may lead to allopatric, sympatric and parapatric speciation.*

Speciation is the formation of new, reproductively isolated species, and generally requires gene flow between populations to be reduced or stopped so that they can diverge genetically. Isolation can occur in several ways:

Allopatric speciation

- Occurs when populations are separated by a physical/geographic barrier (e.g. a mountain range, river, or ocean) that prevents gene flow between them.
- The separated populations experience different mutations, genetic drift and selection pressures, gradually accumulating enough genetic differences that they become reproductively isolated, even if the barrier is later removed.

Sympatric speciation

- Occurs without any physical geographic barrier — populations remain in the same location but become reproductively isolated through other means, such as behavioural differences (e.g. different mating calls/times), habitat/resource specialisation within the same area, or (particularly in plants) polyploidy (a change in chromosome number that immediately prevents successful interbreeding with the original population).

Parapatric speciation

- Occurs when populations are only partially geographically separated, with a narrow zone of contact/overlap where limited gene flow still occurs, but a strong environmental gradient or selection pressure across the range causes populations at either end to diverge despite the ongoing (but reduced) gene flow.

In all three modes, reduced gene flow allows populations to accumulate independent genetic changes (via mutation, drift and selection) until reproductive isolation is complete and a new species has formed.

Types of macroevolutionary change

Syllabus: *Describe how macroevolutionary changes result from the accumulation of microevolutionary changes using examples of divergent, convergent, parallel and coevolution.*

Macroevolutionary patterns emerge over long timescales from the gradual accumulation of many microevolutionary (allele frequency) changes.

Divergent evolution

- Two or more related species (sharing a recent common ancestor) accumulate different traits over time as they are exposed to different environments or selection pressures, becoming increasingly different from one another.
- Example: Darwin's finches on the Galápagos Islands evolving different beak shapes suited to different food sources on different islands.

Convergent evolution

- Unrelated species (with different ancestry) independently evolve similar traits/structures because they face similar environmental pressures or occupy similar ecological niches.
- Example: the streamlined body shape of sharks (fish) and dolphins (mammals), which evolved independently for efficient movement through water.

Parallel evolution

- Related species that have already diverged from a common ancestor continue to evolve in similar ways independently, usually because they experience similar environmental pressures.
- Example: marsupial and placental mammals evolving similar body forms independently on different continents (e.g. marsupial 'wolf' Thylacine and placental wolves).

Coevolution

- Two interacting species exert reciprocal selection pressures on each other, so that each evolves in response to changes in the other over time.
- Example: flowering plants and their specific pollinators evolving matching structures (e.g. flower shape and pollinator mouthpart length), or predator-prey 'evolutionary arms races' (e.g. increasingly toxic prey and increasingly toxin-resistant predators).