IB DP BIOLOGY

Theme A: Unity and Diversity

A4.1 Evolution and Speciation

Revision Notes · Standard and Higher Level

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What the syllabus requires

A4.1 asks you to explain what evolution is, evaluate the many independent lines of evidence that support it, and account for how one species splits into two. Use this checklist as a final revision sweep before the exam.

Understanding	You should be able to...
Evolution	Define evolution as the change in the heritable characteristics of a population, and describe it at the level of allele frequencies.
Evidence for evolution	Explain how fossils, selective breeding, homologous structures, vestigial organs, molecular data and biogeography all point to common ancestry.
Observed evolution	Use antibiotic resistance, the peppered moth and Galapagos finches as examples of evolution occurring within human timescales.
Homology and analogy	Distinguish homologous from analogous structures and link them to divergent and convergent evolution.
Speciation	Define a species biologically and explain how reproductive isolation lets populations diverge into distinct species.
Modes of speciation	Compare allopatric and sympatric speciation, and (HL) explain speciation by polyploidy.
Tempo of speciation	Contrast gradualism with punctuated equilibrium as patterns in the fossil record.

> **Exam note:** Most of A4.1 is common to SL and HL. HL candidates additionally study speciation by polyploidy and are expected to discuss reproductive barriers and differential selection in more detail. HL-only material below is flagged **(HL)**.

1. What evolution is

Evolution is the change in the heritable characteristics of a population over successive generations. Two words in that definition do a great deal of work. *Heritable* means only features that can be passed on through gametes count — a characteristic acquired during an individual's lifetime (a weightlifter's muscles, a gardener's tan) is not inherited and cannot drive evolution. *Population* means evolution is a property of a group, not of an individual: a single organism does not evolve during its life.

Evolution as a change in allele frequency

At the molecular level, the heritable characteristics of a population are encoded by its **alleles** — the alternative versions of each gene. The complete set of alleles carried by all members of a population is the **gene pool**. Evolution can therefore be defined more precisely as a **change in allele frequency** in a gene pool from one generation to the next. If a dark-colour allele rises from 10% to 55% of the copies in a moth population over several generations, that population has evolved, whether or not any individual moth changed.

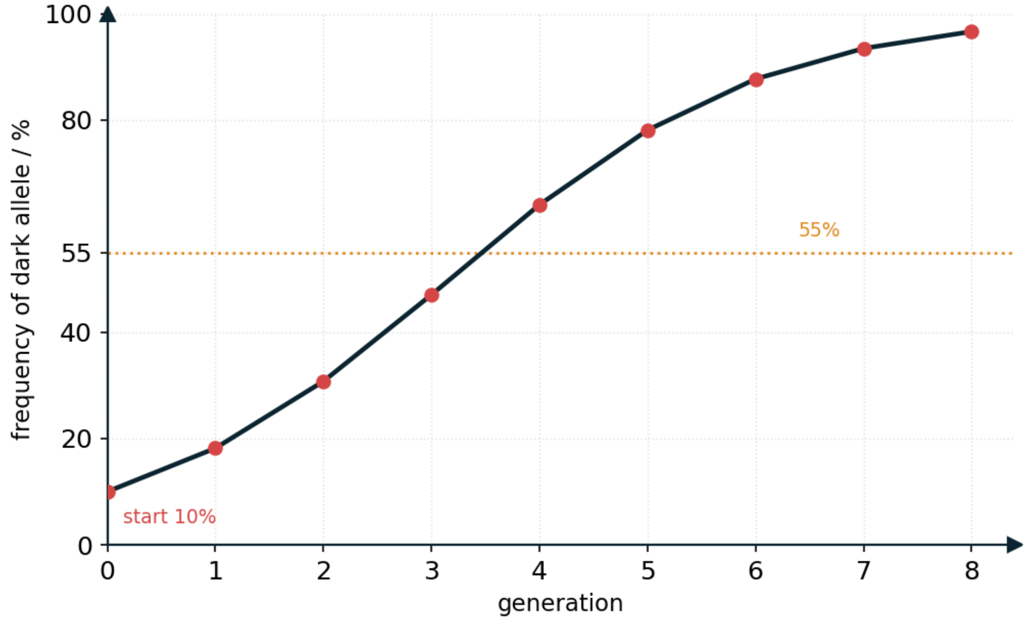

Figure 1. Directional selection modelled on a favoured dark (melanic) allele (relative fitness dark:pale = 1.0:0.5). Starting at 10%, its frequency climbs past 55% within about four generations and approaches fixation — evolution as a change in allele frequency.

Mechanisms such as **natural selection** (covered in A4.2) alter these frequencies by causing individuals with certain alleles to survive and reproduce more successfully. Mutation supplies the new variation; selection, drift and gene flow shape which variants become common.

> **Key distinction:** Individuals are selected, but populations evolve. An individual's alleles are fixed at fertilisation; what changes across generations is the proportion of each allele in the whole population.

2. Evidence for evolution

No single observation proves evolution; its strength is that many independent fields of biology converge on the same conclusion of common ancestry. Examiners reward candidates who can explain *how* each line of evidence supports evolution, not merely list them.

2.1 The fossil record

Fossils are the preserved remains or traces of organisms from the geological past. Arranged by the age of the rock strata that contain them, they reveal a clear sequence: simpler prokaryote-like forms appear in the oldest rocks, and more complex and more recent groups appear progressively higher up. This ordered change through time is exactly what evolution predicts and what a fixed, unchanging living world would not produce.

Transitional fossils show intermediate features linking major groups. *Archaeopteryx*, for example, combines reptilian features (teeth, a bony tail, clawed fingers) with avian features (feathers, wings), bridging dinosaurs and birds. Fossil whales such as *Ambulocetus* show reduced hind limbs, documenting the return of a land mammal lineage to the sea.

Dating. The relative age of fossils is inferred from their position in the strata (deeper is usually older). Absolute ages come from **radiometric dating**, which uses the known half-lives of radioisotopes (such as carbon-14 for recent material, or potassium-argon and uranium series for older rocks) to calculate how long ago an organism lived.

2.2 Selective breeding (artificial selection)

When humans choose which individuals reproduce, heritable characteristics of the domesticated population change dramatically over relatively few generations. All breeds of domestic dog descend from the grey wolf; the wild mustard *Brassica oleracea* has been bred into cabbage, broccoli, cauliflower, kale and Brussels sprouts. This demonstrates that heritable variation exists and that selection acting on it can transform populations. If deliberate human selection can do this in centuries, natural selection acting over millions of years can plainly do far more.

2.3 Homologous structures and comparative anatomy

Homologous structures share the same underlying anatomical plan because they were inherited from a common ancestor, even when they now perform different functions. The classic example is the **pentadactyl (five-fingered) limb** of tetrapods. The human arm, the whale flipper, the bat wing and the horse leg all share the same bone arrangement — a single upper bone (humerus), two lower bones (radius and ulna), a set of wrist bones, and five digits — despite being used for manipulation, swimming, flight and running. This shared plan is only explicable if these animals inherited it, with modification, from a common tetrapod ancestor.

2.4 Vestigial structures

Vestigial structures are reduced, apparently functionless remnants of organs that were fully functional in ancestors. Examples include the human appendix and coccyx (tailbone), the pelvic and hind-limb bones embedded in whales and some snakes, and the tiny eyes of blind cave fish. Their presence makes sense only as inherited leftovers whose original function was lost as the lineage's way of life changed.

2.5 Molecular and biochemical evidence

Perhaps the most powerful modern evidence is molecular. All life shares a **near-universal genetic code**: the same codons specify the same amino acids in bacteria, plants and animals alike. All organisms use DNA (or RNA) as the genetic material, the same 20 amino acids and ATP as an energy currency. This deep chemical unity is strong evidence of descent from a single common ancestor.

Furthermore, the sequences of **conserved proteins and genes** (such as cytochrome c or ribosomal RNA) differ more between distantly related species and less between closely related ones. The number of differences acts as a molecular measure of how long ago two lineages diverged, and molecular trees built this way agree closely with trees built from anatomy and fossils — an independent convergence that would be an astonishing coincidence if evolution were false.

2.6 Biogeography

The geographical distribution of species reflects their evolutionary history rather than simply the environment. Oceanic islands are typically populated by species most closely related to those on the nearest mainland, and often contain many unique endemic species descended from a few founding colonists. Marsupial mammals dominate Australia because the continent became isolated before placental mammals spread. Such patterns follow from descent with modification from ancestors that reached each region, not from independent creation matched to climate.

2.7 Evolution observed within human timescales

Evolution is not confined to the deep past; it can be watched happening.

- **Antibiotic resistance in bacteria.** A random mutation gives a few bacteria resistance to an antibiotic. In the presence of the drug, susceptible bacteria die while resistant ones survive and reproduce, so the resistance allele rises in frequency. Over repeated exposure, whole populations (for example MRSA) become resistant. This is natural selection in real time.
- **The peppered moth (*Biston betularia*).** Before industrialisation, pale moths were camouflaged against lichen-covered bark and the dark form was rare. Soot from industrial pollution killed the lichen and blackened the bark; now the dark moths were better camouflaged from birds and their frequency rose sharply in polluted areas. As air quality improved, the pale form recovered — allele frequencies tracking the environment.
- **Galapagos finches.** Long-term study of ground finches shows average beak size shifting measurably from year to year: droughts that leave only large, hard seeds favour birds with deeper, stronger beaks, and the mean beak depth of the next generation increases.

> **Exam technique:** When asked to describe evidence for evolution, always finish the sentence with the phrase 'which supports common ancestry / descent with modification.' Marks are awarded for making the logical link, not just naming the example.

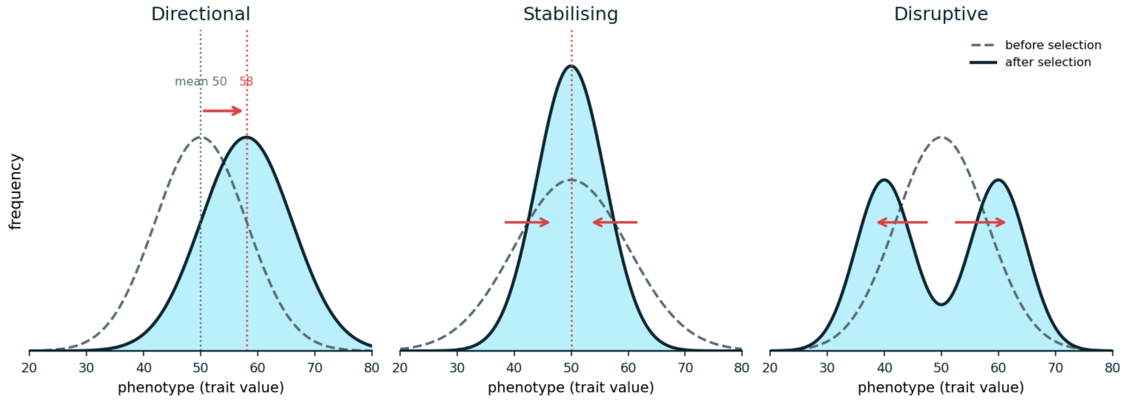

Figure 2. The three modes of natural selection, shown as phenotype distributions before (dashed) and after (shaded) selection. Directional selection shifts the mean (50 to 58); stabilising selection holds the mean at 50 but narrows the spread (SD 10 to 6); disruptive selection favours both extremes, splitting one peak into two.

3. Homology, analogy and patterns of evolution

Structures can resemble one another for two very different reasons, and telling them apart is a frequent exam requirement.

Feature	Homologous structures	Analogous structures
Origin	Same evolutionary/anatomical origin; inherited from a common ancestor	Different origins; not inherited from a recent common ancestor
Function	May differ (e.g. grasping vs flying)	Similar function (e.g. both for flight)
Underlying structure	Same basic plan, modified	Different internal structure
Produced by	Divergent evolution	Convergent evolution

Feature	Homologous structures	Analogous structures
Example	Pentadactyl limbs of human, bat, whale, horse	Wings of birds and insects; streamlined shape of sharks (fish) and dolphins (mammals)

Divergent and convergent evolution

Divergent evolution occurs when populations sharing a common ancestor become increasingly different over time, usually as they adapt to different environments or ways of life. It produces homologous structures. **Convergent evolution** occurs when unrelated lineages independently evolve similar features because they face similar selective pressures; it produces analogous structures. The wings of a bat (mammal), a bird and a pterosaur are homologous as limbs but the wing membrane and flight surfaces are analogous as flight devices — a reminder to specify which feature you mean.

Adaptive radiation

Adaptive radiation is the rapid divergence of a single ancestral lineage into many descendant species, each adapted to a different niche or resource. The classic example is Darwin's finches: a single finch-like colonist of the Galapagos gave rise to many species with beaks specialised for seeds, insects, cactus or even using tools. Adaptive radiation often follows arrival in a new, unexploited environment (such as an island group) or a mass extinction that empties many niches.

4. Speciation and reproductive isolation

Speciation is the formation of new species from pre-existing ones. To understand it you first need a working definition of a species.

The biological species concept

Under the **biological species concept**, a species is a group of organisms that can interbreed in nature to produce **fertile, viable offspring**, and that is reproductively isolated from other such groups. The key criterion is the ability to exchange genes. A horse and a donkey can mate, but their offspring (the mule) is sterile, so they are counted as separate species.

> **Limits of the concept:** The biological species concept cannot be applied to organisms that reproduce asexually (many bacteria), to fossils (interbreeding cannot be tested), or to populations that never meet in nature. In these cases biologists use morphological, ecological or genetic definitions instead.

Reproductive isolation

Two populations become separate species when barriers stop them interbreeding, so their gene pools can no longer mix. These **reproductive isolating mechanisms** are classified by whether they act before or after fertilisation.

Type	Barrier	How it isolates the gene pools
Prezygotic (before fertilisation)	Temporal (seasonal)	Populations breed at different times of day, season or year, so gametes never meet.
	Behavioural	Different courtship displays, songs or mating signals are not recognised by the other population.

Type	Barrier	How it isolates the gene pools
	Ecological (habitat)	Populations live or mate in different habitats within the same area.
	Mechanical	Differences in reproductive structures or flower shape prevent mating or pollination.
	Gametic	Sperm and egg (or pollen and stigma) are chemically incompatible, so fertilisation fails.
Postzygotic (after fertilisation)	Hybrid inviability	Hybrid embryos fail to develop or die early.
	Hybrid sterility	Hybrids survive but cannot produce functional gametes (e.g. the mule).
	Hybrid breakdown	First-generation hybrids are fertile, but their offspring are weak or sterile.

How populations diverge

Speciation generally follows three steps: (1) an ancestral population is split into two groups whose gene pools stop mixing (isolation); (2) the two groups accumulate genetic differences through mutation, and through natural selection and genetic drift acting under different conditions; (3) the differences eventually become large enough that, even if the groups meet again, they can no longer interbreed successfully — reproductive isolation is complete and two species now exist.

5. Allopatric and sympatric speciation

Speciation is classified by whether the initial isolation involves a geographical barrier.

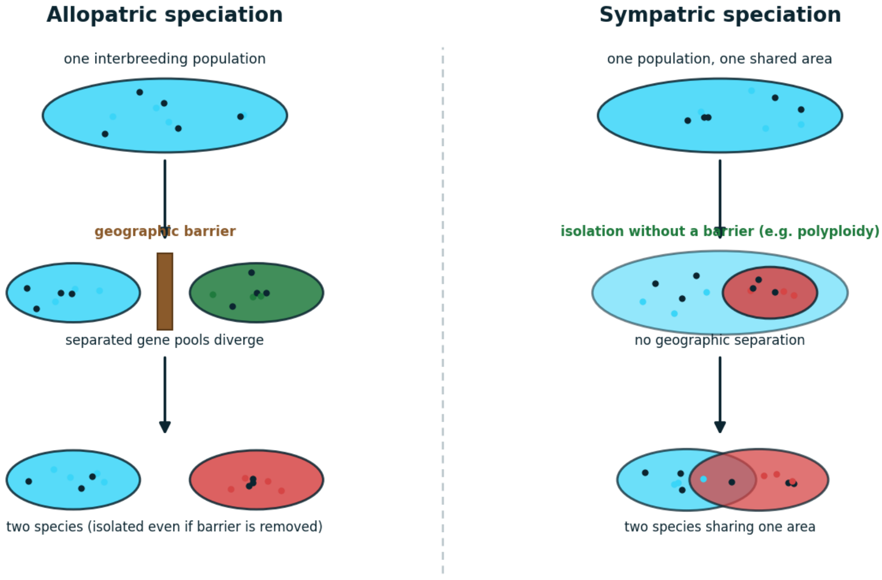

Figure 3. Allopatric speciation (left) begins with a geographic barrier that physically separates the gene pools, which then diverge; sympatric speciation (right) produces reproductive isolation within one shared area, for example by polyploidy, with no barrier required.

Allopatric speciation

Allopatric speciation (Greek *allos* = other, *patris* = homeland) occurs when a population is divided by a **physical/geographic barrier** — a new river, mountain range, sea channel, or the splitting of a habitat. The separated populations can no longer exchange genes. Because they now experience different environments, mutations, and selection pressures, their gene pools diverge over many generations. If they diverge enough, they will remain reproductively isolated even if the barrier later disappears. Darwin's finches, which colonised separate islands, and squirrel populations divided by the Grand Canyon are standard examples.

Sympatric speciation

Sympatric speciation (*sym* = together) occurs **without any geographic barrier**: new species arise within a single, overlapping area. Some population must still be reproductively isolated by a non-geographic mechanism:

- **Polyploidy** — a doubling of chromosome number (common in plants) instantly makes offspring unable to breed with the parent population (see Section 7).
- **Temporal isolation** — a subgroup begins breeding or flowering at a different time, so it no longer exchanges gametes with the rest.
- **Behavioural isolation** — a change in mating signals or preferences means individuals only mate with others sharing the new trait. The cichlid fishes of the African Great Lakes, where female preference for male colour helps split populations, are a classic example.
- **Ecological/host isolation** — a subgroup shifts to a new food source or host and mates there. Apple maggot flies that switched from hawthorn to apple trees are diverging in this way.

	Allopatric speciation	Sympatric speciation
Initial isolation	Geographic/physical barrier separates populations	No geographic barrier; populations share the same area
Isolating mechanism	Physical separation, then genetic divergence	Polyploidy, temporal, behavioural or ecological isolation
Relative frequency	Common; the usual mode in animals	Rarer; especially important in plants (polyploidy)
Example	Galapagos finches; canyon-divided squirrels	Polyploid plants; apple maggot fly; cichlid fish

6. Tempo of evolution: gradualism vs punctuated equilibrium

Two models describe the *rate* at which new species appear in the fossil record. They are not mutually exclusive; different lineages show different patterns.

Feature	Gradualism	Punctuated equilibrium
Rate of change	Slow, steady and continuous over long periods	Long periods of little change (stasis) interrupted by short bursts of rapid change
Fossil pattern	Predicts many intermediate transitional forms	Predicts few intermediates; new forms appear abruptly, then persist unchanged
When change occurs	Throughout a lineage's existence	Concentrated around speciation events, often after environmental upheaval

The apparent scarcity of smooth transitional series in some parts of the fossil record is used to support punctuated equilibrium, though incompleteness of fossilisation also explains gaps. The modern view is that both tempos occur: some lineages change gradually, others in rapid pulses separated by long stasis.

7. Speciation by polyploidy (HL)

Polyploidy is the possession of more than two complete sets of chromosomes (3n, 4n, and so on). It is a major route to sympatric speciation and is especially important in plants, where an estimated large fraction of flowering-plant species arose this way. It can create a new species in a single generation.

How polyploidy causes instant reproductive isolation

Polyploidy usually arises from an error in meiosis (non-disjunction) that produces diploid rather than haploid gametes, or from the doubling of a hybrid's chromosome set. A polyploid individual (say 4n) cannot produce fertile offspring when crossed with the original diploid (2n) parent population: the cross yields a triploid (3n) whose odd chromosome number cannot pair evenly at meiosis, so it is sterile. The polyploid is therefore **reproductively isolated** from its parents the moment it forms, even though they share the same location — the essence of sympatric speciation. Polyploids can perpetuate themselves by self-pollination or asexual reproduction, or by breeding with other polyploids.

Autopolyploidy and allopolyploidy

Autopolyploidy results from chromosome doubling within a single species. **Allopolyploidy** results when two different species hybridise and the hybrid's chromosome set then doubles; the doubling restores pairing partners for every chromosome, so the previously sterile hybrid becomes fertile. Bread wheat (*Triticum aestivum*) is a well-known allopolyploid combining the genomes of three ancestral grasses.

Isolation and differential selection

Polyploidy shows in its purest form the general logic of speciation: a barrier to gene flow (here, chromosomal incompatibility) followed by independent evolution. More generally, once any two populations are isolated, **differential selection** — different environments favouring different alleles — together with genetic drift drives them apart. Where diverging populations still meet, **reinforcement** can strengthen prezygotic barriers: natural selection favours individuals that avoid wasteful matings producing unfit hybrids, so mating preferences that keep the gene pools separate are themselves selected for.

> **(HL) Exam tip:** To explain why a triploid is sterile, state that with three chromosome sets the homologues cannot pair and separate evenly during meiosis, so balanced, viable gametes cannot form.

8. Worked examples and exam practice

Worked example 1 - interpreting evidence for evolution

Cytochrome c is a respiratory protein found in almost all aerobic organisms. Its amino acid sequence differs from the human sequence by 0 residues in chimpanzees, about 13 in birds, and about 44 in yeast. Explain how these data support evolution.

The universal presence of the same protein points to a shared ancestry in which the gene already existed. The number of sequence differences increases with how distantly related the organism is thought to be on independent (anatomical and fossil) grounds: fewest differences with our closest relatives, most with the most distant. This is exactly the pattern expected if sequences accumulate mutations after lineages diverge, so the data support common ancestry and descent with modification.

Worked example 2 - allopatric or sympatric?

Two populations of a lizard once lived together. A new river now divides their range; over thousands of years they diverge and can no longer interbreed. In a separate case, within one meadow a group of plants doubles its chromosome number and can only breed among themselves. Classify each case and justify your answer.

Case 1 is **allopatric**: a geographic barrier (the river) physically separated the populations before they diverged. Case 2 is **sympatric**: no geographic barrier is involved; reproductive isolation arose in the same location through polyploidy. The test is simply whether a physical barrier caused the original separation.

Worked example 3 - explaining reproductive isolation

A horse (2n = 64) and a donkey (2n = 62) can mate to produce a mule, but the mule is sterile. Use this to explain why horses and donkeys are considered separate species.

Under the biological species concept, members of the same species must produce fertile, viable offspring. Horse and donkey chromosomes cannot pair evenly during meiosis in the mule (63 chromosomes cannot form matched homologous pairs), so the mule cannot make functional gametes and is sterile. This is a **postzygotic** barrier (hybrid sterility): no genes flow between the two gene pools through the hybrid, so horse and donkey remain separate species.

Worked example 4 - homologous vs analogous

The wing of a bird and the wing of a butterfly both produce flight. The flipper of a whale and the arm of a human have very different functions. Which pair is homologous and which is analogous, and what does each tell us about evolution?

The whale flipper and human arm are **homologous**: they share the pentadactyl bone plan inherited from a common tetrapod ancestor, despite different functions - evidence of **divergent** evolution. The bird and butterfly wings are **analogous**: they have the same function but completely different internal structure and no recent common winged ancestor - evidence of **convergent** evolution, where similar selection pressures produced similar solutions independently.

Worked example 5 - reading a speciation scenario

A single species of insect lives across a large valley. A rising mountain range slowly splits the range into a cool, wet western side and a warm, dry eastern side. After many thousands of years the two populations, brought back together in a hybrid zone, court at different times of day and rarely mate; the few hybrids that form are weak. Identify the mode of speciation and the isolating mechanisms involved.

The original split was caused by a geographic barrier (the mountains), so this is **allopatric** speciation. Different climates on the two sides mean different **selection pressures**, driving genetic divergence. When the populations meet again, isolation is maintained by a **prezygotic behavioural/temporal** barrier (courting at different times) reinforced by a **postzygotic** barrier (hybrid inviability - weak hybrids). Because gene flow cannot resume, they are now separate species.

Note how selection against unfit hybrids can favour stronger prezygotic barriers - this is reinforcement.

Exam skills: structuring an evolution answer

Long-answer evolution questions follow predictable templates. Learn the skeleton and fill in the specific example.

If the question asks you to...	Structure your answer around...
Explain natural selection	Variation → overproduction/competition → selection pressure → differential survival and reproduction → change in allele frequency over generations
Explain speciation	Isolation (geographic or reproductive) → divergence by mutation, selection and drift → reproductive isolation becomes permanent → new species
Give evidence for evolution	Name the evidence → describe the observation → state that it supports common ancestry / descent with modification
Compare two terms	State the shared feature first, then give a clear point-by-point contrast

> **Marking insight:** Command terms matter. 'State' wants a one-line fact; 'explain' wants causal reasoning (use 'because', 'so that', 'therefore'); 'compare' wants both similarities and differences; 'distinguish' wants differences only.

Common pitfalls

- **Evolution acts on populations, not individuals.** Never write that an individual 'evolved' or 'adapted during its life'. Individuals are selected; populations evolve as allele frequencies change.
- **Avoid 'need' and 'want' language.** Organisms do not develop features because they need them or by trying. Variation arises randomly by mutation first; selection then acts on whatever variation already exists. Write 'individuals with the allele survived and reproduced more', not 'the moths turned dark because they needed camouflage'.
- **Mutations are random, not directed.** The environment does not create the useful mutation; it only selects among mutations that occur by chance.
- **Respect the limits of the species concept.** Do not apply 'interbreeding to produce fertile offspring' to bacteria or fossils.
- **Homologous is about origin, analogous is about function.** Similar-looking structures are not automatically homologous.

Quick reference

Term	One-line meaning
Evolution	Change in the heritable characteristics (allele frequencies) of a population over time
Gene pool	All the alleles present in all members of a population
Homologous structures	Same origin/plan from a common ancestor; product of divergent evolution
Analogous structures	Same function, different origin; product of convergent evolution
Vestigial structure	Reduced, functionless remnant of an ancestral organ
Species (biological)	Group that interbreeds in nature to give fertile, viable offspring
Speciation	Formation of new species via reproductive isolation and divergence
Allopatric	Speciation with a geographic barrier
Sympatric	Speciation without a geographic barrier (e.g. polyploidy)
Polyploidy (HL)	Extra whole chromosome sets; causes instant isolation, common in plants
Gradualism	Slow, continuous evolutionary change
Punctuated equilibrium	Long stasis broken by rapid bursts of change

Test yourself

Attempt these without notes; full answers follow.

1. Define evolution in terms of allele frequency. [2]

2. Explain how the pentadactyl limb provides evidence for evolution. [3]

3. Distinguish between homologous and analogous structures, giving one example of each. [3]

4. Antibiotic resistance is increasing in hospital bacteria. Explain how this arises by natural selection. [4]

5. State the biological species concept and give one situation in which it cannot be applied. [2]

6. Compare allopatric and sympatric speciation. [3]

7. (HL) Explain how polyploidy can produce a new plant species in a single generation. [4]

8. Outline the difference between gradualism and punctuated equilibrium. [2]

Answers

1. Evolution is the change in the heritable characteristics of a population over time (1); measured as a change in the frequency of alleles in the population's gene pool from one generation to the next (1).

2. The human arm, whale flipper, bat wing and horse leg share the same bone arrangement / pentadactyl plan (1) even though they carry out different functions (1); this shared underlying structure is best explained by inheritance, with modification, from a common ancestor - i.e. homology / divergent evolution (1).

3. Homologous structures share a common evolutionary origin/anatomical plan but may have different functions (1) - e.g. pentadactyl limbs (1); analogous structures have similar function but different origin/structure (1) - e.g. bird and insect wings. (Any correct example accepted.)

4. There is natural variation among bacteria; a random mutation makes some resistant to the antibiotic (1). When the antibiotic is present, non-resistant bacteria are killed while resistant ones survive (selection pressure) (1). The survivors reproduce and pass on the resistance allele (1), so the frequency of the resistance allele increases in the population over generations (1).

5. A species is a group of organisms that can interbreed in nature to produce fertile, viable offspring (1). It cannot be applied to asexually reproducing organisms / fossils / geographically separated populations that never meet (1).

6. Both produce new species through reproductive isolation and divergence (1). Allopatric speciation requires a geographic/physical barrier to separate populations (1); sympatric speciation occurs without a geographic barrier, isolation arising by polyploidy, temporal, behavioural or ecological means in the same area (1).

7. (HL) An error in meiosis (non-disjunction) or hybridisation doubles the chromosome number, producing a polyploid (e.g. 4n) individual (1). When the polyploid crosses with the original 2n parents it gives a triploid (3n) (1) whose chromosomes cannot pair evenly at meiosis, so the offspring is sterile (1). The polyploid is therefore reproductively isolated from its parents at once and forms a new species in one generation while living in the same place (sympatric) (1).

8. Gradualism proposes slow, steady, continuous change with many transitional forms (1); punctuated equilibrium proposes long periods of stasis interrupted by short bursts of rapid change, with new forms appearing abruptly (1).