

Evolution and speciation

Revision notes • IB Biology A4.1: evolution as heritable change, evidence from sequences, selective breeding and homologous structures, and how species split.

For IB Diploma Biology, Standard Level and Higher Level (first assessment 2025). **HL only** is additional higher level content, for HL students only.

Evolution and speciation Spec A4.1

Evolution as change in heritable characteristics Spec A4.1.1

Evolution is change in the **heritable characteristics** of a **population**. Heritable means coded in the genes and passed from parents to offspring. Evolution therefore happens to populations over generations, not to individuals during their lives.

At the level of genes, evolution is a change in the frequency of alleles in the gene pool of a population. A new allele may arise by mutation, then become more or less common in later generations.

A characteristic an organism acquires during its life is not evolution. Larger muscles from exercise, a scar, or a plant growing tall in fertile soil do not change the DNA in gametes, so they are not inherited.

Darwinian evolution and Lamarckism compared		
	Lamarckism	Darwinian evolution by natural selection
Where variation comes from	Organisms change during their lifetime through use or disuse of structures	Heritable variation already exists between individuals, from mutation and sexual reproduction
What is inherited	Acquired characteristics	Only genetic (heritable) characteristics
What changes	Individuals	The population: allele frequencies shift over generations
Status	Not supported: acquired changes do not alter the genes passed on in gametes	Supported by a wide range of independent evidence

Common mistake: Do not write that an individual organism evolves or adapts in order to survive. Individuals survive or die; the population evolves.

Exam tip: Nature of science: evolution by natural selection is called a theory because no theory can be formally proved true, not because it is weak. It predicts and explains a broad range of observations and is unlikely ever to be falsified.

Evidence from sequences and selective breeding Spec A4.1.2, A4.1.3

Base and amino acid sequences

All cellular organisms store genetic information as DNA and use almost the same genetic code. This shared chemistry points to a single common origin of life. Comparing sequences between species gives **powerful evidence of common ancestry**.

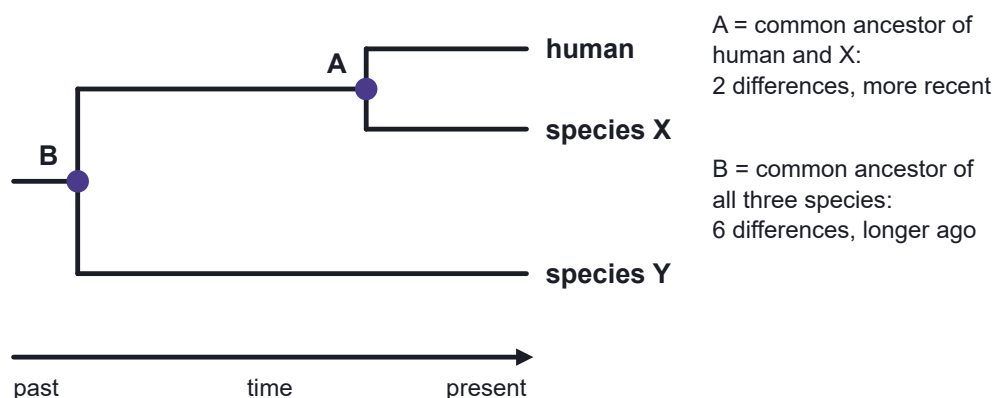
- Mutations change base sequences over time. Once two populations have separated, each lineage accumulates its own mutations.
- So the **fewer differences** between the base sequences of a gene (or the amino acid sequences of a protein) in two species, the **more recently** they shared a common ancestor.
- Proteins found in a very wide range of species, such as cytochrome c (used in respiration) and haemoglobin, are often compared.
- If differences accumulate at a roughly steady rate, the number of differences can also be used to estimate how long ago two lineages diverged.

Base sequences show more differences than amino acid sequences. The genetic code is degenerate, so some base substitutions do not change the amino acid.

Sequence evidence is independent of anatomy, yet the relationships it shows mostly agree with those based on structure. When independent lines of evidence point the same way, the evidence is strong.

position	1	2	3	4	5	6	7	8	9	10	11	12	differences from human
human	Gly	Asp	Val	Glu	Lys	Gly	Lys	Lys	Ile	Phe	Ile	Met	—
species X	Gly	Asp	Ile	Glu	Lys	Gly	Lys	Lys	Ile	Leu	Ile	Met	2
species Y	Ala	Asp	Thr	Glu	Lys	Ala	Lys	Arg	Ile	Tyr	Ile	Leu	6

 = amino acid differs from the human sequence (illustrative sequences)



fewer differences = more recent common ancestor

[\(opens full size in a new tab\)](#)

==Fewer differences = more recent common ancestor==: human and X differ at 2 positions, Y at 6 (illustrative sequences).

Selective breeding

In **selective breeding** (artificial selection), humans choose individuals with desired traits to breed, generation after generation. Domesticated breeds and crop varieties now differ greatly from each other and from the original wild species.

- Wild cabbage (*Brassica oleracea*) has been bred into cabbage, kale, broccoli, cauliflower, Brussels sprouts and kohlrabi, by selecting for large leaves, flower buds, side buds or swollen stems.
- All dog breeds, from chihuahuas to great Danes, descend from domesticated wolves.
- Maize was bred from the wild grass teosinte, which has tiny ears with a few hard-cased grains.

This shows how **rapidly** evolutionary change can occur: large heritable changes in a few thousand years or less. If human selection can do this, natural selection acting over millions of years can produce far greater changes.

Common mistake: Selective breeding is evidence that populations can change, but it is not natural selection. The selecting agent is humans, not the environment.

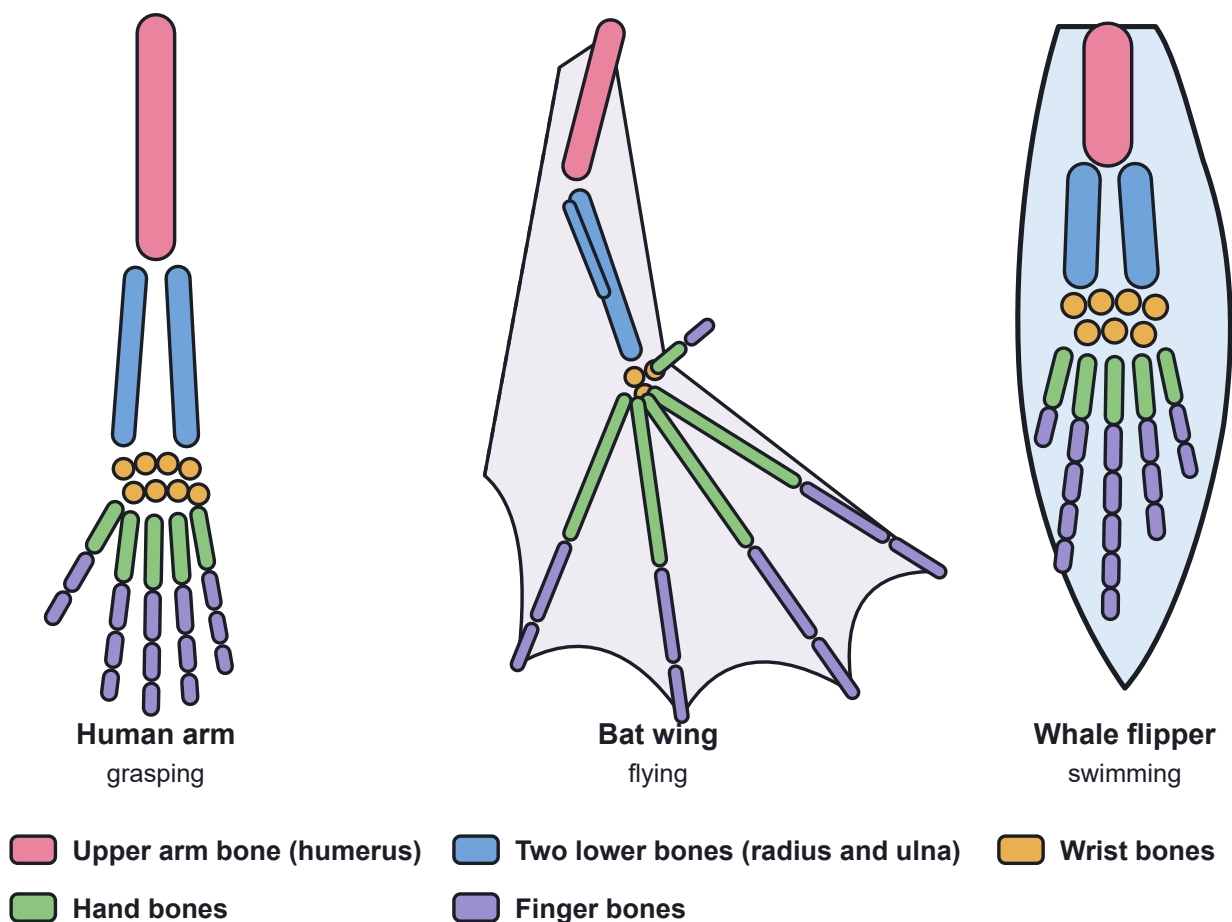
Homologous and analogous structures Spec A4.1.4, A4.1.5

Homologous structures have the same basic structure in different species because they were inherited from a **common ancestor**, even though they may now have different functions. They are evidence of common ancestry followed by divergence.

The pentadactyl limb

The limbs of amphibians, reptiles, birds and mammals are built on the same five-digit (**pentadactyl**) plan:

- one bone in the upper limb: humerus (forelimb) or femur (hindlimb)
- two bones in the lower limb: radius and ulna, or tibia and fibula
- a group of wrist or ankle bones: carpals or tarsals
- a set of bones in the palm or sole: metacarpals or metatarsals
- five digits made of phalanges



[\(opens full size in a new tab\)](#)

The same bones in a human arm, bat wing and whale flipper: humerus, radius and ulna, carpals (wrist), metacarpals (hand) and phalanges (fingers).

One plan, different functions		
Forelimb	Function	How the plan is modified
Human arm	Grasping and manipulating	Long separate digits with an opposable thumb
Bat wing	Flying	Very long metacarpals and phalanges support a membrane of skin
Whale flipper	Swimming	Short, flattened bones enclosed in a paddle
Bird wing	Flying	Carpals and metacarpals fused, digits reduced

There is no functional reason why a flipper, a wing and a hand need the same bones. The shared plan is best explained by descent from a common ancestor with a pentadactyl limb.

Convergent evolution and analogous structures

Analogous structures have the same function but different evolutionary origins. They arise by **convergent evolution**: unrelated lineages meet similar selection pressures, so natural selection produces similar adaptations independently.

- Wings of birds and insects: a bird wing is a modified forelimb with bones and feathers; an insect wing is an outgrowth of the exoskeleton with no bones.
- Camera eyes of octopuses and vertebrates: both focus light with a lens onto a retina, but they develop differently and the octopus retina has no blind spot.
- Streamlined bodies and fins of sharks (fish) and dolphins (mammals).

Homologous and analogous structures		
	Homologous	Analogous
Evolutionary origin	Same, from a common ancestor	Different
Function	Often different	Same
Type of evolution	Divergent	Convergent
Example	Pentadactyl limbs	Bird and insect wings

Exam tip: Linking question: what counts as strong evidence in biology? Homologous structures, sequence data and selective breeding are independent lines of evidence that all support common ancestry.

Speciation, reproductive isolation and differential selection Spec A4.1.6, A4.1.7

Speciation is the formation of new species by the **splitting of a pre-existing species**. One population divides into two or more groups that evolve separately until they can no longer interbreed to produce fertile offspring. This is the only way in which new species have appeared.

- Speciation increases the total number of species on Earth. Extinction decreases it.
- Gradual evolutionary change within a single species over time is not speciation, because the number of species does not increase.

How a species splits

1. **Reproductive isolation**: two populations of one species stop interbreeding, so there is no gene flow between them.
2. **Differential selection**: the populations live under different conditions, so natural selection favours different alleles in each.
3. Different mutations also arise in each population, and chance changes in allele frequency happen separately.

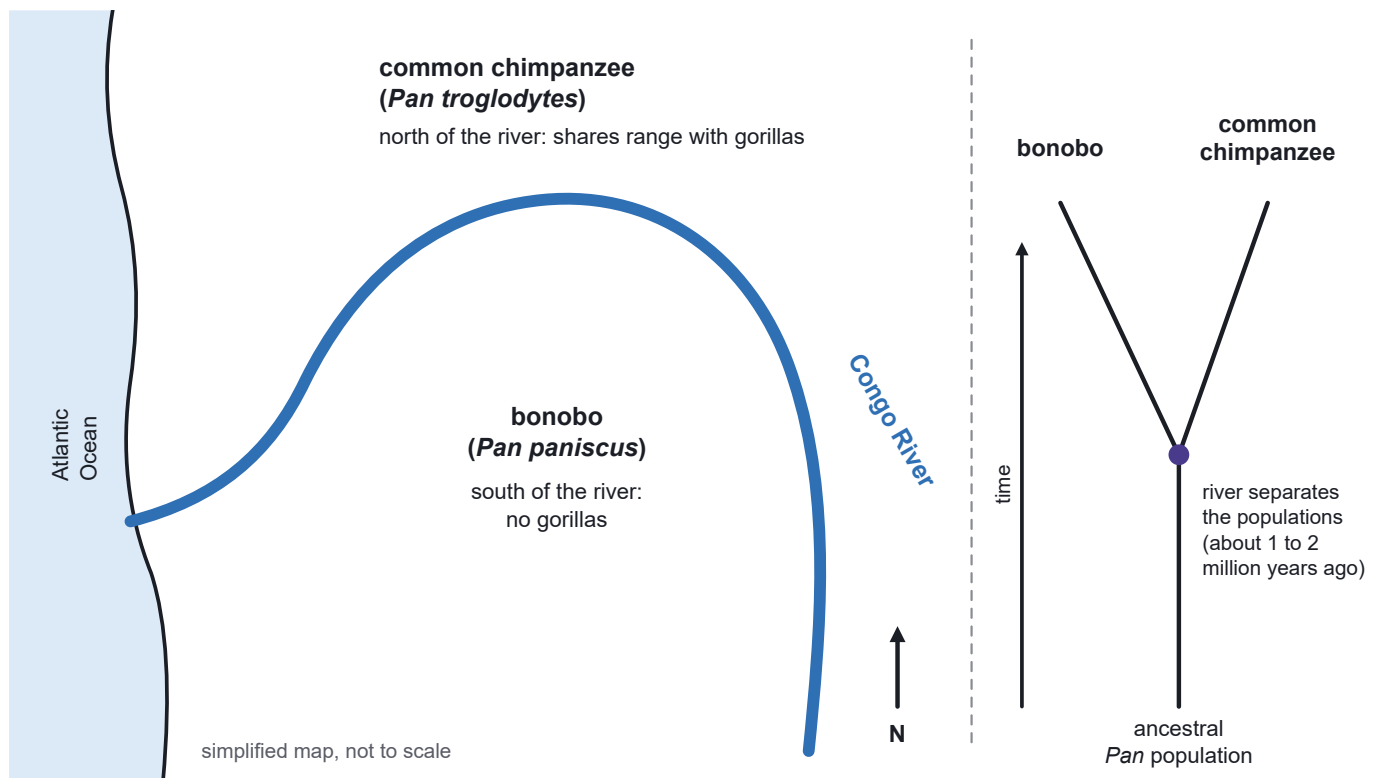
4. Over many generations the gene pools diverge. Eventually the populations could not interbreed and produce fertile offspring even if they met. They are now separate species.

Geographical isolation is one way of achieving reproductive isolation: a physical barrier such as a river, a mountain range or the sea separates the populations.

Bonobos and common chimpanzees

Bonobos (*Pan paniscus*) and common chimpanzees (*Pan troglodytes*) are closely related species in the genus *Pan*. Genetic estimates put the split between the two species at roughly 1 to 2 million years ago. The traditional explanation is that the Congo River formed at about this time and divided the ancestral population. Geological evidence suggests the river is much older, so another hypothesis is that ancestral bonobos crossed to the south bank during a period of unusually low river flow and were then cut off. Either way, the river is the barrier: these apes do not swim, so there is no gene flow across it. Bonobos live only south of the river; common chimpanzees live to the north.

The two populations then faced different selection pressures. One widely discussed explanation is that bonobos, south of the river, had no gorillas competing for ground vegetation, so food was more reliable. This favoured large, tolerant, female-led groups with little aggression. North of the river, chimpanzees share their range with gorillas. This favoured male-dominated groups, more aggression and cooperative hunting.



[\(opens full size in a new tab\)](#)

The Congo River is a **geographical barrier**: no gene flow, different selection pressures on each bank.

Exam tip: In speciation answers name both stages: reproductive isolation stops gene flow, and differential selection makes the isolated gene pools diverge. Isolation alone does not create a new species.

Allopatric and sympatric speciation, and adaptive radiation Spec A4.1.8, A4.1.9 HL only

Reproductive isolation can be **geographic**, **behavioural** or **temporal**. The type of isolation decides whether speciation is allopatric or sympatric.

- **Geographic isolation:** a physical barrier separates the populations.

- **Behavioural isolation:** differences in courtship, mating calls or displays mean individuals do not recognise each other as mates.
- **Temporal isolation:** populations breed or flower at different times of day or year, so they do not mate.

Allopatric speciation happens in different places: populations are separated by geographic isolation.

Sympatric speciation happens in the same place: reproductive isolation arises without a geographical barrier, by behavioural or temporal isolation (or, in plants, by polyploidy).

An example in progress is the apple maggot fly (*Rhagoletis pomonella*) in North America. Its original host is hawthorn, but some flies began to lay eggs on introduced apple trees. Flies mate on their host fruit, and apples ripen earlier than hawthorn fruits, so the two host races breed at different times. Gene flow between them is reduced.

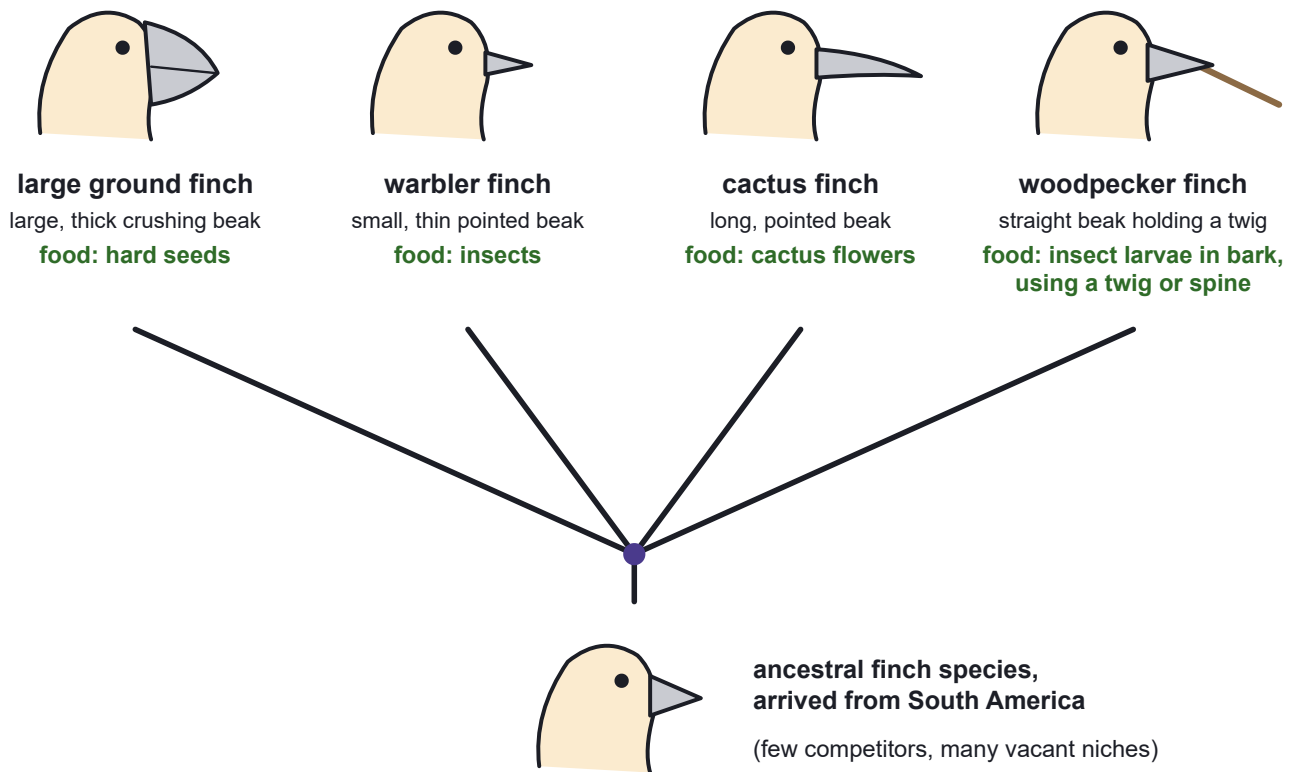
Allopatric and sympatric speciation		
	Allopatric	Sympatric
Geographical barrier	Yes	No: populations share an area
Type of reproductive isolation	Geographic	Behavioural or temporal (or polyploidy in plants)
Gene flow stops	Yes	Yes
Gene pools diverge through differential selection	Yes	Yes
Outcome	New species that cannot interbreed	New species that cannot interbreed

Adaptive radiation

Adaptive radiation is the rapid evolution of many species from a single ancestral species, each adapted to a different niche. It happens when a lineage reaches an area with **vacant niches**, such as a newly formed island group.

The finches of the Galápagos Islands descend from one ancestral species that arrived from South America. They now include species with large crushing beaks for hard seeds, thin beaks for insects, long beaks for cactus flowers, and a species that uses twigs or spines to extract insect larvae. The honeycreepers of Hawaii are a similar example.

Because each species uses different resources, closely related species can coexist without competing. Adaptive radiation therefore increases biodiversity in ecosystems where there are vacant niches.



[\(opens full size in a new tab\)](#)

Adaptive radiation of Galápagos finches: one ancestor, many niches.

Common mistake: Do not confuse adaptive radiation with convergent evolution. Adaptive radiation is one ancestor diverging into many forms; convergent evolution is unrelated lineages becoming similar.

Barriers to hybridization and abrupt speciation by polyploidy Spec A4.1.10, A4.1.11 HL only

Once species have formed, two kinds of mechanism stop their alleles mixing: barriers that prevent hybrids forming, and sterility of interspecific hybrids when they do form.

Barriers to hybridization

In animals, courtship behaviour often prevents hybridization. Courtship signals such as songs, dances, displays, flash patterns or scents are species-specific, so an individual responds only to a mate of its own species. Breeding at different times (temporal isolation) also prevents mating.

Sterile hybrids: the mule

A mule is the hybrid of a male donkey and a female horse. Horses have 64 chromosomes and donkeys 62, so a mule has 63: 32 from its horse parent and 31 from its donkey parent. In meiosis these chromosomes cannot form homologous pairs, so the mule cannot produce viable gametes and is sterile.

Because mules almost never reproduce, no horse alleles pass into the donkey gene pool through them, or donkey alleles into the horse gene pool. The two species stay separate even though they can hybridize.

Abrupt speciation in plants

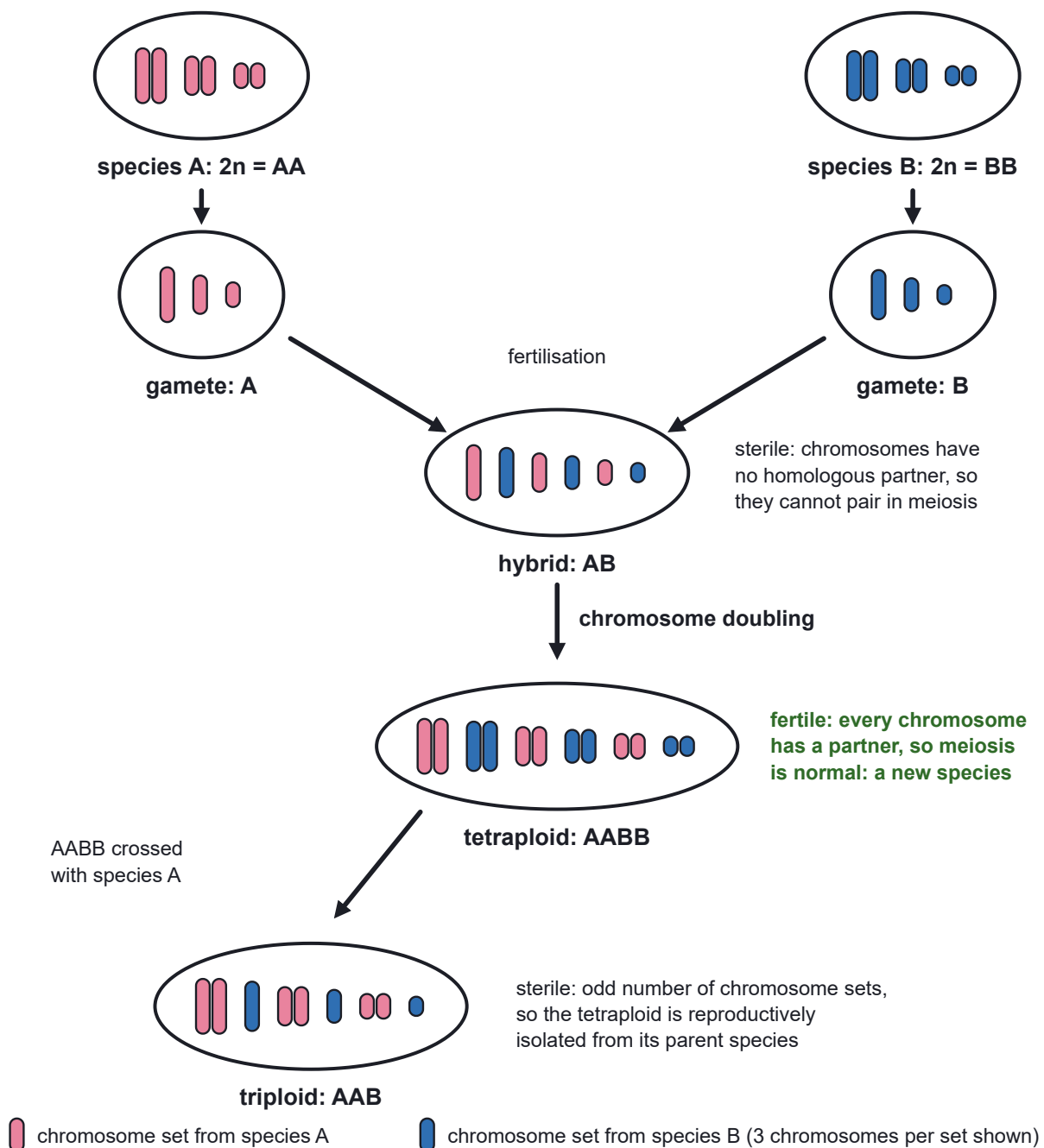
Polyploidy is having more than two sets of chromosomes. Combined with hybridization it can create a new plant species in a single generation.

1. Two related species hybridize. The hybrid has one set of chromosomes from each parent, and these sets are not homologous.

- 2 . The hybrid is sterile because its chromosomes cannot pair up in meiosis.
- 3 . The chromosome number doubles, for example when chromosomes are copied but the cell does not divide. Now every chromosome has a homologous partner.
- 4 . The polyploid can carry out meiosis normally and is fertile.
- 5 . If it crosses with either parent, the offspring have an odd number of chromosome sets and are sterile. The polyploid is reproductively isolated from both parents: it is a new species.

Plants form species this way more easily than animals because many can self-pollinate or reproduce asexually, so a single polyploid individual can found a population.

Knotweeds and smartweeds (genus *Persicaria*) are an example. The genus contains many species formed by hybridization and polyploidy. Molecular studies suggest that about 15 species in the genus are allopolyploids, mostly tetraploids whose chromosome sets come from two different ancestral species, with at least one hexaploid. One diploid species, pale smartweed (*Persicaria lapathifolia*), has been a parent in at least six of these origins.



[\(opens full size in a new tab\)](#)

Abrupt speciation: **hybridization then chromosome doubling** gives a fertile tetraploid isolated from both parents.

Exam tip: In polyploidy answers explain why the hybrid is sterile (no homologous pairs in meiosis) and why doubling fixes it (each chromosome now has a partner). Either the common or scientific name of *Persicaria* is accepted.

Quick check

1. Define evolution.
2. What do fewer differences in the amino acid sequence of a protein between two species suggest?
3. Name the five groups of bones in a pentadactyl forelimb.
4. What two processes are needed for speciation?
5. **HL only** Why is a mule sterile?

Quick check answers

Evolution and speciation

1. Change in the heritable characteristics of a population.
2. They shared a common ancestor more recently.
3. Humerus; radius and ulna; carpals; metacarpals; phalanges.
4. Reproductive isolation and differential selection.
5. Its 63 chromosomes cannot form homologous pairs in meiosis, so it cannot make viable gametes.