Index

The big picture

? Guiding question(s)

- What is the evidence for evolution?
- How do analogous and homologous structures exemplify commonality and diversity?

Keep the guiding questions in mind as you learn the science in this subtopic. You will be ready to answer them at the end of this subtopic. The guiding questions require you to pull together your knowledge and skills from different sections, to see the bigger picture and to build your conceptual understanding.

Often referred to as the graceful giants of the ocean, whales have adapted to life in water. They breathe air, but can feed, mate, give birth, suckle and raise their young in the open waters of the ocean. Looking at them, it is hard to believe that the early relatives of whales lived on land.

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Recent studies show genetic similarities between present day whales and hippos. The latter are thought to be the closest living relatives of whales. There could have been many reasons for their transition from land to water; however, as early relatives moved into the unfamiliar aquatic habitat, those better adapted for living in water survived.

The family tree in **Figure 1** shows the *Pakicetus*, an ancient relative of the present day whales. These were typical land animals, with aquatic adaptations. They had limbs with five digits adapted for walking on land and wading in streams, elongated skulls and large teeth. The *Ambulocetus*, a later relative, for example, had shorter legs with paddle-like hands and feet, indicating that it had lived a more aquatic lifestyle. Over millions of years, the forelimbs evolved into flippers of the present day whales. What acts as evidence for evolution? How do the limbs of these animals exemplify commonality and diversity?

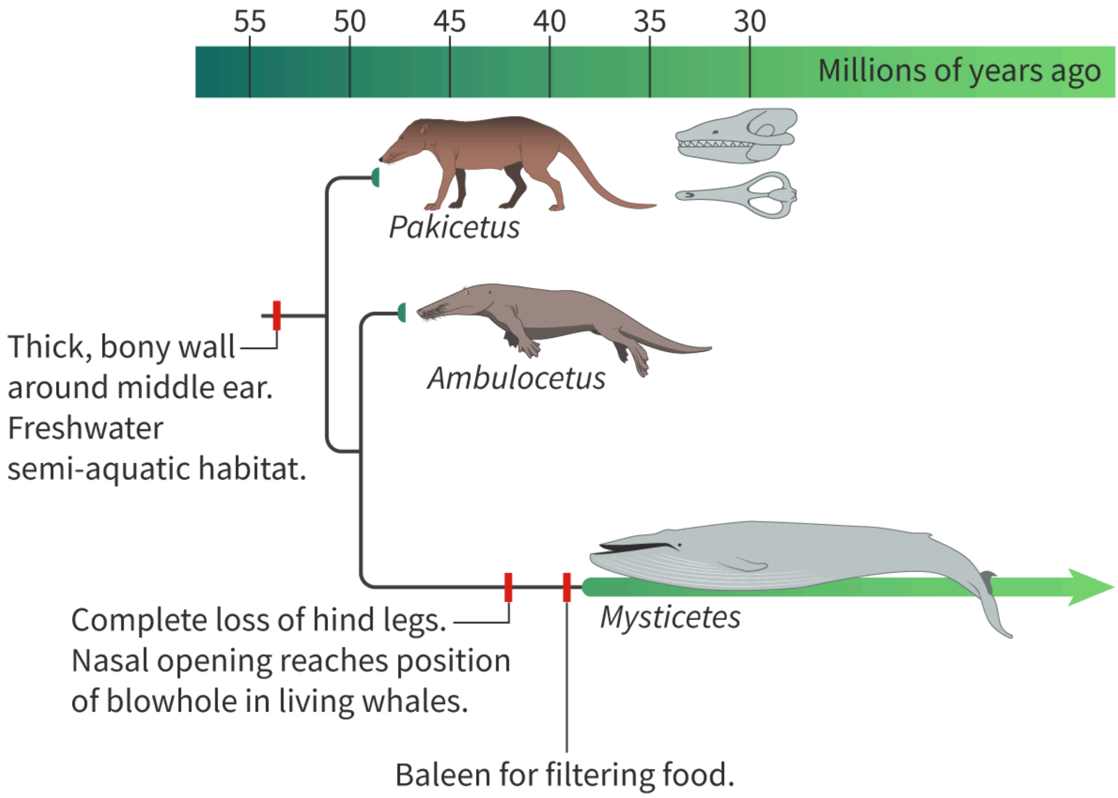

Figure 1. The evolution of whales.

More information for figure 1

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The diagram illustrates the evolutionary history of whales over millions of years. It presents a timeline on top, beginning at 55 million years ago and ending at the present. Three species are depicted along this timeline: Pakicetus, Ambulocetus, and Mysticetes.

Pakicetus, shown at around 50-55 million years ago, resembles a land animal with aquatic adaptations, representing one of the earliest whale ancestors. Annotations describe it as having a thick, bony wall around its middle ear and inhabiting a freshwater semi-aquatic environment.

The diagram then transitions to Ambulocetus, depicted around 45-50 million years ago. This species is presented with shorter legs and paddle-like limbs, indicating a shift towards a more aquatic lifestyle.

Finally, Mysticetes, representing modern whales, are shown nearing the present time. The annotations mention the complete loss of hind legs and the evolution of the nasal opening into a blowhole, typical of current whale species. It also notes the presence of baleen for filtering food.

The diagram effectively demonstrates the evolutionary changes in limb structure and habitat adaptations across these species.

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Prior learning

Before you study this subtopic make sure that you understand the following:

- Fundamentals of genetics (see subtopic A1.2 (/study/app/bio/sid-422-cid-755105/book/the-big-picture-id-43236/)).
- Cell and nuclear division (see subtopic D2.1 (/study/app/bio/sid-422-cid-755105/book/big-picture-id-43548/)).
- Classification of plants and animals (see subtopics A3.1 (/study/app/bio/sid-422-cid-755105/book/the-big-picture-id-43226/) and A3.2 (/study/app/bio/sid-422-cid-755105/book/big-picture-hl-id-43528/)).

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A4. Unity and diversity: Ecosystems / A4.1 Evolution and speciation

Evolution as change in heritable characteristics of a population

A4.1.1: Darwinian evolution

Learning outcomes

By the end of this section you should be able to:

- Define evolution as the change in the heritable characteristics of a population.
- Discuss the theory of natural selection.
- Differentiate between Darwinian evolution and Lamarckian evolution.

What is evolution?

Neck elongation, one of the oldest methods of body modification in humans, is thought to have originated in the 11th century. The rings push down the collarbone and ribs and make the neck look longer (**Figure 1**). Despite being followed for generations, a longer neck is not passed on from the parents to their offspring.

How would you use the language of biology to distinguish between physical changes acquired from the environment and traits that have evolved?

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Figure 1. Neck rings give an illusion of length and do not make the neck longer.

Credit: Buena Vista Images, Getty Images (https://www.gettyimages.co.uk/license/200026357-001)

The study of fossils, selective breeding of domesticated plants and animals, comparative anatomy of animals, nucleotide and amino acid sequences, and the geographical distribution of organisms act as evidence for evolution.

Darwinian evolution vs. Lamarckian evolution

The evidence for evolution comes from multiple sources. One of the theories that is used to explain how organisms change over time was developed by Charles Darwin. He realised that species change over time as evidenced by fossils. Darwin's observations in the Galapagos Islands as well as his own experiments on selective breeding (see section A4.1.2-5 (/study/app/bio/sid-422-cid-755105/book/evidence-from-sequence-data-id-43791/)) paved the way for the theory of natural selection.

Darwin proposed the following points:

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- In nature, there is a tendency to produce more offspring than can be supported by the environment. This ‘overproduction’ eventually leads to competition for natural resources such as food and water, space, etc. As a result, the population size remains fairly constant.
- Individuals within a population are not identical but exhibit variations in their characteristics.
- Individuals with variations that help them adapt better to the environment are more likely to survive, reproduce and pass on the positive variations to their offspring. Similarly, individuals with less favourable variations are less likely to survive. This ‘selection’ by nature is called natural selection.
- Eventually, in a particular environment, individuals with the more favourable variations will form a larger proportion of the population.
- Over many generations, natural selection leads to populations adapted for specific environments. Barriers to reproduction or reproductive isolation (see section A4.1.6–7 (/study/app/bio/sid-422-cid-755105/book/speciation-id-43794/)) may lead to the formation of a new species.

Thus, as per Darwin’s theory, the diversity of life that we see on Earth today has evolved from simpler life forms by the process of natural selection. Darwin’s theory was very different from Lamarck’s theory of evolution.

Lamarck proposed that the physical changes acquired by organisms during their lifetime were passed on to their offspring. In Lamarckism:

- Change in the environment led to the use of certain organs and disuse of others among organisms.
- Organs that were used more would increase in size over the lifetime of the organisms. Similarly, organs that were not used over the lifetime of the organism would shrink.
- These changes acquired over the lifetime of an individual would be passed on to the offspring.

Interactive 1 and **Figure 2** show the differences between Darwinian and Lamarckian evolution.

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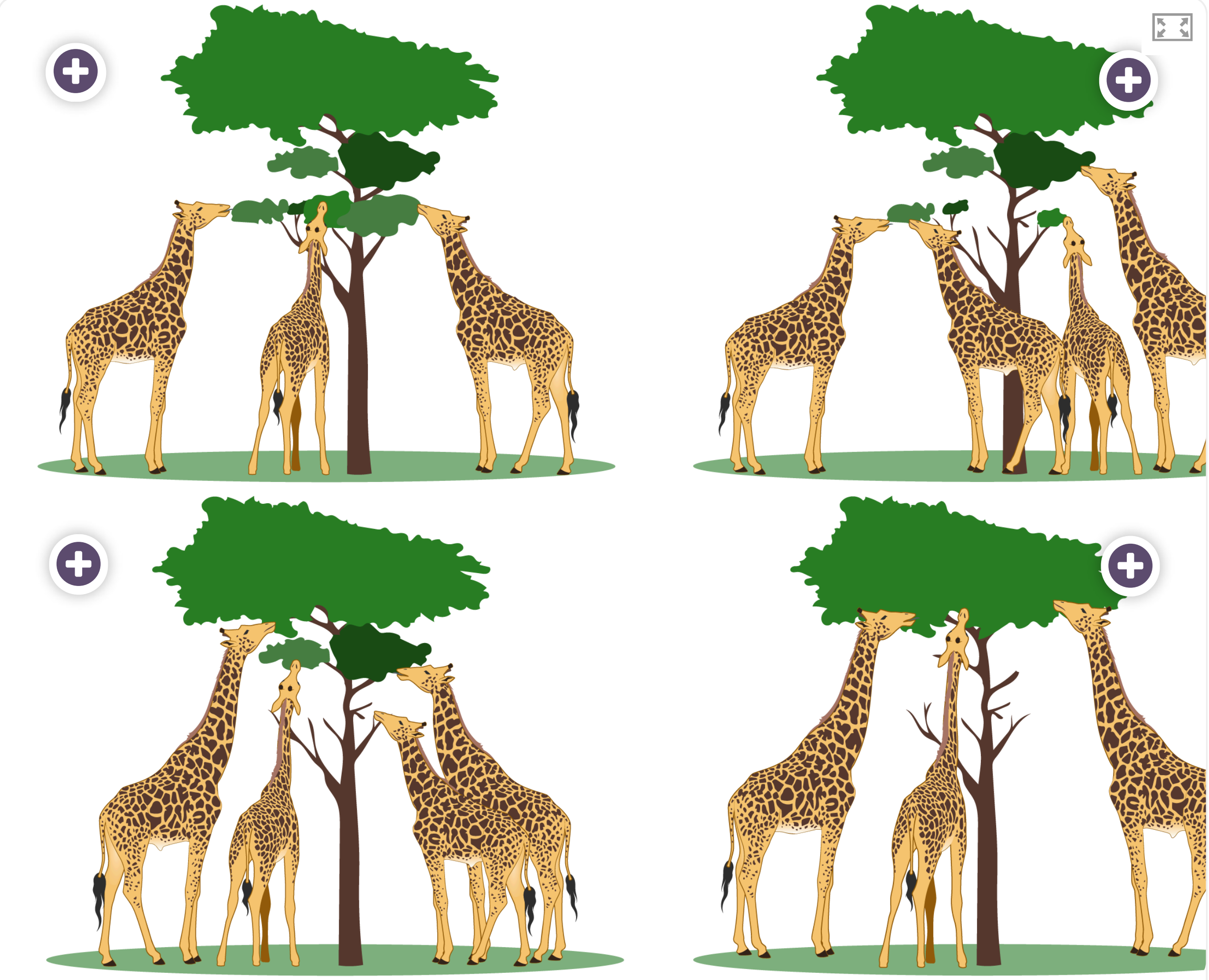

Interactive 1. Darwin's Theory: Evolution of Giraffes.

More information for interactive 1

The illustration represents the process of natural selection and adaptation in giraffes, highlighting variation in neck length that leads to the evolution of longer-necked giraffes over time. This interactivity consists of four sequential illustrations depicting a group of giraffes feeding on a tree. The first illustration, at the top left, shows three giraffes with short neck lengths feeding on the leaves of a large tree; the ancestors of modern giraffes had shorter necks. Some giraffes had slightly longer necks than others. The tree is full of green leaves, and the giraffes are feeding from the lower branches of trees.

In the second illustration at the top right, four giraffes are feeding from different heights. The lower branches are consumed by short-necked giraffes, leaving only the higher leaves accessible. Other lower-necked giraffes struggle to find enough food, and longer-neck giraffes consume upper branches of leaves.

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The third illustration at the bottom left depicts giraffes with longer necks and shorter necks. The longer-necked giraffes have a survival advantage since they can feed on leaves at greater heights. Over time, these giraffes survive at higher rates, reproduce, and pass on the long-neck trait to their offspring. The tree has visibly fewer leaves on the lower branches. The fourth illustration at the bottom right depicts a population of only long-necked giraffes. The shorter-necked giraffes have largely disappeared due to their struggle for food. This illustrates the gradual evolution of longer necks over many generations, demonstrating the principle of natural selection.

There are 4 Hotspots represented by plus signs in the illustrations. Hotspot 1 is on the left side of the first illustration. Hotspot 2 is on the right side of the second illustration. Hotspot 3 is on the left side of the third illustration. Hotspot 4 is on the right side of the fourth illustration. Clicking on the hotspots reveals the description of each illustration.

The following items are revealed at respective hotspots:

Hotspot 1: 1. Variation in neck length: The ancestors of present day giraffes were animals with shorter necks. Variation in the neck size in the population led to some of these animals having longer necks than others.

Hotspot 2: 2. Struggle for existence: A change in the environment led to a shortage of food.

Hotspot 3: 3. Greater fitness: The giraffes with the longer necks had an advantage as they could feed on leaves on the higher branches. These giraffes survived, reproduced and passed on the favourable trait to their offspring.

Hotspot 4: 4. Long-neck trait increases: Over the course of time, the selection of long necks led to an increase in the proportion of giraffes with longer necks.

Nature of Science

Aspect: Falsification

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The theory of evolution provides a perfect example for falsification, which is a primary determinant for acceptance or rejection of a scientific theory. In the case of evolution, there is a large body of proof that has been provided over time but there is no current proof of a continuous line in the evolutionary process. The reason evolution is accepted as a scientific theory, then, is because it is unlikely that falsification will ever occur.

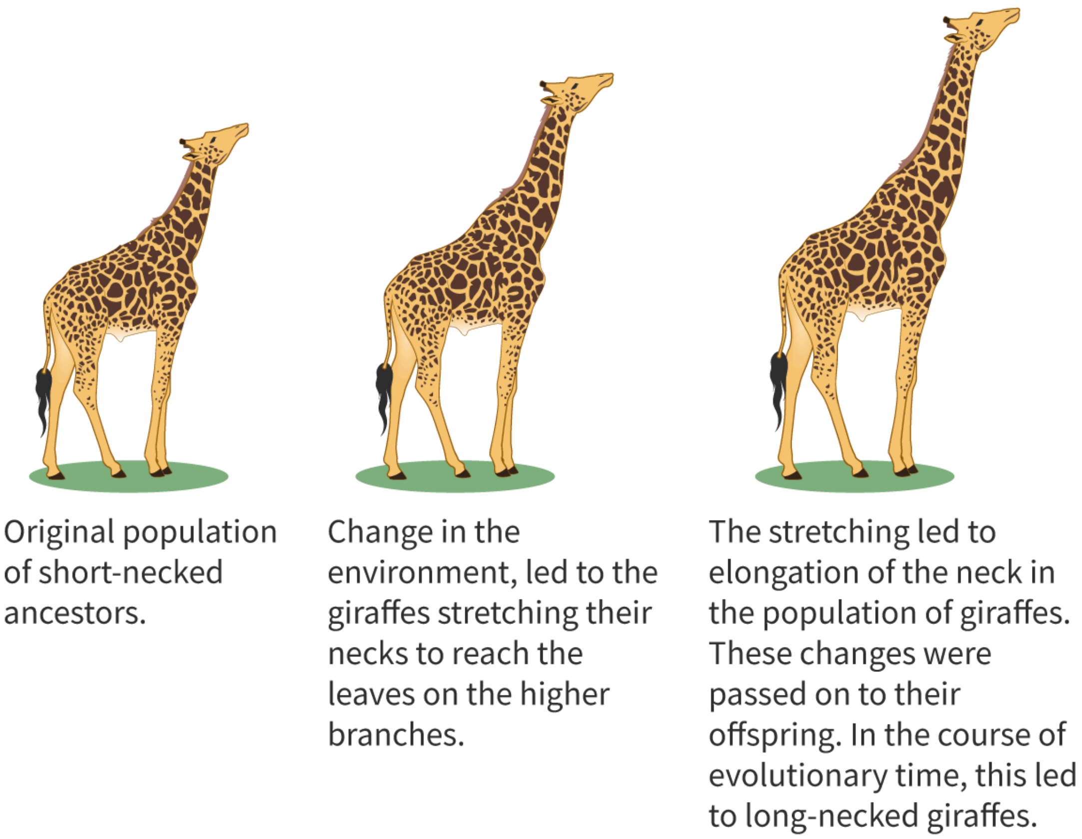

Figure 2. Lamarckism.

More information for figure 2

The image is an illustration depicting the concept of Lamarckism through the evolution of giraffes' necks. It consists of three stages:

1. The first stage on the left shows a short-necked giraffe, labeled "Original population of short-necked ancestors."

2. The middle stage represents a giraffe with a slightly elongated neck, labeled "Change in the environment, led to the giraffes stretching their necks to reach the leaves on the higher branches."

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3. The final stage on the right features a giraffe with a significantly longer neck, labeled "The stretching led to elongation of the neck in the population of giraffes. These changes were passed on to their offspring. In the course of evolutionary time, this led to long-necked giraffes."

Each giraffe is depicted standing on a patch of grass, indicating their natural environment. This illustration visually conveys the idea of Lamarckism, which suggests that characteristics acquired or lost during an organism's lifetime can be passed on to its offspring.

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Nature of Science

Aspect: Hypotheses

Although it may seem obvious now that acquired changes need to be genetic in origin to be inherited, remember that at the time when Darwin proposed his theory, no one in the scientific community knew about genes and genetics.

It is now known that evolution is a change in the inherited characteristics of a population. This is the reason why Lamarckism is no longer accepted, as in most cases, the acquired changes do not affect the germ cells and hence are not passed on from one generation to another.

Theory of Knowledge

How should scientists choose between competing theories? When should a scientist concede that their theory has failed? What sort of evidence would be required?

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Scientists use several methods to evaluate and compare competing theories. One method is to gather evidence and observe which theory best explains the available data. Scientists may also try to test the predictions of each theory using experiments or observations. Additionally, scientists may consider the ability of each theory to make novel predictions, as theories that can accurately predict previously unknown phenomena are typically seen as more robust. Ultimately, the decision of which theory to accept may involve a combination of these and other factors, and may change as new evidence becomes available.

Think along similar lines and discuss the questions at the start of this box.

Try this group activity where you take on the roles of Darwin and Lamarck to help you understand their theories.

Activity

- **IB learner profile attribute:** Thinker
- **Approaches to learning:** Thinking skills — Providing a reasoned argument to support conclusions
- **Time required to complete activity:** 30 minutes
- **Activity type:** Group activity

Resources

If you would like to extend your understanding and have a more in-depth discussion, the following articles on mole rats (https://www.science.org/content/article/blind-mole-rats-show-evolution-action#:~:text=Blind%20mole%20rats%20could%20be,spread%20genes%2 snakes (https://www.scientificamerican.com/article/how-snakes-lost-their-legs/) would be useful.

Instructions

1. Form groups of four.
2. Read a passage.

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3. Discuss the passage in your groups.
4. Take the roles of Lamarck and Darwin and present your arguments.
5. Repeat for the next two passages.

Passages

Passage 1: Weightlifting

Weightlifters undergo intensive training. Over time, due to the lifting of weights, their muscles strengthen and grow.

How would Lamarck extend this as per his theory of evolution? How would Darwin argue against this explanation?

Passage 2: The life of mole rats

Mole rats are adapted to life underground. Approximately 7—8 centimetres long, they have broad heads with powerful jaws and large incisors often used to dig tunnels. They are virtually blind. The ancestors of mole rats lived above the ground and did not have these characteristics.

How would Darwin and Lamarck explain these unique structural adaptations?

Passage 3: The limbless wonders

Well-adapted to life in small holes or burrows, present day snakes have a long, limbless body that can traverse land, water and even the air from one tree to another. Studies show that the ancestors of snakes had limbs.

How would Darwin and Lamarck explain the loss of limbs?

5 section questions

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A4. Unity and diversity: Ecosystems / A4.1 Evolution and speciation

Evidence for evolution

A4.1.2: Evidence from base and amino acid sequences A4.1.3: Evidence from selective breeding
A4.1.4: Evidence from homologous structures A4.1.5: Convergent evolution

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Learning outcomes

By the end of this section you should be able to:

- Analyse how base sequences in DNA or RNA and amino acid sequences in proteins give powerful evidence of common ancestry.
- Examine how selective breeding of domesticated plants and animals acts as evidence for evolution.
- Discuss the role of humans in bringing genetic changes in plant and animal species.
- Explain the difference between homologous and analogous structures.
- Compare the structure of the pentadactyl limb across evolutionary groups.
- Describe convergent evolution.

Evidence from sequence data

A close relative

Are humans similar to chimpanzees? If you answered ‘no’, it may surprise you to know that 98.8% of our DNA is identical to chimpanzees. What does this mean in terms of evolution?

In all living organisms, the building blocks of life, DNA, RNA and proteins, are universal in nature. All living organisms have the same nucleotide bases and amino acids. This indicates a common origin of life.

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Concept

The genetic code is a three-letter codon that specifies a particular amino acid.

After the genetic code of the bacteria *Escherichia coli* was identified in 1968, the genetic code was subsequently determined for many other organisms ranging from bacteria to plants to mammals, including humans. The code was found to be the same for all organisms, leading to the idea that the genetic code is 'universal'. This suggests that life on Earth has a single evolutionary origin, otherwise, there would have been numerous genetic codes.

It is important to understand that the genetic code is different from the genome, which is the complete set of genetic information of an organism.

Making connections

The sequence of the four bases in DNA and RNA form the basis of the genetic code (see section A1.2.4 (/study/app/bio/sid-422-cid-755105/book/complementary-base-pairing-id-43801/)).

Molecular phylogeny

One way of proving the common origin of life is comparative analysis of the sequences of the bases in DNA (subtopic A1.2 (/study/app/bio/sid-422-cid-755105/book/the-big-picture-id-43236/)) and RNA (subtopic A1.2 (/study/app/bio/sid-422-cid-755105/book/the-big-picture-id-43236/)), and the amino acids in proteins (subtopic B1.2 (/study/app/bio/sid-422-cid-755105/book/big-picture-id-43531/)) to infer evolutionary history. This is known as molecular phylogeny and it can be used to determine how closely two species are related to each other at a molecular level. More similarity in genes and proteins indicates more closely related species.

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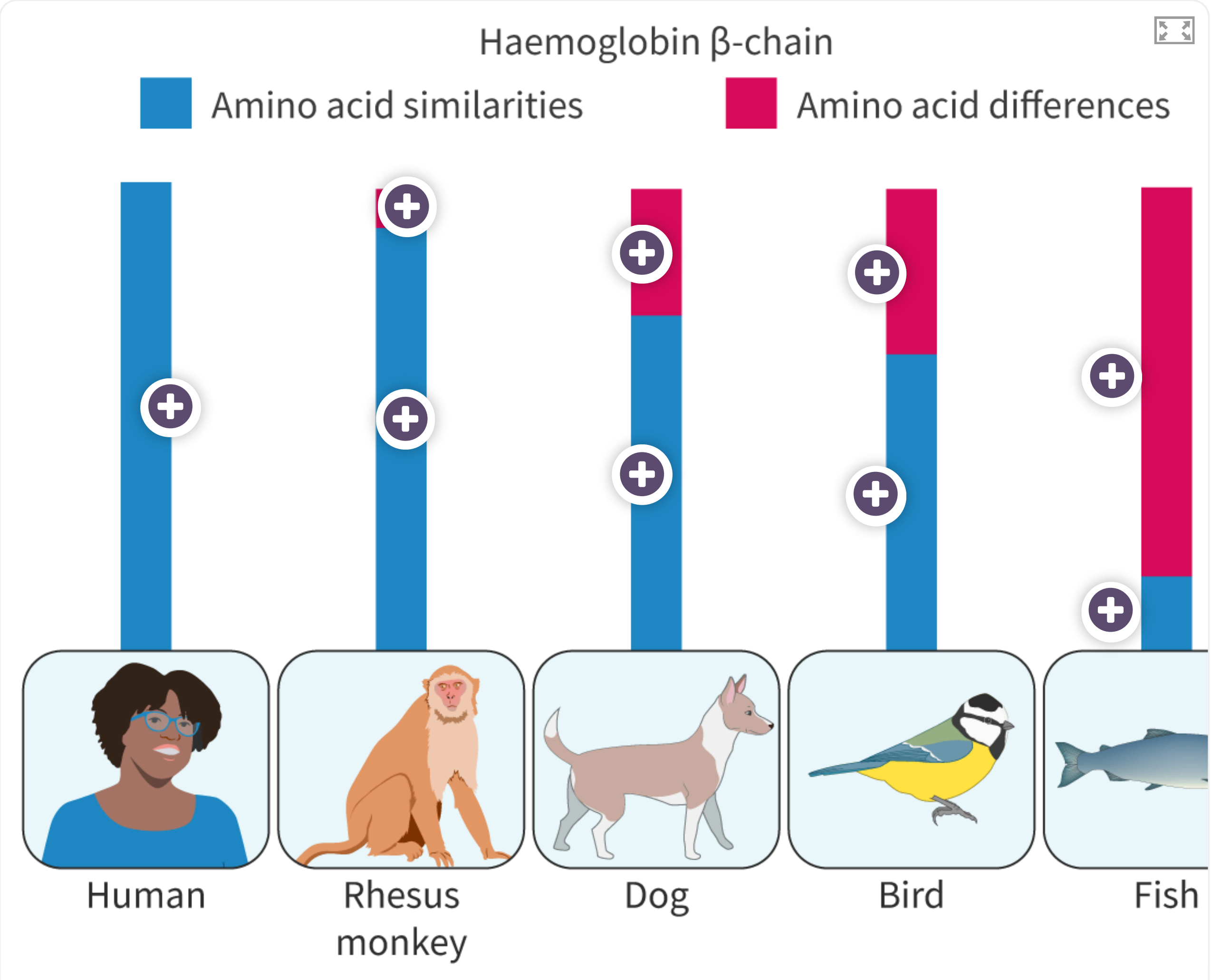
Changes in the genome (and amino acids specified) are due to mutations. The rate of mutation of a gene is fairly constant and leads to differences in the DNA, which accumulate over time. So the number of differences between the sequence of bases of a gene in two species increases with time. This forms the basis of the molecular clock, which measures time from changes in the DNA. For example, species with fewer differences in their genomes (and amino acids) would have recently split or diverged from each other.

Click on the plus signs in **Interactive 1** to compare the amino acid sequences of the represented haemoglobin beta chains.



Interactive 1. Comparing Amino Acid Similarities and Differences of Haemoglobin Beta Chains.

More information for interactive 1

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The analysis of the haemoglobin β-chain illustration presents a comparative analysis of the haemoglobin (protein in red blood cells that carries oxygen) across five different species: humans, Rhesus monkeys, dogs, birds, and fish. The image bar graph depicts the amino acid similarities and differences among these species. Above each species, a vertical bar graph represents the similarity of its haemoglobin β-chain sequence compared to humans. Blue sections of the bars indicate amino acid similarities, and pink sections of the bars indicate amino acid differences. Humans (first column) have a completely blue bar, indicating that their haemoglobin β-chain is the reference sequence with no differences. Rhesus Monkey (second) has a mostly blue bar with a small pink section, indicating few differences. The dog (third) has a larger pink section, showing more differences than the monkey. Bird (fourth) has nearly equal blue and pink sections, indicating significant divergence. Fish (rightmost) have the most pink, indicating the greatest evolutionary difference from humans in haemoglobin β-chain structure.

There are 9 Hotspots represented by plus signs at various places. Hotspot 1 is right to the blue section of the bar of humans. Hotspot 2 is right to the pink section of the bar of Rhesus monkey. Hotspot 3 is right to the blue section of the bar of Rhesus monkey. Hotspot 4 is right to the pink section of the bar of the dog. Hotspot 5 is right to the blue section of the bar of the dog. Hotspot 6 is right to the pink section of the bar of the bird. Hotspot 7 is right to the blue section of the bar of the bird. Hotspot 8 is right to the pink section of the bar of the fish. Hotspot 7 is right to the blue section of the bar of the fish. Clicking on the hotspots near the pink sections reveals the amino acid differences, while hotspots near the blue sections reveal the amino acid similarities.

The following items are revealed at respective hotspots:

Hotspot 1: 146

Hotspot 2: 8

Hotspot 3: 138

Hotspot 4: 32

Hotspot 5: 114

Hotspot 6: 45

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Hotspot 7: 101

Hotspot 8: 125

Hotspot 9: 21

Biological Concept : This image demonstrates evolutionary relationships through molecular evidence. The species more closely related to humans (such as monkeys) have fewer amino acid differences in their haemoglobin β-chain, while more distantly related species (like fish) have greater differences. The rhesus monkey, being a fellow primate, shares the most similarity with humans. The dog is more distantly related than the monkey and has more sequence differences. The bird and fish, being non-mammalian species, have more significant differences, showing their evolutionary divergence from humans occurred much earlier. By comparing protein sequences, users can trace evolutionary connections and understand how species have evolved over time.

The number of differences is highest between the amino acid sequence of humans and fish in **Interactive 1**, suggesting that more time has passed since these species diverged.

If we go back to the question of whether humans are similar to chimpanzees, a 98.8% match indicates that humans and chimpanzees shared a common ancestor in the recent past!

Evidence from selective breeding

Looking around, you will see a variety of dog breeds, from huge Alsatians to tiny Chihuahuas (**Figure 1**). Studies show that all these breeds can trace their ancestry to an extinct wolf species. Humans played a big role in creating these breeds. For centuries, through the process of selective breeding, dogs have been bred for their desired characteristics. But how does selective breeding act as evidence for evolution?

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Figure 1. Breeding for desired characteristics has resulted in a variety of dog breeds.

Credit: Compassionate Eye Foundation/David Leahy, Getty (https://www.gettyimages.co.uk/license/175928868) Images

Mechanism of selective breeding

Unlike natural selection, where organisms better adapted to the environment survive, reproduce and pass on the traits to their offspring, in selective breeding, humans decide the favourable variations. We select organisms with desirable characteristics and use them as the next generation of parents. Over generations, humans continually select organisms with desirable characteristics, removing those with less desirable traits, leading to a rapid genetic change in the population.

Selective breeding is not new to humans. For centuries, we have been breeding plants and animals for genetic characteristics that are beneficial to humans. For example, farmers often selectively breed cows to increase the milk production or hens to increase egg size. Similarly, they may selectively breed crops to increase disease resistance and yield.

Interactive 2 illustrates the selective breeding of the wild mustard plant (*Brassica oleracea*). Centuries of selective breeding of desired characteristics has led to different vegetables.

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Interactive 2. Selective Breeding in Multiple Ways of the Wild Mustard (*B. oleracea*).

More information for interactive 2

This interactivity illustrates the selective breeding of the wild mustard plant (*Brassica oleracea*), showing its structures, including yellow flowers, green leaves, and a strong central stem. This plant belongs to the Brassicaceae family, which includes several commonly consumed vegetables.

There are 5 Hotspots represented by plus signs at various plant parts. Hotspot 1 is on the clusters of green buds covered by yellow flowers. Hotspot 2 is on the leaf bud of the plant. Hotspot 3 is on the flower bud of the plant. Hotspot 4 is on the leaf of the plant. Hotspot 5 is below the image of the plant.

Student view

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Clicking on the hotspots reveals specific parts of the plant that have evolved into different vegetables due to selective breeding.

The following items are revealed at respective hotspots:

Hotspot 1: Broccoli (flower buds/stems). It illustrates an image of broccoli, a vegetable that originates from the flower buds and thick stems of the Brassica plant.

Hotspot 2: Cabbage (terminal leaf bud). It shows an image of cabbage, which comes from the tightly packed terminal leaf bud of *Brassica oleracea*.

Hotspot 3: Cauliflower (flower buds). It shows an image of cauliflower, a vegetable consisting of undeveloped flower buds.

Hotspot 4: Kale (leaves). It displays an image of kale, a variety of Brassica grown for its edible foliage.

Hotspot 5: Wild mustard plant (*Brassica oleracea*)

Biological Concept: This image demonstrates artificial selection and plant evolution within the *Brassica oleracea*. All these vegetables such as broccoli, cabbage, cauliflower, and kale originate from a common ancestor, selective breeding has modified specific plant structures for different purposes: Flower buds modified into broccoli and cauliflower. The terminal leaf bud was modified into cabbage. Broad leaves were modified into kale. This interactivity illustrates how human agricultural methods influence the characteristics of plants and demonstrates how a single plant species can give rise to a variety of vegetables through the process of selective breeding.

Selective breeding thus brings rapid changes in the genetic make-up of a population, eventually leading to evolution. **Video 1** shows how domesticated plant and animal breeds undergo rapid evolutionary changes due to selective breeding.

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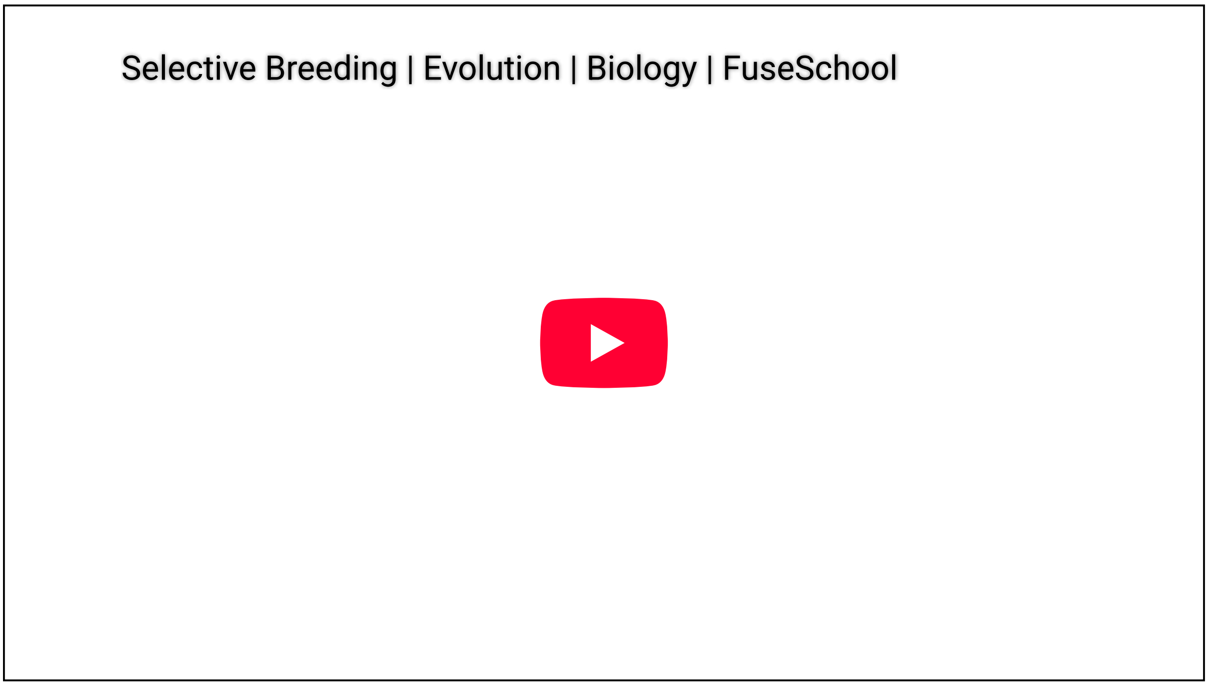

Video 1. Selective breeding.

Darwin and selective breeding

Darwin’s pigeon breeding experiments helped him frame his theory of natural selection (see section A4.1.1 (/study/app/bio/sid-422-cid-755105/book/evolution-as-change-in-heritable-characteristics-id-43790/)). He noted that the breeds, while morphologically distinct from each other, were descendants of the wild rock pigeon that evolved over years of selective breeding.

Figure 3 shows the variation of pigeon breeds descended from the wild rock pigeon.

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Rights of use

Figure 3. Variation in Pigeons.

Darwin extrapolated his understanding of selective breeding to frame his theory of natural selection. He drew parallels between the process of selective breeding due to human intervention and natural selection by the environment. He stated that while selective breeding was a more rapid process, in both cases, selection of favourable characteristics over generations, led to evolution.

Theory of Knowledge

The world that we inhabit is often limited by the world that we see. Can we draw any distinction between knowledge claims dependent on observations made by sense perception and knowledge claims dependent on observations assisted by technology? For example, science looks at understanding the world through the lens of reason, evidence and observation. Explanation of evolution through science is

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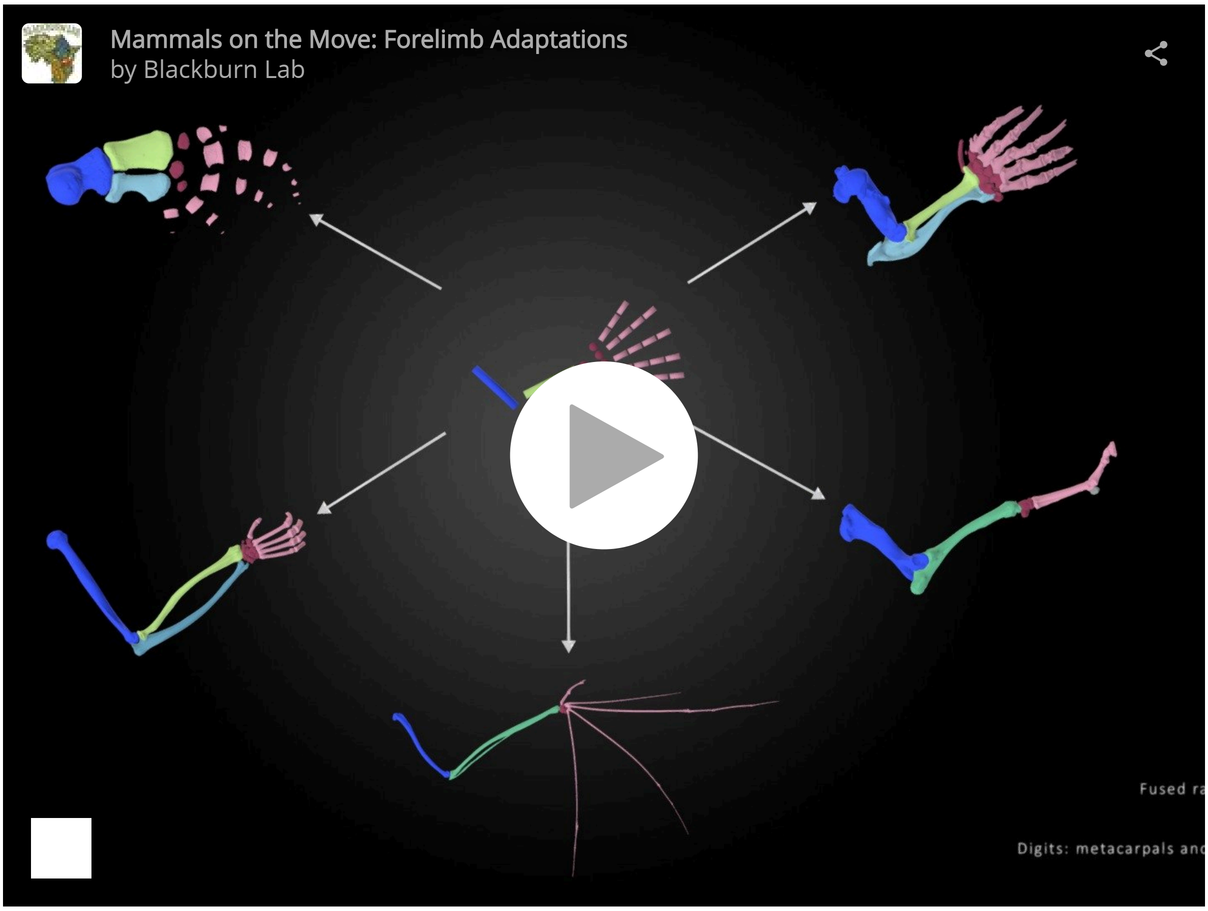
very different from the explanation of evolution using other knowledge systems. This does not necessarily mean that any one system is superior to another.

Evidence from homologous structures

Vertebrates such as a human, a whale, a bat, a pigeon or a lizard have limbs that look different and carry out different functions yet have the same basic bone structure. How would you use this similarity as evidence of evolution by natural selection?

Studies show that the body structures of some organisms are fundamentally similar. Homologous structures have the same basic structural plan, indicating a common ancestry. One typical example is the pentadactyl (five-fingered) limb of vertebrates. **Interactive 4** shows a 3D model of the arrangements of bones in the pentadactyl vertebrate limbs of different mammals. Note that, although the limbs are used for different functions, there is a striking similarity in their structures and the general arrangements of the humerus, radius, ulna, carpals and digits.



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Interactive 4. Pentadactyl limb in mammals.

Mammals on the Move: Forelimb Adaptations (https://sketchfab.com/3d-models/mammals-on-the-move-forelimb-adaptations-edc963a36388486ab3f27f1a2b92b267?utm_medium=embed&utm_campaign=share-popup&utm_content=edc963a36388486ab3f27f1a2b92b267) by Blackburn Lab (https://sketchfab.com/ufherps?utm_medium=embed&utm_campaign=share-popup&utm_content=edc963a36388486ab3f27f1a2b92b267) on Sketchfab (https://sketchfab.com?utm_medium=embed&utm_campaign=share-popup&utm_content=edc963a36388486ab3f27f1a2b92b267)

More information for interactive 4

This interactive presents a 3D model showcasing the arrangement of bones in the pentadactyl (five-fingered) limbs of various mammals, including the chimpanzee, vampire bat, Poitou donkey, orca, and star-nosed mole. Users can drag and rotate the model to view the three-dimensional bone structure from different angles. Each bone is numbered, and users can click on a number to reveal detailed information about the corresponding bone. The bones are color-coded, with a color legend displayed in the bottom right corner of the interactive.

Although these limbs serve different functions—such as walking, flying, grasping, swimming, and digging—their structures exhibit striking similarities. The arrangement of bones like the humerus, radius, ulna, fused radius and ulna, carpals, and digits indicates a shared evolutionary origin, suggesting a common ancestral species. This interactive helps users understand how homologous structures with a similar basic design provide evidence for evolution, demonstrating both common ancestry and divergent evolution.

Clicking on numbers 1 to 6 reveals information about the general arrangement and names of the bones, while clicking on numbers 7 to 11 provides insights into the function of these bones in different animals. For example, clicking on number 7 displays data about the orca (Orcinus orca) and how its limb structure supports swimming.

Homologous structures indicate divergent evolution. Divergent evolution occurs when organisms arising from the same ancestral species adapt to different environmental conditions according to the pressures of natural selection.

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Homologous structures (or organs) thus act as evidence for evolution as they indicate a common evolutionary organ.

Convergent evolution as the origin of analogous structures

If you compared the wings of birds and insects, you would note that while they have the same function, they are very dissimilar in structure. Analogous structures are body parts that have the same or similar function in different groups of organisms but have different structures.

Analogous structures do not indicate evolutionary relationships but they are the result of a process known as convergent evolution. Convergent evolution occurs when distantly related groups of organisms face similar environmental conditions and adapt in similar ways. Insect wings and bird wings evolved when their different ancestors independently adapted to a similar mode of life, that is, flight (**Figure 2**).

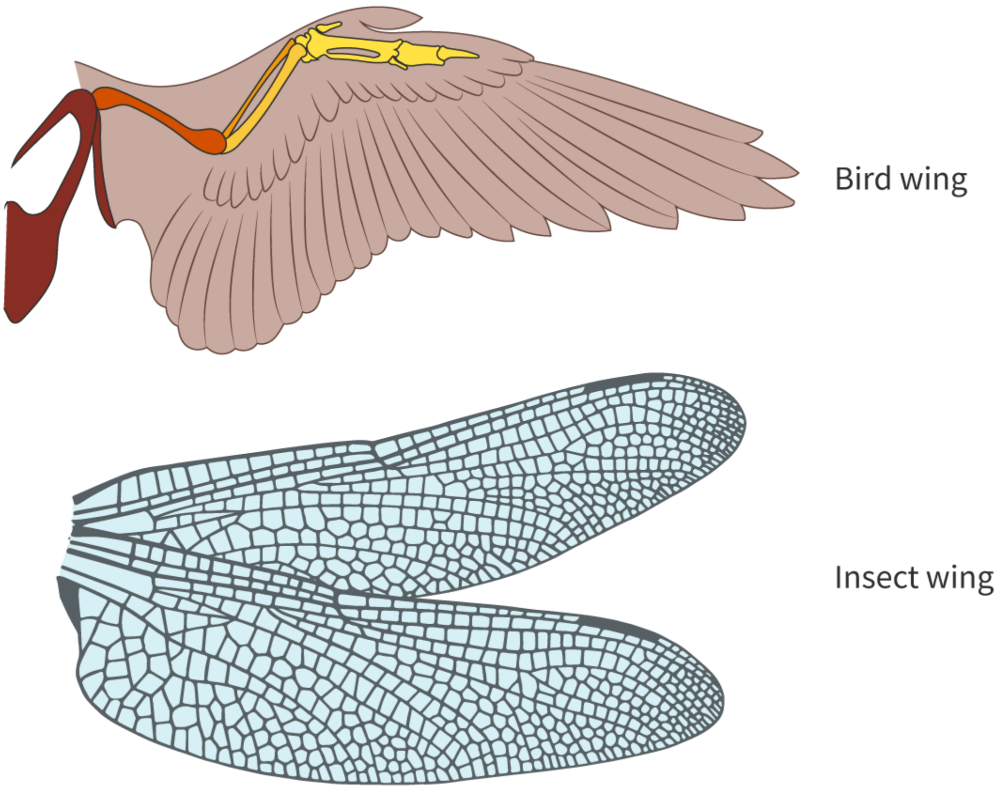

Figure 2. Wings in insects and birds indicate convergent evolution.

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Nature of Science

Aspect: Evidence

Scientific knowledge must be supported by evidence. Claims that are not supported by verifiable evidence are not scientific. Homologous and analogous structures provide evidence for evolution.

Try the model-making activity below to check your understanding of pentadactyl limbs.

Activity

- **IB learner profile attribute:** Knowledgeable
- **Approaches to learning**: Social skills — Working collaboratively to achieve a common goal
- **Time required to complete activity:** 30 minutes
- **Activity type:** Group activity

Aim: Make models of pentadactyl limbs.

Materials: toothpicks, tape, lolly sticks, clay, straw, glue, etc.

Instructions

- In groups of four, select a mammal from the following: mole, horse, human, bat, whale, monkey.
- Discuss and prepare a rough sketch of your model.
- Select the materials and build the model. For example, you could use lolly sticks and toothpicks to represent the bones.
- Present your model and discuss the evolutionary relationship it indicates.

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5 section questions

A4. Unity and diversity: Ecosystems / A4.1 Evolution and speciation

Speciation

A4.1.6: Speciation A4.1.7: Reproductive isolation and differential selection

Learning outcomes

By the end of this section you should be able to:

- Describe the process of speciation.
- Discuss how reproductive isolation and differential selection results in speciation.
- Investigate the example of divergence due to differential selection in the separation of bonobos and common chimpanzees.

Defining a species

What defines a species? When do we say a new species has evolved? When similar organisms can mate with each other and produce viable, fertile offspring, they are considered to be members of the same species. In other words, reproductive compatibility defines a species. This holds true for most plants, animals and fungi.

Polar bears and Alaskan brown bears have always been considered as two separate species. However, in 1936 at the U.S. National Zoo, a male polar bear accidentally got into an enclosure with a female Alaskan brown bear. Three offspring were the result and these offspring were able to breed successfully. How does this fit with the accepted definition of ‘species’?

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Making connections

Subtopic A3.1 (/study/app/bio/sid-422-cid-755105/book/the-big-picture-id-43226/) introduces the concept of species. The original morphological concept of a species as a group of organisms with shared traits was used by Linnaeus. More recently, according to the biological species concept, a species is a group of organisms that can breed and produce fertile offspring. In evolution, species is a fundamental unit, but often there are exceptions to the rules of speciation. For example, lions and tigers belong to different species, differing in appearance, behaviour and geography, but when brought together in an artificial environment can successfully interbreed and produce offspring. The offspring are not fertile, however. In other words, the variation cannot be passed on. Only inherited traits can evolve (see section A4.1.1 (/study/app/bio/sid-422-cid-755105/book/evolution-as-change-in-heritable-characteristics-id-43790/)). Another example would be the bear cubs produced by the mating of the Alaskan brown bear and the polar bear.

Speciation

It is estimated that there are approximately 8.7 million eukaryotic species on Earth. Speciation is the process by which new species arise. It involves the splitting of one ancestral species into two or more descendent species which are genetically different from each other and can no longer interbreed.

A population of species shares a gene pool (see section D4.1.9 (/study/app/bio/sid-422-cid-755105/book/gene-pools-and-changes-in-their-composition-hl-id-43804/)) or a collection of the variants of the genes in the species. Speciation results in modifying the original gene pool into separate gene pools in a way that interbreeding is prevented, that is, speciation leads to genetic separation. Speciation increases the total number of species on Earth. On the other hand, extinction or dying out of species reduces the total number of species on Earth.

Note that gradual evolutionary changes may not lead to formation of a new species. There could be evolutionary changes in the gene pool prior to speciation. In speciation the make-up of the gene pool must change sufficiently to define a

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new species. Changes should be such that it is impossible for the members of the two or more descendant populations to interbreed.

Reproductive isolation and differential selection

Reproductive isolation due to geographical barriers

There are many hypotheses to explain speciation. One of the drivers for speciation is reproductive isolation. Reproductive isolation refers to barriers that prevent populations of the same species from interbreeding and/or producing fertile offspring.

Reproductive isolation could result from geographical barriers such as:

- physical barriers like mountain ranges or river
- large distances between populations
- human-made barriers like large roads or dams.

The stages of reproductive isolation due to geographical barriers are detailed below (refer to **Interactive 1**):

- A large population of individuals occupies a habitat.
- The formation of a new geographical barrier divides the original population into two smaller populations: A and B.
- The geographical barrier prevents members of the two populations from mixing and interbreeding.
- In different environments, evolutionary forces such as natural selection (section D4.1.1 (/study/app/bio/sid-422-cid-755105/book/natural-selection-id-43805/)), mutation (section D1.3.1 (/study/app/bio/sid-422-cid-755105/book/gene-mutations-id-43806/)) and genetic drift act independently on the gene pools of the two populations for many generations.
- Due to the action of the evolutionary forces, genes that provide better adaptation to environmental challenges are selected over others and

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transmitted through generations. In other words, natural selection leads to differential reproduction and in a way differential selection.

- Differential selection eventually leads to genetic separation.
- The resulting behavioural and/or physiological changes prevent the populations from mating.
- Even if the barrier is now removed, the members of the two populations cannot interbreed. Two new species A and B are formed.

Click through the slides in **Interactive 1.** In this case, geographical isolation and differential reproduction lead to reproductive isolation, eventually leading to the formation of new species.

Interactive 1. Geographical Isolation Leading to Reproductive Isolation and Speciation.

More information for interactive 1

An interactive animation illustrating the process of allopatric speciation through five sequential slides. Each slide contains a scene with color-coded bug populations (red, orange, and yellow) to represent genetic variation. The interface shows a continuous evolutionary progression, from a unified interbreeding population to two genetically distinct species.

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Slide 1: A population occupies a habitat.

A mixed-color population of bugs occupies a single habitat, all capable of interbreeding.

Slide 2: A river splits the original population into two.

A river appears, splitting the habitat and isolating the bug population into two groups on either side.

Slide 3: Evolutionary forces act independently on both the populations.

Each isolated group undergoes independent evolution; environmental differences begin to shift bug colors on each side.

Slide 4: Many generations later, populations A and B are genetically different.

The two populations are now visibly distinct in color and traits, representing genetic divergence.

Slide 5: Even if the barrier disappears, A and B now cannot interbreed.
A and B are two new species.

The river disappears, but the two bug populations no longer interbreed, signifying the formation of two new species.

Navigation buttons allow users to move between slides. Color changes and animations visually represent evolutionary change.

The selection differential is the difference between the mean of a quantitative character in a whole population and the mean of the individuals selected to reproduce in the next generation. It is a measure of the association between a trait value and its ability to confer reproductive success or increase survival rates.

Student view

An example of differential selection leading to divergence is described in the case study that follows.

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A case study

Chimpanzees and bonobos are African apes that live in close proximity with each other. While chimpanzees are distributed across equatorial Africa, bonobos are restricted to a region south of the Congo River (**Figure 2**). Chimpanzees are larger, more aggressive and live in male-dominated groups. Bonobos are more slender, more playful and have female-dominated groups.

The chimpanzees and the bonobos belonged to a common ancestral species living in the rainforests of the Democratic Republic of the Congo. The formation of the Congo River, the deepest river in the world, nearly 1.5 to 2 million years ago, divided the ancestral population into two groups. The group north of the river faced intense competition for resources. They had to compete not only with each other, but also with the ancestral population of gorillas. Aggressive tendencies were evolutionarily selected. Over time, this group evolved to the present day chimpanzees.

To the south of the Congo River, where the resources were plentiful, the apes evolved to become slender and more cooperative, eventually giving rise to the bonobos.

Thus, development of a geographical barrier and differential selection over the course of time led to reproductive isolation. This, in turn, led to speciation. You can read more in this article (https://www.bonobos.org/post/bonoboschimpsandthecongoriver).

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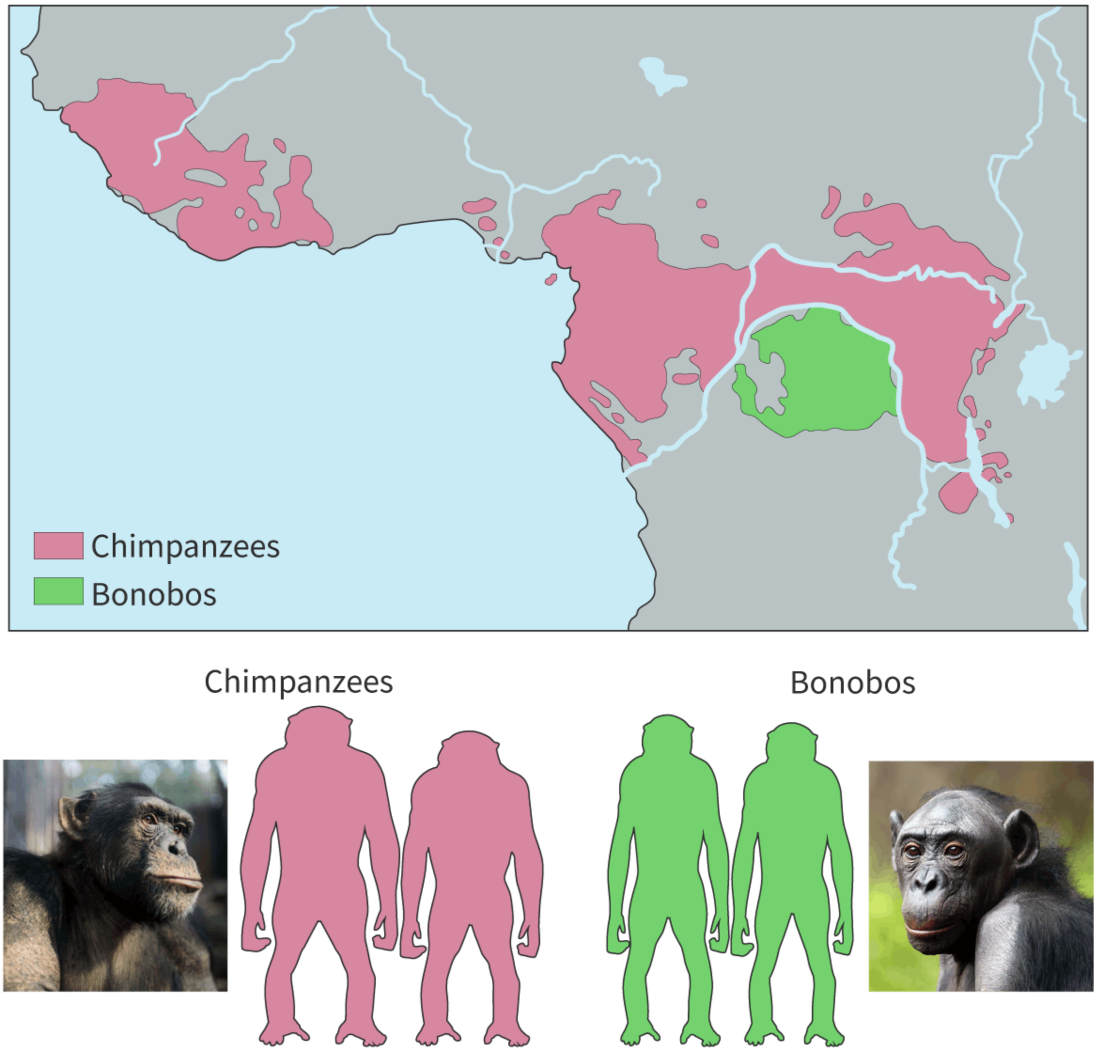

Figure 2. Physical and behavioural differences are evident in bonobos and chimpanzees.

More information for figure 2

The image is divided into two sections. The top section features a map highlighting the geographical distributions of chimpanzees and bonobos in Africa. Chimpanzee regions are marked in pink, located mainly in West and Central Africa, while bonobos regions are marked in green, located in the Democratic Republic of the Congo.

The lower section of the image presents silhouettes and photographs to illustrate physical differences between chimpanzees and bonobos. On the left are images of chimpanzees, showing two pink silhouettes of typical body shapes and a photo of a chimpanzee. On the right are images of bonobos, featuring two green silhouettes and a photo of a bonobo. The silhouettes highlight distinct physical characteristics, with chimpanzees generally being larger and having a more robust build compared to the more slender and lighter-colored bonobos.

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Creativity, activity, service

Strand: Service
Learning outcome: Demonstrate engagement with issues of global significance

Chimpanzees and bonobos are endangered species. Bonobos, the gentle apes, face a high risk of extinction. Habitat loss due to the clearing of the rainforests, civil unrest, poaching and disease transmission threaten the existence of these apes, with whom we share more than 98% of our DNA. Global collaboration is needed to save these species.

Become a global citizen and take action in conserving these great apes from their greatest threat — humans!

Try the activity below to check your understanding of how chimpanzees and bonobos evolved.

Activity

- **IB learner profile attribute**: Communicator
- **Approaches to learning**: Communication skills — Reflecting on the needs of the audience when creating engaging presentations
- **Time required to complete activity:** 30 minutes
- **Activity type:** Pair activity

Student view

Aim: Create a three to five frame cartoon to tell the complex story of the evolution of chimpanzees and bonobos.

Materials: Paper, art materials

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Instructions

- Work in pairs.
- Discuss and visualise:
  - The beginning, middle and end of your strip.
  - Characters, settings and speech.
- Draw the frames on a sheet of paper.
- Use basic shapes to draw the characters.
- Add speech bubbles if needed.
- Display in class.

5 section questions

A4. Unity and diversity: Ecosystems / A4.1 Evolution and speciation

Types of speciation: allopatric vs sympatric (HL)

A4.1.8: Sympatric and allopatric speciation (HL)

Higher level (HL)

Learning outcomes

By the end of this section you should be able to:

- Compare sympatric and allopatric speciation.
- Explain how temporal, geographic or behavioural isolation can lead to reproductive isolation.

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The Kaibab squirrels

The Grand Canyon National Park is famous for Kaibab squirrels and Abert squirrels (**Figure 1**). The squirrels are similar in shape and size, with long tails and tufted ears. If you visit the northern rim of the Grand Canyon National Park, you will see the Kaibab squirrels. These squirrels are brown in colour with dark bellies and white tails. On the southern rim of the canyon, however, you would see Abert squirrels that are charcoal grey, with white bellies and dark tails. What led to the formation of these evidently closely related yet distinct types of squirrels?

Credit: mlharing, Getty Images (https://www.gettyimages.co.uk/license/1314630049)

Credit: Stan Tekiela Author / Naturalist / Wildlife Photographer, Getty Images (https://www.gettyimages.co.uk/license/1218803887)

Figure 1. On either side of the Grand Canyon, the Kaibab squirrels (*Sciurus aberti kaibabensis*, left) and Abert squirrels (*Sciurus aberti*, right).

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Allopatric and sympatric speciation

As discussed in section 4.1.6-7 (/study/app/bio/sid-422-cid-755105/book/speciation-id-43794/), speciation is the formation of two or more species from an ancestral species. There are two types of speciation:

- allopatric speciation
- sympatric speciation.

Allopatric speciation

As illustrated by the example of chimpanzees and bonobos in the previous section, allopatric speciation is nothing but geographical isolation. It occurs when a population of a species is split into two by a geographical barrier preventing exchange of genetic material. The two populations that are now isolated, experience different selection pressures and diverge genetically. This in turn may lead to reproductive isolation. Even if at a later stage, the two species come into contact they are unable to interbreed, resulting in speciation.

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The Kaibab squirrels are an example of allopatric speciation. The ancestors of the Abert squirrels had a wide distribution. Thousands of years ago, when the Grand Canyon formed, a small population of squirrels got cut off from the main population. These populations could no longer mate with each other. Different evolutionary pressures acting on both the populations caused them to evolve distinct and unique characteristics. Today, the Kaibab squirrels and the Abert squirrels can no longer interbreed with each other naturally.

Sympatric speciation

When a new species is formed within the same location due to isolating mechanisms, this is known as sympatric speciation. But what leads to a reduced gene flow in a randomly mating population living in the same area? While geographical isolation is the key to allopatric speciation, behavioural isolation and temporal isolation could lead to sympatric speciation.

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Apple maggot flies: sympatric speciation in process

One example of sympatric speciation in process is the apple maggot flies. The ancestors of these flies fed and laid their eggs on hawthorns (a plant native to North America). When apples came to America, the flies started using apples as food sources and laid their eggs on them. Today, there are flies that lay their eggs on both hawthorns and apples.

Reproduction is fruit specific, so apple flies mate with other apple flies and hawthorn flies with other hawthorn flies. As mating is within the species, it is an example of intraspecific breeding. This resulted in the population, despite being in the same area, being divided into two groups with limited gene flow. Over a period of 200 years, selection pressure specific for apple and hawthorn fruits has led to two genetically divergent groups.

Study skills

For speciation to occur, the gene flow between the populations must be minimal or non-existent.

Mechanisms of reproductive isolation

The key to speciation is reproductive isolation. Reproductive isolation can occur due to:

- geographical isolation
- temporal isolation
- behavioural isolation.

Geographical isolation

As discussed in section A4.1.6–7 (/study/app/bio/sid-422-cid-755105/book/speciation-id-43794/), geographical isolation is the separation of species by natural or human-made physical barriers. One example is the Galapagos finches (see section A4.1.9-10 (/study/app/bio/sid-422-cid-755105/book/adaptive-radiation-and-barriers-

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to-id-43796/)). These finches originated from an ancestral species that reached the Galapagos Islands from mainland South America. The distance between the islands and the mainland resulted in geographical isolation.

Temporal isolation

Temporal isolation is a result of differences in the timing of the reproductive cycle like mating seasons or gamete production. This prevents interbreeding even though the species may share the same geographical location.

As an example, consider two species of cicadas in the USA. One species, *Magicicada tredecim*, attains sexual maturity in 13 years while the other, *Magicicada septendecim*, attains sexual maturity in 17 years. Thus the opportunity to mate comes only once in 221 (13×17) years.

Behavioural isolation

Many animals use mating rituals like courtship dances or mating calls to attract other members of the same species. Due to environmental factors, organisms of the same species may develop different mating rituals over a period of time. When their potential mates do not recognise these mating rituals, this results in behavioural isolation and the individuals do not interbreed (**Figure 2**). Over generations, this could lead to reproductive isolation and speciation.

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Figure 2. Behavioural isolation.

For example, male fireflies use specific light patterns to attract the female flies. Male fireflies of different species display their lights differently. This means that if the male of one species tries to attract a female of another species, the latter will not be able to recognise the pattern and will not mate.

Reproductive isolation can result in:

- prezygotic barriers or barriers that prevent the formation of the zygote.
- postzygotic barriers or barriers that occur after the zygote is formed. This could include zygote inviability or sterility.

Watch **Video 1** for an overview of speciation, considering geographical, behavioural and temporal isolation.

Student view

Video 1. Formation of new species by speciation.

Have a go at this activity in which you will create a mind map to help summarise your understanding of speciation.

Activity

- **IB learner profile attribute:** Reflective
- **Approaches to learning:** Thinking skills — Reflecting at all stages of the assessment and learning cycle
- **Time required to complete activity:** 20 minutes
- **Activity type:** Individual activity

Your task

Summarise your understanding of speciation by creating a mind map. You can use online tools like mindmeister (https://www.mindmeister.com/) or you can create a physical mind map.

Instructions

- Begin in the centre with an image of what the topic conveys to you. The lines (branches) should radiate from

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the centre.

- Put the first level of associations on each branch.
- Put the second level of associations on the sub-branches and so on.
- Use key words instead of sentences.
- Use at least three colours.

5 section questions

A4. Unity and diversity: Ecosystems / A4.1 Evolution and speciation

Adaptive radiation and barriers to hybridisation (HL)

A4.1.9: Adaptive radiation (HL) A4.1.10: Sterility of interspecific hybrids (HL)

Higher level (HL)

Learning outcomes

By the end of this section you should be able to:

- Explain the role of adaptive radiation in enhancing biodiversity.
- Identify the barriers to hybridisation.
- Analyse reasons for the sterility of interspecific hybrids as means of preventing the mixing of alleles between species.

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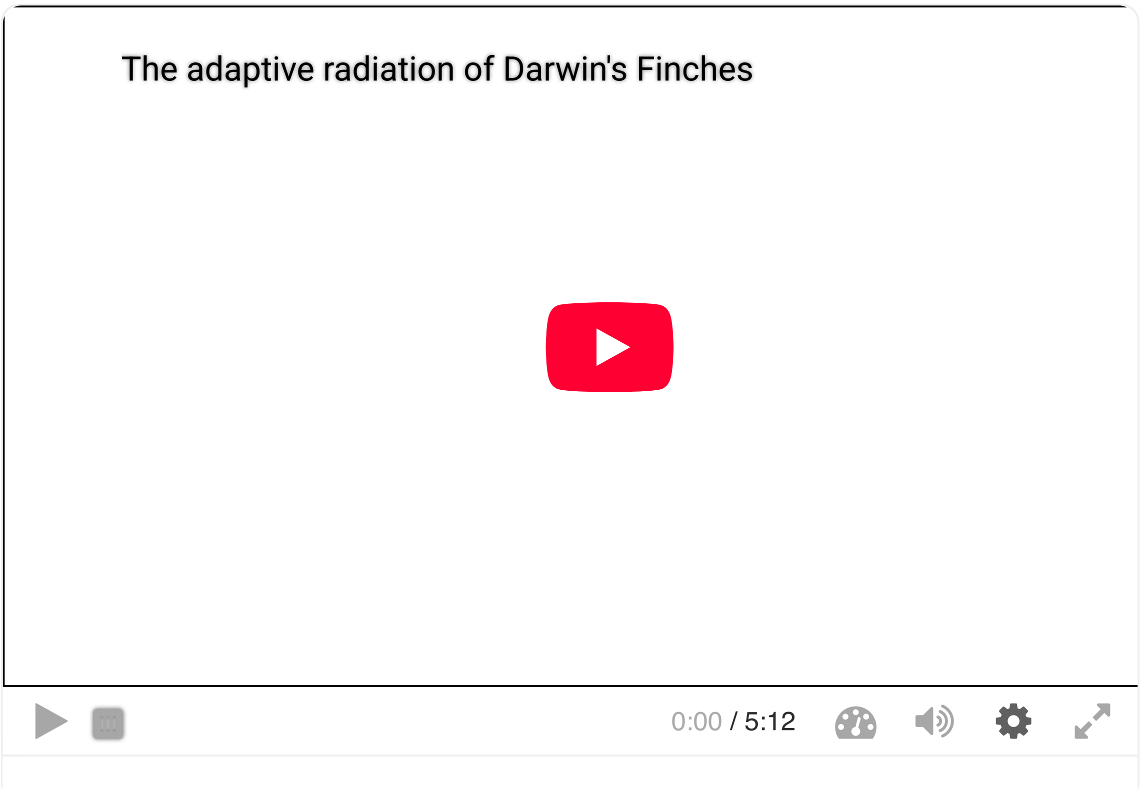
Adaptive radiation

A visitor to Australia would be amazed by the diversity in marsupial life. Apart from the well-known kangaroos and koalas, there are the numbats or anteaters, the marsupial moles, the cat-like quolls, the groundhog-like wombats and many more. But what led to this evolution?

The origin of the Galapagos finches

Yet another mechanism of evolution is adaptive radiation. This mechanism describes the rapid evolution of an ancestral species in different lines to utilise the available ecological niches.

An example of adaptive radiation is Darwin's (Galapagos) finches on the Galapagos Islands off the west coast of South America. The ancestral finch species that arrived on the islands were seed-eating birds with a short, thick beak. The uninhabited islands provided unlimited food resources including insects, fruits, buds, seeds and grubs in rotting wood. Variations in the beaks meant that these diverse sources of food could be exploited. Over time, selection of favourable beak variations led to a rapid diversification of the finches into diverse ecological niches. Watch **Video 1** to see Darwin's finches in action.



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Video 1. Adaptive Radiation in Darwin's Finches.

More information for video 1

The video features Darwin's finches in their natural habitat. The creator of the video explains adaptive radiation in Darwin’s finches in the video with the help of a compilation of footage, photographs and explanatory onscreen texts.

0:00-0:55: The video begins with an introductory text, “A short video story of the dietary drivers of adaptive radiation in Darwin’s finches.” The frame changes and a Darwin finch perching on a twig appears on the screen with the following texts: “ The diets of different Darwin’s finch species overlap considerably but they sometimes differ in key ways. During hard times, different species specializes on foods for which their beaks are differently suited. This video tells a short story of that adaptive link between diets, beaks and species. I start with a very quick summary of the major finch groups and then provide a more detailed consideration of the ground finches on Santa Cruz Island. (Note: the Warbler finches are not shown.)”

0:56 - 1:16: The scene transitions to show the photographs of different varieties of finches with respective explanatory texts as follows:

A photo of a tree finch with a grub in its beak is featured with the text “Tree finches mainly feed on insects. A small tree finch (Camarhynchus parvulus) has here extracted a grub”.

A photo of a woodpecker finch perched on a tree tearing away its bark is featured with the text “The woodpecker finch (Camarhynchus pallidus) also prefers insects but tears away at trees to get them.”

A photo of a vegetarian finch perched on a twig is featured with the text “The vegetarian finch feeds mostly on fruits and leaves.”

The scene transitions to a plain black background to display the text “and now the major player in the story of Santa Cruz ground finches”

1:16 - 1:40: In the next frame, photo of a small ground finch is featured with the text, “The small ground finch (Geospiza fuliginosa) has a very small beak. In the same frame a photo of a medium ground finch is placed next to the photo of the small ground finch with the text, “The medium ground finch (Geospiza fortis) has a medium beak. A photo of a large ground finch is then introduced in the same frame with the text, “The large ground finch (Geospiza magnirostris) has a very large beak.” Lastly a photo of a cactus finch is added to the frame with the text “The cactus finch (Geospiza scandens) has a pointed beak.”

1:40 - 2:37: The scene transitions to display footage of a small ground finch feeding on a bunch of Portulaca oleracea followed by photo of a small ground finch with tiny seeds of grasses in its beak and another photo of small ground finch with the seeds of Cryptocarpus

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pyriformis in its beak. The following text is displayed onscreen: “The small ground finch uses its dextrous beak to pick at the buds and tiny seeds of Portulaca oleracea. It is also effective on the tiny seeds of grasses and of Cryptocarpus pyriformis.”

The scene transitions to display footage of a cactus finch feeding on Portulaca oleracea with the text, “Other finches will sometimes also eat small seeds such as this cactus finch on Portulaca ...” The scene transitions to footage of the cactus finch feeding on Opuntia cactus with the text “ ... but what the cactus finch really likes is the Opuntia cactus.”

2:37- 3:10: The scene transitions to display footage of a cactus finch feeding on a flower of Opuntia cactus with the text “It uses its beak to probe Opuntia for seeds, pollen and nectar.” As the footage progresses, another type of ground finch tries to pick on the same Opuntia flower but is driven away by the cactus finch, the following text appears: “While other ground finches might be tempted by what they haven’t got ...” The cactus finch continues to pick on the Opuntia flower and the following text appears: “Opuntia nectar and pollen are hard to get without a longer beak.”

3:11 - 4:00: In the next scene, footage of a cactus finch picking on a dried Opuntia fruit is displayed with the text, “Opuntia seeds, however, are a treat even for the medium finch. The scene transitions to the footage of a ground finch perched on the tiny branches of Scutia Spicata feeding on the small fruits of the plant. The following text appears “What the medium finch likes most of all is Scutia spicata. It uses its beak to pick the fruit, extract the seed, and split the seed open edgewise although they aren’t always easy to get.”

4:00 - 4:16: The scene then transitions to footage of a medium finch cracking a seed with its beak. The following text appears: “Finches with smaller beaks have more trouble on such seeds. Here a medium finch cracks seeds extracted from a Conocarpus cone.”

4:17- 4:44: In the following scene, footage of a medium finch trying to reach the seeds of smaller grasses is displayed with the text, “Medium beaked birds less frequently eat smaller seeds including Portulaca and Cryptocorpus (see earlier) and Commicorpus tuberosus (here) ...” The scene changes to display photos of large ground finches with the text, “...and they leave the really big seeds for the large ground finch whose very large beak can crush even Cordia lutea seeds. As they work to crack Cordia seeds, their beaks become gummed up by the very sticky fruit.

4: 45-500 The scene transitions to footage of a small ground finch perched on a branch with the text, “The radiation of finch beaks thus matches the types of food on which they feed.” The video ends here.

Interactive 1 shows the adaptive radiation of the Galapagos finches.

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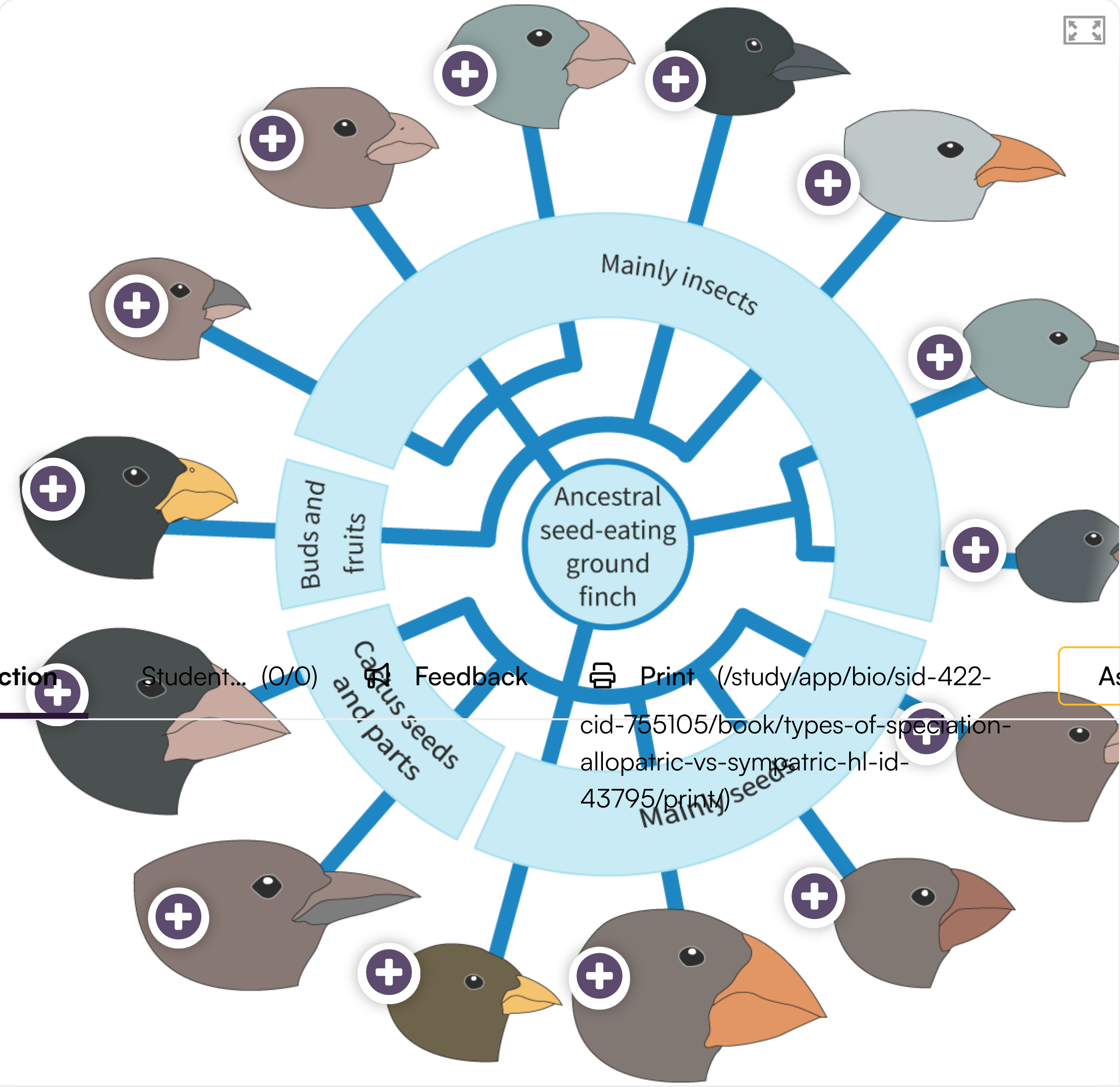

Interactive 1. Galapagos Finches: An Example of Adaptive Radiation.

More information for interactive 1

This interactive explores **adaptive radiation** and **barriers to hybridization** through the example of the **Galápagos finches**, a classic case of evolutionary divergence. These finches evolved from a **single ancestral species**—a **seed-eating ground finch**—which diversified into multiple species, each uniquely adapted to different **ecological niches.**

Natural selection has driven this diversification, resulting in a wide variety of **beak shapes and feeding habits**, allowing finches to exploit different food sources. The diagram shows how various finch species have evolved distinct traits. Each hotspot represents a different species and its ecological adaptation:

Finches that Eat Insects

Hotspot 1. Large Tree Finch (*Camarhynchus psittacula*) — Specializes in insect consumption.

Hotspot 2. Mangrove Finch (*Camarhynchus heliobates*) — Insectivorous and found in mangrove habitats.

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Hotspot 3. Medium Tree Finch (*Camarhynchus pauper*) — Feeds primarily on insects.

Hotspot 4. Woodpecker Finch (*Camarhynchus pallidus*) — Uses tools like cactus spines or twigs to extract insects from tree holes, demonstrating cultural evolution in feeding strategies.

Hotspot 5. Small Tree Finch (*Camarhynchus parvulus*) — Also adapted to an insectivorous diet.

Hotspot 6. Warbler Finch (*Certhidea fusca*) — Consumes insects, resembling warblers in feeding behavior.

Finches that Eat Buds and Fruits

Hotspot 7. Vegetarian Finch (*Platyspiza crassirostris*) — Primarily consumes buds and fruits, showing specialization distinct from its seed- and insect-eating relatives.

Finches that Eat Cactus Seeds and Parts

Hotspot 9. Large Cactus Finch (*Geospiza conirostris*) — Has a specialized beak for breaking cactus seeds and consuming other parts of the plant.

Hotspot 12. Cactus Finch (*Geospiza scandens*) — Also relies on cactus seeds and plant material, showing an adaptation to arid environments.

Finches that Eat Seeds

Hotspot 10. Small Ground Finch (*Geospiza fuliginosa*) — Consumes small seeds, taking advantage of finer food resources.

Hotspot 11. Medium Ground Finch (*Geospiza fortis*) — Feeds on a variety of seeds, showing an intermediate adaptation.

Hotspot 13. Sharp-beaked Ground Finch (*Geospiza difficilis*) — Specializes in seed consumption but is also known to supplement its diet with other food sources.

Hotspot 14. Large Ground Finch (*Geospiza magnirostris*) — Has a robust beak suited for cracking large, hard seeds.

A Unique Outlier

Hotspot 9. Cocos Island Finch (*Pinaroloxias inornata*) — The only Galápagos finch species found outside the archipelago, on Cocos Island, showcasing geographical isolation in its evolutionary history.

Barriers to Hybridization

Despite originating from a common ancestor, these species rarely interbreed due to several reproductive barriers, including Behavioral isolation—Different mating songs and courtship behaviors prevent interbreeding. Temporal isolation—Some species have different breeding

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seasons. Morphological isolation—Differences in beak structure make interspecific mating less likely.

This interactive representation of adaptive radiation demonstrates how natural selection, ecological pressures, and reproductive barriers have shaped the diversity of Galápagos finches into specialized species with unique feeding strategies.

Another example of adaptive radiation is the marsupials of Australia that have diversified from a central ancestral stock to occupy different habitats (**Figure 1**). There are about 200 species of marsupials. Adaptive radiation of marsupials occurred in a similar way in South America.

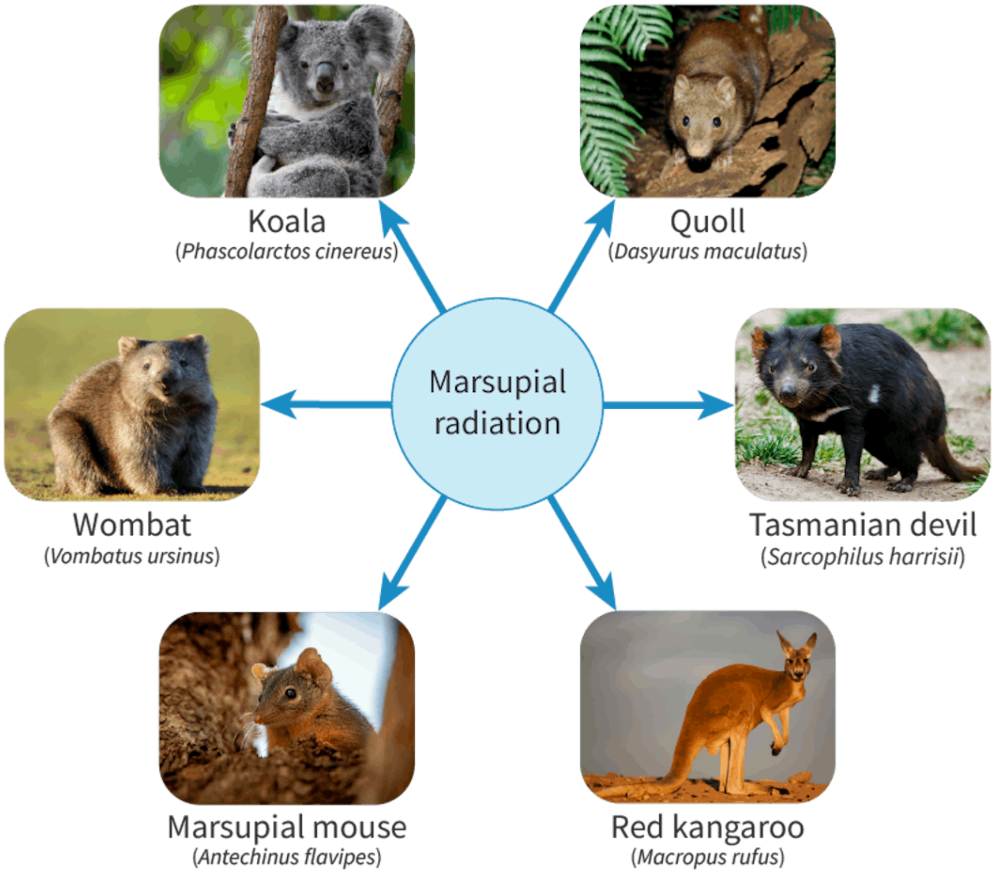

Figure 1. The marsupials of Australia have evolved through adaptive radiation.

Credits: Michael Siward, Getty Images (https://www.gettyimages.co.uk/license/117949558) (Koala); Jason Edwards, Getty Images (https://www.gettyimages.co.uk/license/71993302) (Quoll); Mark Newman, Getty Images (https://www.gettyimages.co.uk/license/579966391) (Tasmanian devil); Jami Tarris, Getty Images (https://www.gettyimages.co.uk/license/520278958) (Red kangaroo); tracielouise, GettyImages

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(https://www.gettyimages.co.uk/license/1460642288) (Marsupial mouse); keiichihiki, Getty Images (https://www.gettyimages.co.uk/license/173872734)(wombat)

More information for figure 1

The image shows a diagram illustrating the concept of adaptive radiation in marsupials. At the center is a circle labeled "Marsupial radiation." Radiating out from this circle are arrows pointing towards images of six different marsupials, each accompanied by a common name and scientific name.

1. Koala (Phascolarctos cinereus) - An image of a koala on a tree.
2. Quoll (Dasyurus maculatus) - An image of a quoll among foliage.
3. Tasmanian devil (Sarcophilus harrisii) - An image of a Tasmanian devil on grass.
4. Wombat (Vombatus ursinus) - An image of a wombat outdoors.
5. Marsupial mouse (Antechinus flavipes) - An image of a small marsupial mouse.
6. Red kangaroo (Macropus rufus) - An image of a red kangaroo standing on sandy terrain.

The overall shape of the diagram resembles a spoke wheel with the central node representing the ancestral stock and each spoke representing diversification into different habitats.

[Generated by AI]

Yet another example of adaptive radiation is the Hawaiian silversword (**Figure 2**). The ancestors of these plants arrived on the island of Kauai from western North America. Adaptation to different ecosystems led to rapid diversification. Currently, there are 28 species, a prime example of how adaptive radiation leads to biodiversity.

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Figure 2. Haleakalā silversword (*Argyroxiphium sandwicense*) is one of the rarest Hawaiian silverswords.

Credit: Douglas Peebles, Getty Images (https://www.gettyimages.co.uk/license/535299160)

Adaptive radiation is thus the rapid evolution of closely related groups adapted to specialised modes of life, from an ancestral stock. The species occupy different ecological niches (see subtopic B4.2 (/study/app/bio/sid-422-cid-755105/book/big-picture-id-43537/)). Hence, despite being closely related, the species can coexist without competing for resources. In ecosystems with vacant niches, this increases biodiversity (see section A4.2.1 (/study/app/bio/sid-422-cid-755105/book/title-to-come-id-43810/)).

Barriers to hybridisation

Some of you may recognise the animal shown in **Figure 3** – it is a mule, a hybrid offspring of a male donkey and a female horse.

Student view

Figure 3. A mule is a hybrid between a donkey and horse.

Credit: Jose A. Bernat Bacete, Getty Images (https://www.gettyimages.co.uk/license/1284597152)

Hybridisation refers to interbreeding between two different species producing offspring known as hybrids. Hybridisation rarely leads to speciation as:

- The hybrids could be infertile like mules
- The hybrids are not reproductively isolated from the parent species like ligers

In nature, both prezygotic and post zygotic mechanisms prevent hybridisation, and ensures that species remain distinct.

For example, prezygotic mechanisms, like variation in the courtship behaviour or behavioural isolation, often prevent hybridisation between species.

Postzygotic mechanisms act after fertilisation and can:

- reduce the viability of the zygote
- reduce the viability of the young one and the adult
- decrease the fertility of the hybrid and its offspring

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Thus, the hybrid incompatibility prevents both the mixing of alleles of the parent species and subsequent transmission to the future generation. As natural selection often does not work in favour of the hybrid, it shows that the two parent species are better adapted to their environments as separate species.

The mule provides an example of hybrid sterility. A donkey has 62 chromosomes and a horse has 64 chromosomes. The mule has 63 chromosomes. It does not have the required pairs of homologous chromosomes and so is infertile.

Hybridisation is more common among plants, with many of the fruits and vegetables we consume today being hybrids. However, barriers to hybridisation exist, such as pollen-pistil incompatibility. For example, most varieties of common wheat rarely form seeds when pollinated with pollen from rye plants. Hybrid watermelons are seedless and unable to produce offspring.

It is to be remembered that though rare, hybridisation can lead to the formation of a new species, provided that the hybrids are fertile and reproductively isolated from both the parent species.

Nature of Science

Aspect: Global impact of science

Every development in science has ethical and environmental impacts. These impacts can be positive or negative, but all should be weighed carefully.

Try the activity below to discuss whether you think hybridisation is ethical.

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Activity

- **IB learner profile attribute:** Caring
- **Approaches to learning**: Social skills — Actively seeking and considering the perspective of others
- **Time required to complete activity:** 30 minutes
- **Activity type:** Group or whole-class activity

Aim: Debate on the topic ‘Hybridisation: ethical or not?’

Instructions

- Read the passage below for a basic understanding.
- Research more by reading articles such as ethics of hybridisation (https://www.pbs.org/newshour/science/analysis-the-thorny-ethics-of-hybrid-animals) or human—animal hybrids (https://www.theguardian.com/science/2021/may/15/mixed-messages-is-research-into-human-animal-hybrids-ethical-chimera).
- Discuss and document your arguments weighing the pros and cons of the issue.
- Form 2 groups:
  - One group (3—4 members) would support the statement (Affirmative team).
  - One group (3—4 members) would oppose the statement (Opposing team).
  - The remaining students form the audience.
- Debate the issue as outlined:
  - Open the debate with lead speaker of the Affirmative team.
  - Repeat the process for the second speaker in each team and so on.
  - Have a short break (5 min) for both the teams to prepare their rebuttals.

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- Follow by the rebuttal session, where each team gets a chance for rebutting the arguments of the opponents.

- Have an open discussion with the non-participants being given opportunities to ask questions and contribute their opinions on the arguments that were presented.

Passage

What happens when you cross a lion with a tigress in captivity? You get a liger. Similarly, crossing a tiger (male) with a lioness, gives a tigon and the story goes on. Hybrids have been created not only with big cats, but also with bears, zebras and so on. Hybridisation in the natural world is a part of evolution. But hybridisation in captivity has consequences such as birth defects and sterility.

5 section questions

A4. Unity and diversity: Ecosystems / A4.1 Evolution and speciation

Hybridisation and polyploidy in speciation (HL)

A4.1.11: Abrupt speciation in plants (HL)

Higher level (HL)

Learning outcomes

By the end of this section you should be able to describe the role of polyploidy in speciation of plants such as knotweed.

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Watermelons and bananas contain seeds. Yet seedless varieties of common fruits like watermelon and banana are commonplace. Strawberries are not just red and sweet, they come in a variety of colours, sizes and even flavours! But what causes this explosion in diversity of species?

Hybridisation and polyploidy: a cause of abrupt speciation in plants

Common in plants and some animals like fish and salamanders, polyploidy is suggested to be the cause of explosions in species diversity. But, what causes polyploidy? When a diploid (see section D2.1.9 (/study/app/bio/sid-422-cid-755105/book/meiosis-id-43812/)) cell or organism acquires one or more additional sets of chromosomes, this is called polyploidy. A rapid and relatively simple form of speciation, polyploidy is caused due to non-disjunction (see section D2.1.10 (/study/app/bio/sid-422-cid-755105/book/the-cell-cycle-hl-id-43813/)) of chromosomes during mitosis (see section D2.1.7 (/study/app/bio/sid-422-cid-755105/book/mitosis-id-43811/)) or meiosis (see section D2.1.9 (/study/app/bio/sid-422-cid-755105/book/meiosis-id-43812/)). This results in the formation of gametes with additional sets of chromosomes.

Haploid refers to a single set of chromosomes represented as ‘n’. A diploid organism has two sets of chromosomes (2n), whereas polyploid organisms have more than two sets of chromosomes. Polyploid organisms can be triploid (3n), tetraploid (4n), pentaploid (5n) and so on (**Figure 1**). For example, if a plant with a haploid number 7 ($n = 7$) has 42 chromosomes, it is hexaploid i.e., it has 6 sets of chromosomes ($6 \times 7 = 42$).

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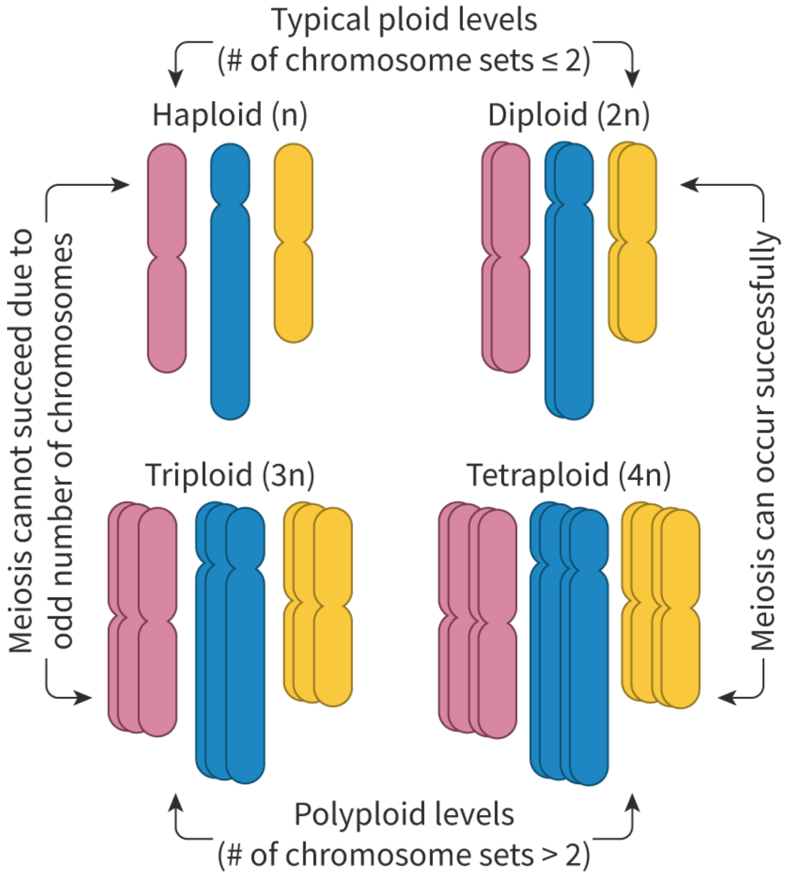

Figure 1. Ploidy levels in a species where n = 3.

More information for figure 1

The diagram illustrates different ploidy levels using chromosome representations. In the upper half, it shows typical ploidy levels where the number of chromosome sets is less than or equal to 2, including Haploid (n) and Diploid (2n). The Haploid section displays a single set of three chromosomes in distinct colors: pink, blue, and yellow. The Diploid section shows two sets of these chromosomes, arranged side by side. An arrow indicates that meiosis can occur successfully with these configurations.

In the lower half, the diagram presents polyploid levels where chromosome sets are greater than 2, depicting Triploid (3n) and Tetraploid (4n) conditions. The Triploid section shows three sets of chromosomes in the pink, blue, and yellow colors, while the Tetraploid section displays four sets. An arrow explains that meiosis cannot succeed due to the odd number of chromosomes in triploid forms, whereas tetraploid forms can undergo successful meiosis. This diagram visually underscores how chromosomal configurations change with increasing ploidy levels and their implications for meiosis.

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Nature of Science

Aspects: Patterns and trends

Looking for patterns and trends in speciation through polyploidy in plants.

Most naturally occurring polyploids have an even number of chromosome sets. Polyploids with odd chromosome sets like 3n, 5n tend to be sterile as chromosomes cannot pair up correctly during meiosis.

Allopolyploidy

Allopolyploidy or alloploidy is a special case of polyploidy. An allopolyploid is a hybrid and has multiple chromosome sets that are derived from the different parental species. Studies show that the polyploid offspring is often more vigorous and resistant to disease than the parent species.

In **Figure 2**, the normal gamete (species 1) combines with the polyploid gamete (species 2). The resulting cell is sterile due to the abnormal number of chromosomes. However, if mated with normal gamete, viable offspring can be produced. If the offspring are unable to interbreed with the parental species however can mate with each other, this would result in speciation.

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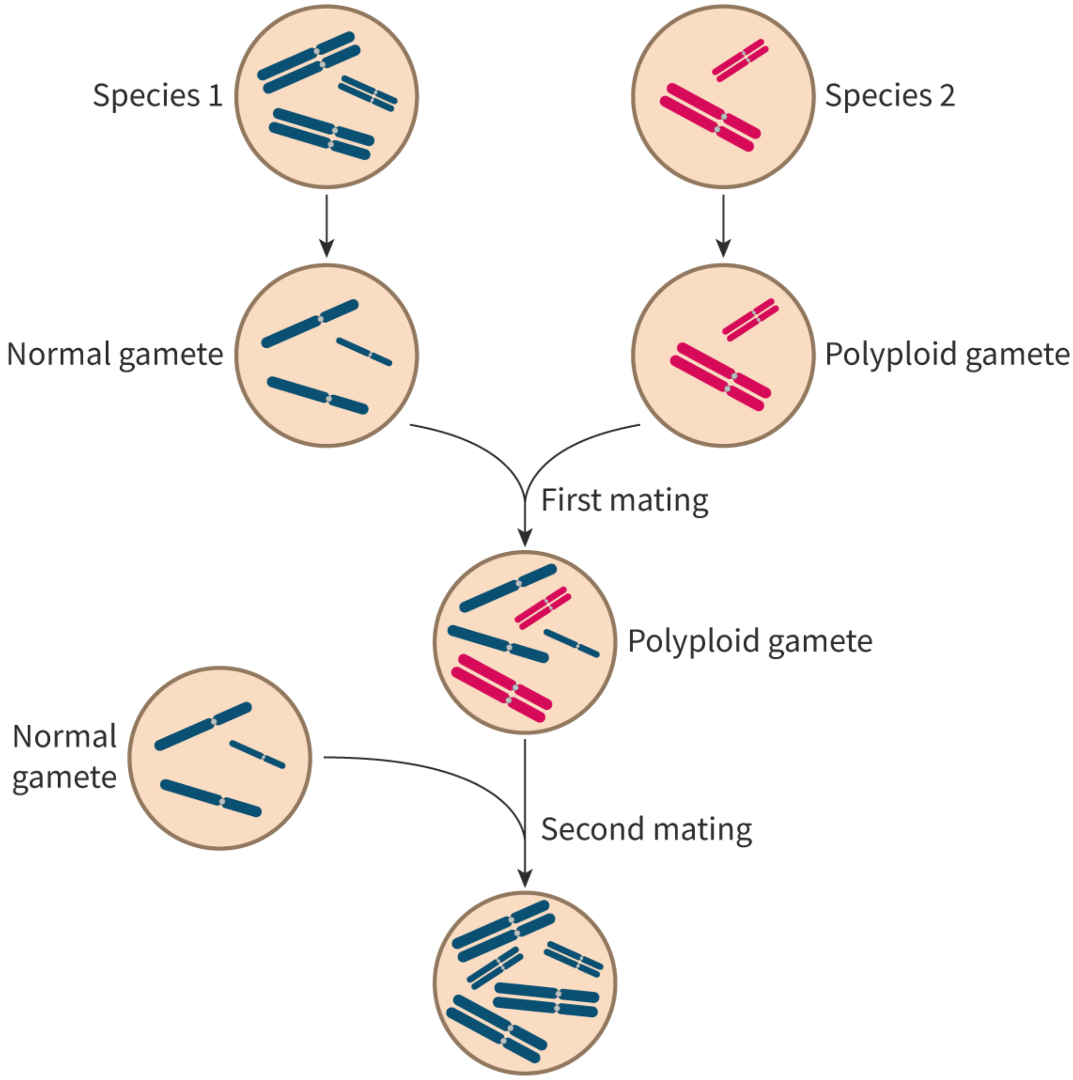

Figure 2. Allopolyploidy in action.

More information for figure 2

The diagram illustrates the process of allopolyploidy. At the top, there are two circles labeled 'Species 1' and 'Species 2', each containing chromosomes depicted as blue and pink lines, respectively. Below, from 'Species 1', a circle labeled 'Normal gamete' shows blue chromosomes. From 'Species 2', a circle labeled 'Polyploid gamete' shows pink chromosomes. These lead into a 'First mating' circle where blue and pink chromosomes are mixed. Below this, another 'Normal gamete' labeled circle with blue chromosomes is shown next to the 'First mating' result. These lead into a 'Second mating' circle, resulting in a final circle containing a complete set of blue and pink chromosomes, demonstrating the formation of a new polyploid organism.

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Allopolyploidy is seen in a number of crops such as tobacco, wheat, etc. Knotweed, an invasive species, is another example. A hypothetical process of hybridisation (see section A4.1.9-10 (/study/app/bio/sid-422-cid-755105/book/adaptive-radiation-and-barriers-to-id-43796/)) and allopolyploid formation is shown in **Figure 3**. Studies show that a widespread diploid species of knotweed, genus *Persicaria*, has contributed to the formation of at least six other allopolyploid hybrids (**Figure 4**).

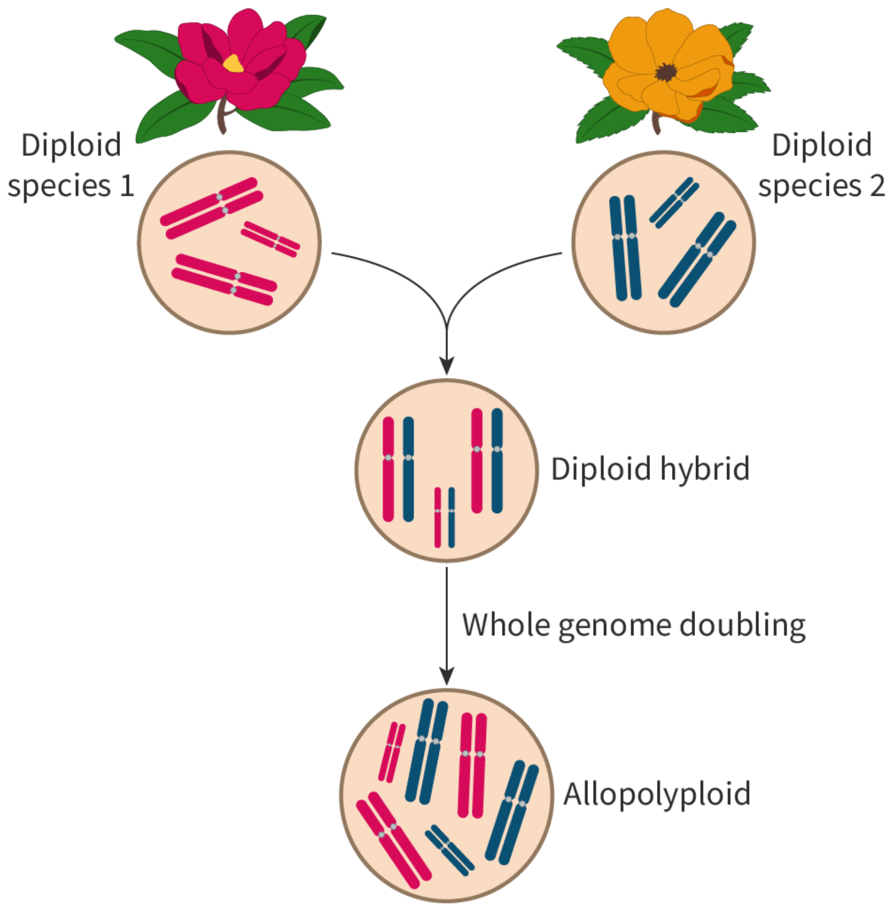

Figure 3. Allopolyploid formation from two diploid parents (hypothetical).

More information for figure 3

The diagram illustrates the process of allopolyploid formation starting with two different diploid species, each represented by flowers with distinctly colored chromosomes in circles labeled as Diploid species 1 and Diploid species 2. The chromosomes in Diploid species 1 are pink, while those in Diploid species 2 are blue.

The central panel shows the hybrid formation, where chromosomes from both species are combined to form a diploid hybrid. This hybrid contains a mixture of pink and blue chromosomes.

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Arrows point downward from the diploid hybrid to another stage labeled 'Whole genome doubling,' indicating that the chromosomes in the hybrid double to form an allopolyploid. In this final stage, a circular depiction shows chromosomes doubled but maintaining their original colors, signifying that both genomes from the parent species contribute to the allopolyploid formation.

[Generated by AI]

Figure 4. *Persicaria.*

Credit: Paul Starosta, Getty Images

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Other examples include Japanese knotweed, an octoploid with 88 chromosomes and giant knotweed, a tetraploid with 44 chromosomes. The female Japanese knotweed plant can be fertilised by pollen from other species of knotweed like the giant knotweed. Hybrids of these two species with varying numbers of chromosomes have been discovered. This indicates the pervasive nature of the weed and its capacity to rapidly speciate.

Try answering the questions in the activity below to help with your learning of polyploidy.

Activity

- **IB learner profile attribute**: Knowledgeable
- **Approaches to learning**: Thinking skills — Applying key ideas and facts in new contexts
- **Time required to complete activity:** 20 minutes
- **Activity type:** Individual activity

Questions

1. Species A is tetraploid (n = 4). Species B is diploid (n = 2). Species A produces unreduced gametes (chromosomes did not separate). Species B forms haploid gametes. Species A is mated with species B resulting in a sterile offspring. The second mating with Species B results in a fertile, viable allopolyploid. Illustrate the process.
2. In plants like onion, garlic and leeks belonging to the genus *Allium* (n = 7) polyploidy is common. Calculate the chromosome number for each species and complete the rows in **Table 1**.

Table 1. *Allium* species

Species	Ploidy level
Allium canadense	Diploid

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Species	Ploidy level
Allium canadense lavendulae	Tetraploid
Allium validum	Octoploid

5 section questions

A4. Unity and diversity: Ecosystems / A4.1 Evolution and speciation

Summary and key terms

- Evolution occurs when the heritable characteristics of a population change.
- The universal nature of the genetic code makes it a powerful evidence for evolution.
- Selective breeding leads to variations in the gene pool resulting in rapid evolutionary changes.
- Homologous structures like the pentadactyl limb of vertebrates provide evidence for evolution.
- Analogous structures indicate convergent evolution.
- Reproductive isolation and differential selection drives speciation, as seen in bonobos and chimpanzees.

Higher level (HL)

- Speciation can be sympatric or allopatric.
- Reproductive isolation can be driven by geographical, behavioural and temporal isolation.
- Adaptive radiation, hybridisation and polyploidy lead to speciation.

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- Hybridisation in animals is prevented by prezygotic and postzygotic barriers.

Key terms

Review these key terms. Do you know them all? Fill in as many gaps as you can using the terms in this list.

Section Student... (0/0) Feedback Print (/study/app/bio/sid-422-cid-755105/book/adaptive-radiation-and-barriers-to-id-43796/print/) Assign

1. As per Darwin's theory of , the accumulation of favourable variations over generations leads to evolutionary changes.
2. One of the most powerful pieces of evidence for evolution is the comparative analysis of nucleotide sequences of DNA and RNA known as .
3. The of the wild mustard plant has given us many of the vegetables we use today like cauliflower and cabbage.
4. are organs with a similar structure and indicate evolution. On the other hand, organs are structures that are similar in function and indicate evolution.
5. The basis of formation of a new species or is that prevents interbreeding.
6. The evolution of chimpanzees and bonobos into two new species illustrates how barriers and can drive speciation.

divergent | molecular phylogeny | analogous | Homologous structures | natural selection | selective breeding | convergent | reproductive isolation | geographical | speciation | differential selection

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Interactive 1. Understanding Key Terms in Evolution.

Higher level (HL)

Key terms

Review these key terms. Do you know them all? Fill in as many gaps as you can using the terms in this list.

1. The species of squirrels living on either side of the Grand Canyon have evolved from a common ancestor indicating __________.
2. __________ speciation happens when potentially compatible organisms living in the same geographical area are prevented from interbreeding due to __________ and behavioural isolating mechanisms.
3. The anole lizards have evolved from a __________ to occupy the niches available in the Caribbean islands. This evolutionary mechanism is known as __________.
4. __________ is common in the knotweed and results in viable __________ leading to rapid speciation.

Sympatric | hybrids | adaptive radiation | allopatric speciation | common ancestor | temporal | Polyploidy

Check

Interactive 2. Evolution and Speciation: Key Terms.

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A4. Unity and diversity: Ecosystems / A4.1 Evolution and speciation

Checklist

What you should know

After studying this subtopic you should be able to:

- Define evolution as the change in the heritable characteristics of a population.
- Discuss the theory of natural selection.
- Differentiate between Darwinian evolution and Lamarckian evolution.
- Analyse how base sequences in DNA or RNA and amino acid sequences in proteins act as evidence in evolution.
- Examine how selective breeding of domesticated plants and animals acts as evidence for evolution.
- Discuss the role of humans in bringing genetic changes in plant and animal species.
- Explain the difference between homologous and analogous structures.
- Compare the structure of the pentadactyl limb across evolutionary groups.
- Describe convergent evolution.
- Describe the process of speciation.
- Discuss how reproductive isolation and differential selection results in speciation.
- Investigate the example of divergence due to differential selection in the separation of bonobos and common chimpanzees

Higher level (HL)

- Compare sympatric and allopatric speciation.

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- Explain how temporal, geographic or behavioural isolation can lead to reproductive isolation.
- Explain the role of adaptive radiation in enhancing biodiversity.
- Identify the barriers to hybridisation.
- Analyse reasons for the sterility of interspecific hybrids as means of preventing the mixing of alleles between species.
- Describe the role of polyploidy in speciation of plants like knotweed.

Investigation

- **IB learner profile attribute:**
  - Inquirers
  - Thinkers
  - Communicators
- **Approaches to learning:**
  - Thinking skills – Experimenting with new strategies for learning
  - Communication skills – Presenting data appropriately
  - Research skills – Using search engines and libraries effectively
- **Time required to complete activity:** 6–8 hours
- **Activity type:** Individual, then group activity

In this subtopic, you have learned about evidence for evolution and speciation. To finish this subtopic, why not try the following task?

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Your task

Antibiotics are drugs that help to cure bacterial infections. In 1928, Alexander Fleming's discovery of penicillin started the antibiotic revolution. The use of antibiotics has saved millions of lives. Studies show that antibiotics have increased the average human life by 23 years. However, the evolution of drug (antibiotic) resistance in bacteria has led to a medical crisis such as MRSA (methicillin-resistant *Staphylococcus aureus*) and drug-resistant *Streptococcus pneumoniae*. Drug resistance in bacteria is nothing but a basic evolutionary mechanism.

Section Student... (0/0) Feedback Print (/study/app/bio/sid-422-cid-755105/book/checklist-id-43799/print/) Assign

Section Student... (0/0) Feedback Print (/study/app/bio/sid-422-cid-755105/book/summary-and-key-terms-id-43798/print/) Assign

Nature of Science

Aspect: Theories

Section Student... (0/0) Feedback Print (/study/app/bio/sid-422-cid-755105/book/investigation-id-43800/print/) Assign

Scientific theories are often structured explanations generated to make sense of tested hypotheses. Theories can be used to explain natural phenomena. For example, Darwin's theory of evolution by natural selection helps to explain the evolution of antibiotic resistance in bacteria.

Section Student... (0/0) Feedback Print (/study/app/bio/sid-422-cid-755105/book/hybridisation-and-polyploidy-in-speciation-hl-id-43797/print/) Assign

1. Research and find out:

- How does antibiotic (antimicrobial) resistance in bacteria act as evidence for evolution?

Refer to the evidence for evolution covered in this subtopic.

- Why do bacteria evolve antibiotic resistance strategies rapidly?

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2. Consult a variety of relevant sources of information to build your understanding on antibiotic resistance. Some possible sources are:

   Antimicrobial resistance-WHO (https://www.who.int/news-room/fact-sheets/detail/antimicrobial-resistance)
   Antimicrobial resistance-CDC (https://www.cdc.gov/drugresistance/index.html)
   Antimicrobial resistance: a global multifaceted phenomenon (https://www.ncbi.nlm.nih.gov/pmc/articles/PMC4768623/)
3. Refer to the data given here (https://atlas.ecdc.europa.eu/public/index.aspx?Dataset=27&HealthTopic=4).

   A. Select any one species of bacteria.
   B. Select any one country. Make sure that R-resistant isolates (%) (or microbes isolated from individuals of a population resistant to one or more antibiotics) is greater than zero.
   C. Collect data on the R-resistant isolates proportion, by age for 3 years from 2019 to 2021 (refer to the bar graph).
   D. Repeat steps A–C for two more species of bacteria.

4. Analyse and interpret the data collected. Look for trends and patterns.
5. Relate this to the research questions.
6. Evaluate the limitations of the research and think about ways the investigation could have been improved.
7. Prepare a report. Make sure that you include concepts that were covered in subtopic A4.1 like molecular phylogeny, speciation etc.
8. Present your findings in class using any presentation tool. Your presentation should not exceed 10 minutes.
9. Make sure that your presentation includes:

   - Title
   - Background
   - Methods
   - Result (emphasise the most important findings)

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- Discussion (interpretation of the results, limitations if any, recommendation for future studies, etc.)
- Acknowledgement.

10. Discuss in groups the challenges faced by the drug and medical industry in terms of rapidly evolving drug-resistant bacteria.
11. Find an answer to 'How can we prevent bacteria from evolving antibiotic resistance?'

A4. Unity and diversity: Ecosystems / A4.1 Evolution and speciation

Reflection

Section Student… (0/0) Feedback Print (/study/app/bio/sid-422-cid-755105/book/reflection-id-46869/print/) Assign

Teacher instructions

The goal of this section is to encourage students to reflect on their learning and conceptual understanding of the subject at the end of this subtopic. It asks them to go back to the guiding questions posed at the start of the subtopic and assess how confident they now are in answering them. What have they learned, and what outstanding questions do they have? Are they able to see the bigger picture and the connections between the different topics?

Students can submit their reflections to you by clicking on 'Submit'. You will then see their answers in the 'Insights' part of the Kognity platform.

Reflection

Now that you've completed this subtopic, let's come back to the guiding question introduced in The big picture (/study/app/bio/sid-422-cid-755105/book/the-big-picture-id-43246/).

- What is the evidence for evolution?

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- How do analogous and homologous structures exemplify commonality and diversity?

With these questions in mind, take a moment to reflect on your learning so far and type your reflections into the space provided.

You can use the following questions to guide you:

- What main points have you learned from this subtopic?
- Is anything unclear? What questions do you still have?
- How confident do you feel in answering the guiding questions?
- What connections do you see between this subtopic and other parts of the course?

⚠ Once you submit your response, you won't be able to edit it.

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Submit

Rate subtopic A4.1 Evolution and speciation

Help us improve the content and user experience.

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