CHAPTER 21

Adaptation and Speciation

Reflecting Questions

- What determines a species?
- How do new species arise?
- What is the relationship among adaptation, natural selection, and the formation of new species?
- How might life on Earth have formed?

From the bacteria that thrive in your digestive tract, to a species of algae that survives on glaciers, to the elephants in the forests of Asia, there are millions of species on Earth inhabiting vastly different habitats. As well, there are innumerable species that once thrived and are now extinct. The formation of most new species takes thousands of years, but as you read this page, there are forces at play that are affecting populations. These forces may ultimately lead to the creation of a new species. The bacterial species shown here (*Staphylococcus aureus*), for example, is common in hospitals. For years, the antibiotic penicillin was highly effective in killing this bacteria and others. In fact, the discovery of penicillin meant that World War II was the first war in which fewer soldiers were killed by disease than by bullets or other shells. But today, just over 60 years since the discovery of penicillin, this wonder drug is virtually unable to fight off *S. aureus*. The ability of populations (such as bacteria) to adapt rapidly to changes in their environment is just part of the story of speciation in bacteria.

Defining a species is an ever-present challenge for biologists. For example, speciation differs in sexually reproducing species and in micro-organisms. In the past, biologists measured and recorded differences between individuals and noted their habitat and behaviour. However, this is not a practical approach for all species. With new advances and discoveries in microbiology and the unearthing of new fossils, we are learning more about how and when species form. Through experimentation and observation, a biologist can determine differences between populations and also determine the evolutionary lineage of a species. What criteria would you use to distinguish the eastern maple shown here from maple trees in western Canada or Europe?

In this chapter, you will investigate adaptation and speciation. What are the situations needed for new species to form? How quickly do species form? How do populations adapt to new environments? How do we distinguish one species from another? These are some of the questions that you will explore in this chapter.

What determines whether this Ontario maple is a different species from maple trees that grow in other parts of Canada?

Chapter Contents

21.1 Adaptation

OUTCOMES

- **Explain the process of adaptation of individual organisms to their environments.**
- **Describe the relationship between natural selection and adaptation.**
- **Describe different types of adaptations, explain how complex adaptations might have evolved, and describe exaptation.**

The broad, flat leaves of a maple tree and the spines of a cactus are features that enable these plants to live in environments that have different conditions. A species of broad-leafed tree would not survive in the hot, dry desert or in the cold, dry tundra of northern Canada. In these environments, such trees would lose too much water across the large surface of their leaves. In contrast, the spines (which are modified leaves) of cacti, along with other characteristics, reduce water loss. With respect to absorption of light, the broad maple leaf provides a large area to absorb the moderate amounts of sunlight present in a temperate climate. In contrast, cacti live in an environment with an abundance of strong sunlight and a generally dry atmosphere, so they can absorb enough light through their small leaves or through their stems without losing moisture. Leaf shape is an important trait with respect to survival in plants. The sharp canine teeth of cougars and other carnivores; the agile, flexible hooves of mountain goats; and the ability of Arctic char to withstand near-freezing water temperatures are all traits that are important to survival (see Figure 21.1). Any trait that enhances an organism's fitness or that increases its chance of survival and probability of successful reproduction is called an **adaptation**. How exactly do adaptations arise?

Adaptation is essentially a product of natural selection. Organisms become adapted to their immediate environment over a period of time through natural selection. As populations are subjected to the vagaries of their environment, the genetic characteristics that are best adapted or well-suited to the environment are selected. For instance, populations living in cold areas will have a variety of features and behaviours that make them better adapted to withstand the cold. Those individuals that possess characteristics that enable them to survive in the cold will reproduce and may pass on these favourable adaptations to their offspring. Natural selection can, along with selective pressures, affect the number of individuals with particular traits. The result may be an adaptation of the population.

When discussing adaptations, it is important to note that the environment is more than just the immediate surroundings of an organism. Environment includes all the factors, other than genetic make-up, that can affect whether or not an organism lives through the embryo, juvenile, and adult stages to reproduce. For example, whether a plant successfully resists the selective pressure of its environment depends on many factors. These factors include the speed and normality of its germination, whether bacteria or fungi infect it as a seedling, and whether the soil in which it grows can support it. To complicate matters further, selective pressures can be contradictory. For example, warm or hot temperatures may increase the rate of plant growth, but they can also dry out the soil, thus impeding proper root growth.

Figure 21.1 The Arctic char (*Salvelinus alpihus*) has adapted to cold Arctic waters.

Adaptations may occur as particular variations increase in frequency within a population of organisms. However, variation and adaptation are not the same. A variation may improve fitness, but it may also have no effect on or even reduce fitness. Any variations that are the result of changes in the dominant alleles in the population and that may reduce fitness in the current environment will decrease in frequency in the population by natural selection. For example, the length and shape of dragonfly wings are adaptations for flight and, thus, for survival, since dragonflies prey on other insects in flight. Wing length within a population will vary slightly, but there is an optimal wing length that best suits the current environment in which the population lives. If a dragonfly has wings that are too short, it may not be able to generate enough lift to stay off the ground. If its wings are too long, they may become too heavy. So, there is a certain length of wing that results in the greatest fitness for dragonflies. Variations — such as the length of dragonfly wings, or the sharpness of eagle talons — that aid in survival and increase fitness will be preserved in a population by natural selection. If a variation is favourable for an individual, the chances are greater that the individual will survive to pass on its genes to its offspring. Over time, all surviving members of a population will have inherited that variation, at which point the original variation becomes an adaptation. In other words, the adaptation has become a general characteristic of the entire population, like a dragonfly's wing length or the sharpness of eagle talons. *In summary, while adaptations are products of natural selection, variations within a species are the raw material upon which natural selection acts.*

Evolution of Complex Adaptations

When you imagine the human eye, it seems impossible that all of its intricate parts (the lens, pupil, retina, muscles, vitreous humour, blood, nerves, and pigment), which work together to focus light into images, could have combined randomly to make such a complex organ. Adaptations, particularly ones such as the change from a simple to a complex eye, do not arise all at once. Rather, adaptations evolve over time as a result of a series of small adaptive changes. Each change is a slight modification of the traits of the previous generation.

The adaptations in the organisms living today are the result of natural selection acting on chance variations that arose at particular times in the evolutionary history of these organisms. For example, the eye has evolved in a series of steps, with each step providing organisms with vision that was slightly better for its given environmental conditions. Many marine invertebrates, such as the scallop in Figure 21.2, have ocelli — clusters of light-sensitive cells that allow the organisms to detect movement and luminosity (light level). Their eyes do not form an image. On the other hand, insects such as the fly in Figure 21.3 have compound eyes, which are excellent for detecting movement and which also form an image.

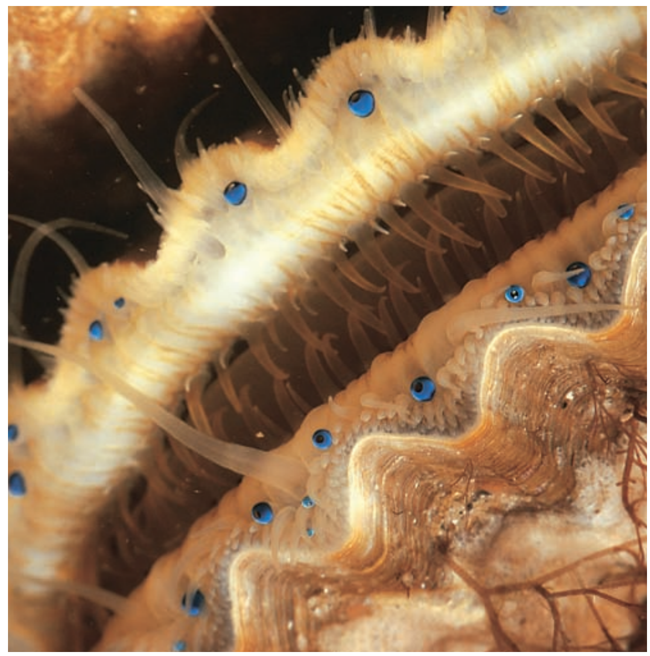


Figure 21.2 Scallops have simple eyes that are able to detect changes in light and movement, but they cannot form an image.

Figure 21.3 A compound eye enables a fly to see images.

Primitive eyes were simply a cluster of light-sensitive cells. These rudimentary "eyes" probably gave the ancient organisms an ability to see movement and to distinguish between light and dark. This gave them a selective advantage in their environment as they could detect movement of a potential predator. Over time, new variations of eyes arose in populations. For example, natural selection resulted in the formation of a simple lens that provided a blurry image. Since seeing even a blurred image is generally an advantage over seeing no image at all, this characteristic would be selected for in the population and would eventually become fixed in the population. Subsequent changes in some animals led to a sharpening of focus and, eventually, permitted colour vision. In other animals, there was no selective pressure for an advanced type of eye. In these cases, the genes for a simple lens would continue to be passed on to future generations. Each step in the evolution of eyes was due to random variations that arose in populations, and to the perpetuation of these variations within the population where the traits provided a selective advantage in a particular habitat. As a structure such as an eye becomes more adaptive for some animals and improves an animal's chances of survival, the chances of these genes being passed to offspring are increased.

WEB LINK

www.mcgrawhill.ca/links/atlbiology

While the eyespots of flatworms are not nearly as complex as the human eye, they still provide the flatworm with an advantage in its environment. To learn more about the evolution of a fish eye, and how long biologists think this might have taken, go to the web site above, and click on **Web Links**. Make a time line showing the changes that might have led from an eyespot to a fish eye.

MINI LAB

Small Changes, Large Gains

The adaptations that enable species to live within their environment are often difficult, or impossible, to see. Many adaptations are internal, such as changes in biochemical pathways responsible for metabolic processes. Other adaptations happen in very small steps. In the population of finches that you read about in Chapter 19 (on page 648), researchers found than even a millimetre in beak length could mean the difference between life and death in some situations. In this MiniLab, you will learn how small advantages can result in large gains for particularly well-adapted individuals.

You will need a number of different sizes, lengths, and styles of forceps and/or household tweezers. You will also need three types of small- to medium-sized seeds, such as sesame seeds, lentils, and rice. (These seeds are referred to as seeds A, B, and C here.) Mix about 30 to 40 of each of the three types of seeds together in one tray, making sure that there are an equal number of each type of seed at the beginning of the lab. Choose one style of forceps and attempt to gather seeds (any type) for 20 s. Record the number of seeds gathered by type, and record the particular characteristics of the forceps used to gather each seed. Repeat this trial three times and determine the average number of seeds gathered. Repeat this procedure using two other styles of forceps.

Now assume that there has been an environmental event (such as a drought or flood) that has reduced the availability of seed A. To simulate this, leave only 10 percent of seed A in the tray. Repeat the trials and compare the results.

Finally, assume there is an environmental event that has reduced the number of seeds B and C and doubled the number of seed A. Leave only 10 percent of seeds B and C in the tray and double the number of seed A. Repeat the trials and compare the results.

Analyze

1. Graph your results from these trials.
2. Describe any correlation between the characteristics of the forceps and their ability to pick up particular types of seeds.
3. Describe what happened after the first environmental event when the number of seed A available was reduced. How might this have affected the subsequent generations if the tweezers were actually a type of bird beak?
4. Describe what happened after the third trial. Were any of the effects of the first trial reversed? Explain how this might happen in natural situations.
5. Natural populations can have good years when the populations boom and poor years when the populations decline. Did your experiment demonstrate this phenomenon? How could you have adjusted your experiment to make it more realistic?

The Changing Function of Adaptations

Sometimes an adaptation that evolved for one function can be co-opted for another use. Originally this was called pre-adaptation, but since this term implies that there is a level of conscious planning in advance (which is not the case in evolution), a new term was coined — **exaptation**. As an example, the invertebrate ancestors of vertebrates may have stored phosphate in their skin to help them survive lean times. It turns out that the best way to store phosphate was in a matrix of calcium, which created a hard tissue. This hard tissue (for example, the shell in Figure 21.4) could also protect an animal from predators. Therefore, what originally evolved as an adaptation for metabolic processes was exapted and used for protection. Later, a calcium matrix of bone was used for muscle attachment and became the framework, or skeleton, of vertebrates.

The limbs and digits of terrestrial vertebrates did not evolve in response to a demand for walking on land. Instead, they evolved in fully aquatic tetrapods (four-legged creatures) such as *Acanthostega* that used legs and toes to move in coastal wetlands. (You were introduced to *Acanthostega* in section 19.3 on page 662.) These organisms used these limbs to crawl over logs, grip onto rocks, and clamber through marshy areas. When some of these tetrapods ventured onto land, the limbs proved useful. A living example is the lungfish of Africa, that uses its fleshy fins to move from pond to pond and to bury itself in the mud during dry periods. Paleontologists have discovered approximately 12 species of early tetrapods and all appear to have been aquatic. Thus, what evolved as an adaptation for an aquatic existence eventually became useful for a life on land. It is as though evolution borrowed something adapted for one function to perform a new function.

Types of Adaptations

Adaptations can be broadly classified as structural (or anatomical), physiological, or behavioural. The different arrangement of teeth in carnivores, herbivores, and omnivores; the tissues in vascular plants that allow transport of water and food; and the shape of fins or beaks are all **structural adaptations**. These adaptations can be anatomical (that is, dealing with the shape or arrangement of particular features), but structural adaptations can also include **mimicry** and **cryptic coloration**.

Mimicry enables one species to resemble another species or part of another species. Often, a harmless species will mimic a harmful species; the result is that predators that avoid the harmful species will also avoid the mimic. For example, the fly in Figure 21.5 is a harmless mimic of a yellow-jacket wasp. This fly, as well as other insects including some beetles, capitalizes on the fact that many predators will avoid anything with black and yellow patterning after being stung a few times by bees or wasps.

Figure 21.4 Shells are made of calcium carbonate. Calcium was originally stored by invertebrates as a way to stockpile phosphates, an energy source.

Figure 21.5 Mimics, such as this syrphid fly, copy the coloration or patterns of harmful species as a defence against predators.

Cryptic coloration makes potential prey difficult to spot. For example, animals may have colouring that blends well with their surroundings. Other animals can be camouflaged by shape and colouring, such as the bizarre sea horse (called a sea dragon) that lives among a particular type of seaweed. Figure 21.6 shows how a sea dragon can look like the algae in which it lives. Potential prey do not distinguish the sea dragon from its seaweed surroundings, and can be lured into the relative safety of the seaweed only to be consumed by the sea dragon.

Many structural adaptations are internal rather than external. For example, the strong muscle walls of the human heart are an adaptation than enables the heart to pump blood throughout the body. As another example, the digestive tracts of herbivores and omnivores are much longer relative to body size than the digestive tracts of carnivores. Vegetation is more difficult to digest than meat because of its tough cellular walls. A longer digestive tract permits more time for digestion and a greater surface area for the absorption of nutrients.

Physiological adaptations are those adaptations associated with functions in organisms. The enzymes needed for blood clotting, the proteins used in spiders' silk, the chemical defences of plants, and the ability of certain bacteria to withstand extreme heat are all examples of physiological adaptations.

Figure 21.6 The coloration and leafy appearance of the sea dragon's (*Phycodurus sp.*) fanlike fins keep it well hidden among the seaweed in which it usually lives.

Organisms are also adapted in how they respond to the environment. These **behavioural adaptations** include migration, courtship displays, foraging behaviour, and the response of plants toward light and gravity. Animals have found different ways to avoid severe environmental conditions with adaptations such as the migration of monarch butterflies, hummingbirds, caribou, and wildebeests; the winter sleep of bears and skunks; and the hibernation of jumping mice, some turtles, and garter snakes. No doubt, some of these adaptations evolved in response to changes in environmental conditions as the continents formed and moved. All these behavioural changes are the result of natural selection — those individuals that survived passed on their genes to the next generation. For example, the monarch butterflies that moved to warmer climates survived and passed on the behavioural traits for migration.

In natural situations, it is unrealistic to isolate and classify adaptations in rigid categories because adaptations often depend upon one another. For example, bird migration is considered a behavioural adaptation. But migration would not be possible without a complex set of structural adaptations such as feathers, light bones, and strong wing muscles. As well, a variety of physiological adaptations, from nerve impulses to the release of hormones, enable flight and migration to happen.

BIO FACT

The feathers and lightweight, honeycombed bones of birds are examples of exaptation. The fossil record shows that light bones actually predated flight. This means that lightweight bones must have had some use on land. It is thought that the agile, bipedal (two-legged) dinosaurs that were the probable ancestors of birds benefited from a lightweight frame. The wing-like forelimbs and the feathers (which originally had other uses, perhaps in courtship displays or in providing warmth) were also co-opted for flight. The first flights may have been hops when pursuing prey or escaping predators. As this behaviour became advantageous in the environment, the structural adaptations that allowed it to happen were passed on.

WEB LINK

www.mcgrawhill.ca/links/atlbiology
To learn more about mimicry, go to the web site above, and click on **Electronic Learning Partner**.

Is Evolution Perfection?

It is sometimes assumed that the result of adaptation and natural selection is perfection in organisms. This is not the case, however, for a variety of reasons. As mentioned earlier in this section, selection can only edit variations that already exist in a population; evolution essentially has to "make do" with what is presented. As a result, designs are often awkward or less than optimal. An example is the human eye, since the neurons in our retina point backward. Although our eye works well, in many ways it is quite inefficient. In general, organisms are locked into the constraints of their evolutionary history; therefore perfection is not easily achieved. Since species have descended from a long line of ancestors, they are tied to their existing anatomy. It is not the case that old structures are scrapped and new structures are created with each step in evolution. Rather, existing structures are co-opted and adapted for the new environment. The result is designs that are sometimes less than perfect. The chronic back pain experienced by many humans is thought to result from the musculature and skeleton that have been modified from our four-legged ancestors, who were not adapted specifically for an upright posture.

Another reason that adaptations and natural selection do not achieve perfection is that adaptations are often compromises. A sea lion must swim, but it must also move about on land. In their present structure, sea lions can swim well but they are far less efficient at walking.

Finally, not all evolution is necessarily adaptive. Chance events such as tropical storms or volcanoes can also affect the composition of the gene pool. Some individuals survive this type of event randomly, and it is these individuals that remain to supply the variation upon which natural selection acts as future generations emerge.

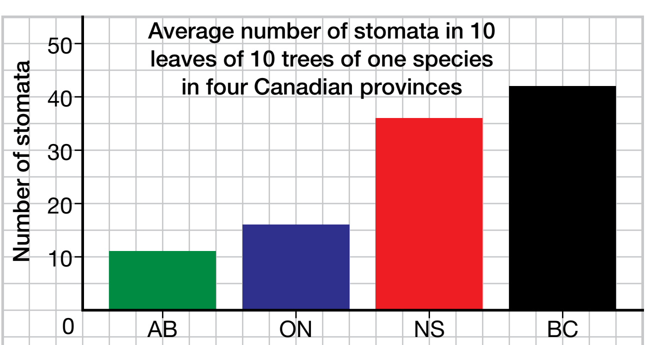
The individuals that survive and reproduce will pass on their genes to their offspring. Over time, the populations of individuals change. In the next section, you will find out how new species can be formed from changing populations.

BIO FACT

Examples of ineffective adaptations include thumbs in pandas (which require the redirection of muscles from the hand to operate), hollow bones in flightless birds such as penguins (which do not need light bones since they do not fly anyway), as well as teeth in fetal baleen whales and tails in humans (both of which are re-absorbed before birth, and thus never used).

SECTION REVIEW

1. Describe two mammal adaptations. Explain how each trait is adaptive.
2. Stomata are openings on the surface of leaves that allow plants to release water. Analyze the following data showing the number of stomata on the leaves of one tree species. What might these data tell you about the rainfall in the areas where the data were collected? What is the relationship between rainfall and number of stomata?



3. Describe, with the aid of a sketch, a plausible pathway for the evolution of a complex adaptation such as the vertebrate eye.
4. Was a primitive eye that was 95 percent less effective than a modern eye useless? Explain your answer.
5. Are the following adaptations behavioural, structural, or physiological? Give reasons for your answers.
   (a) plant stems grow toward light
   (b) woodpeckers' bills are pointed and sharp
   (c) cacti have spines
   (d) spiders use proteins in their webs
   (e) flowers produce scent
6. Describe the relationships among variations, adaptations, and natural selection.
7. Give two examples of behavioural adaptations and explain how they may have evolved.
8. Explain why adaptation and natural selection do not result in perfection.
9. Evolutionary biologist Karel Liem said that "Evolution is like modifying a machine while it's still running." Explain what this statement means.

21.2 How Species Form

OUTCOMES

- **Define the concept of speciation and explain the mechanisms of speciation.**
- **Explain how geographic and reproductive isolation can contribute to speciation.**
- **Describe alternative concepts of species.**

The meadowlarks in Figure 21.7 look remarkably similar, yet they are different species. How is a species defined? Historically, species were described in terms of their physical form. But obviously physical similarity does not necessarily mean organisms are the same species. To this end, scientists now also consider physiology, biochemistry, behaviour, and genetics when distinguishing one species from another.

The most common definition of a species describes a **biological species** concept. In this context, a species consists of a reproductively compatible population; that is, a population that can interbreed and produce viable, fertile offspring. To accomplish this, the populations must be able to interbreed in the same time period. If one population breeds in the spring and one in the fall, the two populations would generally not interbreed. The concept of a biological species, therefore, centres on the inability of two species to hybridize. (A hybrid is the offspring of a cross between individuals of two species.) In those cases where hybrids can form, they are usually infertile or the gametes produced are not viable. A well-known example of two biological species are the horse and the donkey. According to the biological species concept, the horse and the donkey are two separate species. They may interbreed, but the offspring of a horse and donkey (called a mule or hinny) is almost always infertile.

There are two general pathways that lead to the formation of new species: transformation and divergence. Figure 21.8 illustrates the two pathways. A species can be the result of accumulated changes over long periods of time such that one species is transformed into another (**transformation**). The alternative is **divergence**, in which one or more species arise from a parent species that continues to exist. Both pathways are the result of natural selection. Divergence promotes biological diversity because it increases the number of species. In transformation, however, a new species is gradually created while the old species is gradually lost. Identifying instances of transformation is subjective, since it is difficult to determine when the new species became reproductively isolated from the original species, which no longer exists.

Figure 21.7 Even though eastern and western meadowlarks (*Sturnella magna* and *S. neglecta*, respectively) overlap in parts of their range, they are separate species.

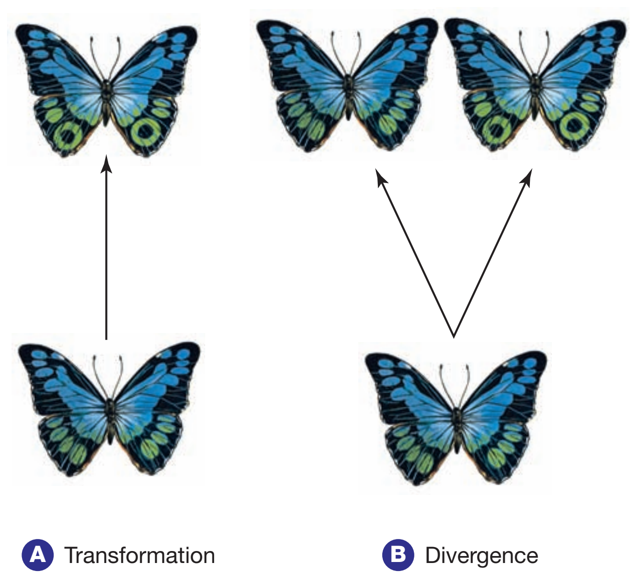


Figure 21.8 There are two patterns of speciation: (A) transformation (or anagenesis), in which one species evolves into another; and (B) divergence (cladogenesis), in which one or more species arise from a parent species.

Speciation, the formation of species, is a continuous process. Examples of speciation occurring today are often difficult to pinpoint because there are so many factors affecting the natural selection of individuals within a species. It is challenging to determine exactly when a species becomes a new species, or whether two different populations are the same species. For example, bird species such as the Baltimore oriole (*Icterus galbula*) and the Bullock's oriole (*I. bullockii*) in North America were once considered to be one species, called the northern oriole. After more research, the northern oriole (*Icterus galbula*) was again separated into the two species. Modern DNA analysis helps scientists to determine which populations may be a single species and which ones (such as the Baltimore oriole and the Bullock's oriole) may be two or more species.

Biological Barriers to Reproduction

In order for species to remain distinct, they must remain reproductively isolated. Various barriers prevent interbreeding and restrict genetic mixing between species, and species are generally separated by more than one type of barrier. **Geographical barriers** such as rivers prohibit interbreeding because they keep populations physically separated. However, there are many **biological barriers** that keep species reproductively isolated even when their ranges overlap.

It is clear that a bat will not mate with a squirrel, nor will a fern fertilize a rose, but what biological barriers keep species that are closely related to each other from interbreeding? Reproductive barriers are one example — they can act before or after fertilization to isolate gene pools.

Pre-zygotic Barriers

Pre-zygotic barriers (also known as pre-fertilization barriers) either impede mating between species or prevent fertilization of the ova if individuals from different species attempt to mate.

- **Behavioural isolation** The songs of birds, the courtship rituals of elk, and the chemical signals (called pheromones) of insects are all examples of behavioural barriers to reproduction. Any special signals or behaviours that are species-specific prevent interbreeding with closely related species. For example, even bird species that look virtually identical (such as the meadowlarks in Figure 21.7) and have overlapping ranges can remain separate biological species, largely because of differences in their songs. The songs allow them to recognize individuals of their own species. Another example of behavioural isolation is that females of some species release powerful, species-specific pheromones to attract males.
- **Habitat isolation** Although two species may live in the same general region, they may live in different habitats and therefore encounter each other rarely, if at all. For example, two species of North American garter snakes — the common garter snake and the northwest garter snake — live in the same area, but the northwest garter snake prefers open areas (such as meadows) and rarely enters water, while the common garter snake is most commonly found near water. These snakes are shown in Figure 21.9.

Figure 21.9 The northwest garter snake (*Thamnophis ordinoides*) (A) and the common garter snake (*T. sirtalis*) (B) occupy different habitats in a similar geographical area. This keeps the two species reproductively isolated.

- **Temporal isolation** Many species are kept separate by temporal (timing) barriers. For example, two species may occupy the same habitat but mate or flower at different times of day, in different seasons, or in different years (not all species mate every year). In a dramatic example, three tropical orchid species in the genus *Dendrobium* bloom for a single day, with the flowers opening at dawn and withering in the evening. Flowering in all three species occurs in response to various stimuli in the weather. However, the lapse between the stimulus and flowering is eight days in one species, nine in another, and 10 in the third. Because of this difference in timing, the three species remain reproductively isolated even though they live in the same habitat. As another example of temporal isolation, species of giant silkworm moths fly and mate at different times during the day.
- **Mechanical isolation** Species that are closely related may attempt to mate but fail to achieve fertilization because they are anatomically incompatible. For example, the genitals of some insects operate in a kind of lock-and-key system. If a male and female of different species attempt to breed, their genitals will not fit together. Genital anatomy is so distinctive in many organisms (particularly insects) that it is often used to classify species based on morphology.

  In plants, variations in flower structure may impede pollination if the flower and the pollinator are incompatible. In two species of sage, for example, the flowers have different arrangements of stamen and style. One species is pollinated by bees that carry pollen on their backs and the other species is pollinated by bees that carry pollen on their wings. If the "wrong" pollinator visits a flower, pollination cannot occur because the pollen does not come into contact with the stigma of the other species.
- **Gametic isolation** If gametes from different species do meet, gametic isolation ensures they will rarely fuse to form a zygote. The methods of gametic isolation vary among species. For example, in species in which the eggs are fertilized within the female reproductive tract, the sperm of one species may not be able to survive in the environment of the female reproductive tract of another species. In plants, pollen grains of one species typically fail to germinate on the stigma of another species, so fertilization is prevented.

  Many aquatic animals, such as the sea urchin in Figure 21.10, broadcast their gametes into the surrounding water and the eggs are fertilized in the water column. If gametes from two different species meet, chemicals on the surface of the eggs will recognize and reject sperm cells from another species.

WEB LINK

www.mcgrawhill.ca/links/atlbiology
To learn more about how a geographical barrier can isolate populations, go to the web site above, and click on **Electronic Learning Partner**.

Post-zygotic Barriers

In some cases, the sperm of one species successfully fertilizes an ovum of another species and a zygote is produced. There are several **post-zygotic** (post-fertilization) **barriers** that prevent these hybrid zygotes from developing into normal, fertile individuals.

- **Hybrid inviability** Genetic incompatibility of the interbred species may stop development of the hybrid zygote at some stage during embryonic development. For example, hybrid embryos created artificially between sheep and goats die in their early developmental stages before birth. Hybrid inviability is usually due to genetic incompatibility, which prevents normal mitosis after fusion of the nuclei in the gametes.

Figure 21.10 Chemicals on the surface of this sea urchin's eggs prevent sperm from a different species from successfully fertilizing them.

BIO FACT

The concept of reproductive isolation as a determinant of biological species applies to natural systems. In artificial situations such as labs and zoos, species that are reproductively isolated in natural situations can and sometimes do have viable, fertile offspring.

- **Hybrid sterility** Sometimes, two species can mate and produce hybrid offspring (such as a horse and donkey producing a mule or hinny, as discussed earlier). However, a reproductive barrier still exists between the two species if the hybrid offspring is sterile. If meiosis fails to produce normal gametes in the hybrid (because the chromosomes of the two parent species differ in number or structure), this barrier may come into effect.
- **Hybrid breakdown** In some cases, the first-generation hybrids of crossed species *are* viable and fertile. However, when these hybrids mate with each other or with an individual from either parent species, offspring of the next generation are sterile or weak. For example, different cotton species can produce fertile hybrids, but the offspring of the hybrids die as seeds or early in development.

Limitations of the Concept of Biological Species

The situations listed above are based on a concept of biological species, which is based on the fact that individuals cannot interbreed and produce viable, fertile offspring. There are limitations to this idea, however, so evolutionary biologists are beginning to look at different models for delineating species.

The biological species concept does not work in all situations. For instance, this definition cannot be applied with absolute certainty to species known only as fossils. In addition, many organisms (such as prokaryotes, protists, and some fungi, plants, and even some animals) are asexual. While bacteria do transfer genes to a certain extent, bacteria do not have anything equivalent to the genetic

THINKING LAB

Leopard Frogs — One Species or Seven?

(A) Northern leopard frog (*Rana pipiens*)
(B) Southern leopard frog (*Rana sphenocephala*)

Background

Leopard frogs were once believed to be a single, extremely variable species (*Rana pipiens*) that ranged across North America. Today, however, scientists know that what they thought of as the "leopard frog" is actually at least seven different, but related, species in North America. This was determined using the biological species concept.

You Try It

1. Listen to the calls of two different species of leopard frogs supplied by your instructor or by using the connections on the Web Link. Analyses of frog calls were one of the clues that led biologists to realize that there were more than one species of leopard frog. What type of biological barrier is a mating call? Explain how this type of biological barrier keeps species separate.
2. Choose two species of leopard frogs and describe in point form the differences that result in them being regarded as closely related but separate species. (They are referred to as sibling species.) Use connections on the Web Link or library resources. Leopard frogs in North America include the northern, southern, Rio Grande, plains, relict, Florida, Ramsey Canyon, and lowland leopard frogs.
3. Populations of amphibians, including frogs, are on the decline in North America, and scientists are tracking population numbers to try to determine the cause of the decline. When it comes to conservation and monitoring of species, why is it important to know that there are seven species of leopard frog rather than just one, wide-ranging species?

WEB LINK

www.mcgrawhill.ca/links/atlbiology
To listen to the calls and view photographs of the northern leopard frog and the southern leopard frog, go to the web site above, and click on **Web Links**.

recombination that occurs during sexual reproduction by two parents. As a consequence, defining species based on their inability to interbreed does not fit well with asexual organisms.

In other cases, the definition of biological species may be too rigid to apply directly. For example, coyotes can interbreed with domestic dogs and wolves to produce fertile hybrid offspring, yet all three remain distinct species. As well, other populations seem to be in the midst of evolving into two species, where it is difficult to distinguish the exact point at which adjacent and closely related species start to interbreed and where, or if, they stop. This inability to fit all organisms into the biological species concept has led evolutionary biologists to propose some alternative concepts to define species.

Canadians in Biology

Sticklebacks and Speciation

A three-spined stickleback is a scaleless fish with a row of three spines on its back. Dr. Dolph Schluter believes this little fish may provide evidence that natural selection can create new species. This view of speciation, which is central to the theory of evolution, is widely accepted by scientists. However, actual examples from living animals have not been easy to find. Dr. Schluter is also looking at the possibility that the "same" species may arise more than once.

The Montréal-born Dr. Schluter, who received his BSc from the University of Guelph and his PhD from the University of Michigan, is a zoology professor at the University of British Columbia. Dr. Schluter's earliest work included studying the Galápagos finches with Peter and Rosemary Grant (whose research on the Galápagos finches is discussed in section 19.1). Since then, his studies have included the three-spined sticklebacks in coastal B.C. lakes.

When the last ice age ended some 13 000 years ago, three-spined sticklebacks lived in ocean waters throughout much of the northern hemisphere. They ate microscopic plankton near the surface of the water. As the ice retreated and the ocean level dropped, some three-spined sticklebacks became stranded in newly formed lakes along the coasts. In the fresh-water lakes, these three-spined sticklebacks found plankton near the surfaces of deep, open areas. They also found a new source of food — insect larvae, snails, and other invertebrates near the bottoms of shallower areas.

A number of years later, according to Dr. Schluter's hypothesis, the ocean rose again, depositing more water and more three-spined sticklebacks in some of the coastal lakes. The newly arrived sticklebacks and those already in the lakes then had to compete for food. In a few lakes, two forms of sticklebacks evolved. One form, the limnetics (inhabitants of open water in fresh-water lakes), became very good at feeding on plankton near the surface. For example, they developed smaller mouths, smaller bodies, and longer gill rakers, which they used to strain food out of the water. Meanwhile, the bottom feeders, or benthics, were developing better adaptations as well. For example, because their food was bigger than the plankton they had previously eaten, benthics developed wider mouths and bigger bodies. Their gill rakers, which were no longer so useful to them, became shorter and less numerous. The limnetics and benthics each lived in their own separate parts of the lakes.

Dr. Dolph Schluter

Dr. Schluter and his colleagues regard the limnetics and benthics as separate species. "By calling them species," he says, "we imply that they don't interbreed — or interbreed so rarely that their differences in mating behaviour, genetics, and so on are maintained by natural selection against hybrids." But their definition of a species is a "soft" one, with which some scientists would disagree. Laboratory studies have shown that while limnetics and benthics that come from the same lake do not mate readily, they do nevertheless mate. On the other hand, limnetics from one lake willingly mate with limnetics from other lakes, and benthics from one lake willingly mate with benthics from other lakes.

People tend to think of the origin of a species as a unique, unrepeatable event in evolution. "One of the most exciting implications of this work," says Dr. Schluter, "is that the same 'species' (defined by mating compatibility) can actually arise more than once."

Alternative Concepts of Species

The biological species concept requires almost complete isolation of the gene pool. Alternative concepts of what defines species generally recognize that there is often some degree of genetic exchange between species. No single concept gives the perfect definition for species and, in reality, different concepts fit better in particular situations.

Historically, and still to a large extent today, organisms have been classified into separate species based on measurable physical features (essentially, the phenotype). This is called the **morphological species concept**. This model can be applied to both fossils and living organisms. Other models emphasize species-specific mating adaptations (*recognition species concept*); the fact that species have distinct clusters of genetic traits (*cohesion species concept*); the ecological role of a species within the environment (*ecological species concept*); and the evolutionary history and ecological role of a species (*evolutionary species concept*).

Regardless of how species are specifically defined, it is important to remember that speciation requires populations of organisms to become, and to largely remain, genetically isolated from others. The next section explores the mechanisms that lead to genetic isolation of a gene pool from that of a parent species.

BIO FACT

Part of the difficulty in applying the morphological species concept is that individuals within a species can be very different at different stages in their life history. Indeed, the juvenile and adult stages of some organisms have been considered separate species for long periods of time before their life cycle became better understood. Another difficulty is that there is slight variety in size, shape, and other morphological characteristics within a population; therefore, misclassification can result. For example, approximately 600 species of snails in the genus *Cerion* have been identified in the Caribbean islands based primarily on differences in size, shape, and coloration. It has since been shown that almost all of these differences result from slight variations in genes that regulate growth and that there may be, in fact, only two species of *Cerion*.

SECTION REVIEW

1. Explain how biological diversity contributes to speciation.
2. Explain the difference between habitat isolation and geographical barriers.
3. If two species produce a hybrid offspring that is infertile, is reproductive isolation between the two species still maintained? Explain your answer.
4. Plant breeders have artificially created new species and varieties of plants such as roses, cotton, apples, day lilies, and chrysanthemums. Give some reasons why these plants were developed. List some other species that have also been created by plant breeders.
5. Explain why it is difficult to fit all organisms into the biological species concept.
6. Using a flow diagram, describe the two pathways that can lead to the formation of a new species. Which pathway leads to an increase in biodiversity?
7. Prepare a chart that lists the five types of pre-zygotic barriers, provides a brief description of each barrier, and gives an example of a species or group of species that shows the result of this type of barrier.
8. Identify the type of reproductive barrier each of the following situations describe, and note in each case whether the barrier is pre-zygotic or post-zygotic.
   - **(a)** fireflies use distinctive patterns of flashes
   - **(b)** crossing frogs from two different populations produces frogs that never produce any offspring
   - **(c)** two species of grass flower at different times of year, yet live in the same habitat
   - **(d)** two species of flycatcher overlap in range, but one lives in open woods and farmland while the other lives in swampy areas
   - **(e)** the crossing of two species of fly produces a fertile hybrid offspring, whose offspring is weak and infertile
9. List the advantages and disadvantages of basing classification only on morphological characteristics.

21.3 The Patterns of Evolution

OUTCOMES

- Explain the mechanisms of speciation.
- Evaluate adaptive radiation as a mechanism for speciation.
- Compare two models describing the relative pace of evolution.

Types of Speciation

Speciation is the process by which a single species becomes two or more species. Biologists generally recognize two modes of speciation, the definitions of which are based on how gene flow is disrupted within a population.

Sympatric Speciation

When populations become reproductively isolated — even when they have not become geographically isolated — **sympatric speciation** occurs. In sympatric speciation, factors such as chromosomal changes (in plants) and non-random mating (in animals) alter gene flow. This type of speciation is far more common in plants than in animals.

Given the right set of conditions, a new species can be generated in a single generation if a genetic change results in a reproductive barrier between the offspring and the parent population. For example, errors in cell division that result in extra sets of chromosomes (a mutant condition called **polyploidy**) can lead to speciation.

A polyploid organism has three or more sets of chromosomes in the nucleus of each of its cells. Most animals are diploid — they have one set of chromosomes inherited from each parent. While it is quite rare for animals to be polyploid, this condition is relatively common in plants, particularly among flowering plants. (Polyploidy in plants is possible because many species are able to self-fertilize and reproduce vegetatively.)

Recall that during reproduction, a sequence of events must occur during meiosis in order for organisms to reproduce successfully. If errors occurred during meiosis and chromosomes did not separate, the gametes produced would have two sets of chromosomes (diploid, $2n$), instead of one set (haploid, $1n$). Then, if two diploid gametes fuse, the offspring would have four of each chromosome (tetraploid, $4n$). If tetraploid offspring survive, they could undergo normal meiosis and produce diploid gametes. The plant can now self-pollinate or reproduce with other tetraploids. However, it cannot produce viable seeds when crossed with diploid plants from the original population, since any offspring from this mating would be triploid ($3n$) and therefore sterile (because unpaired chromosomes result in abnormal meiosis). In just one generation, a reproductive barrier has been established in a population, because gene flow is interrupted between a small population (as small as one individual) of tetraploids and the parent population.

Figure 21.11 shows the stages in speciation by polyploidy. Many species, including cotton, apples, day lilies, and chrysanthemums, have been developed by plant breeders who artificially double the chromosomes in a plant and hybridize the resulting polyploids.

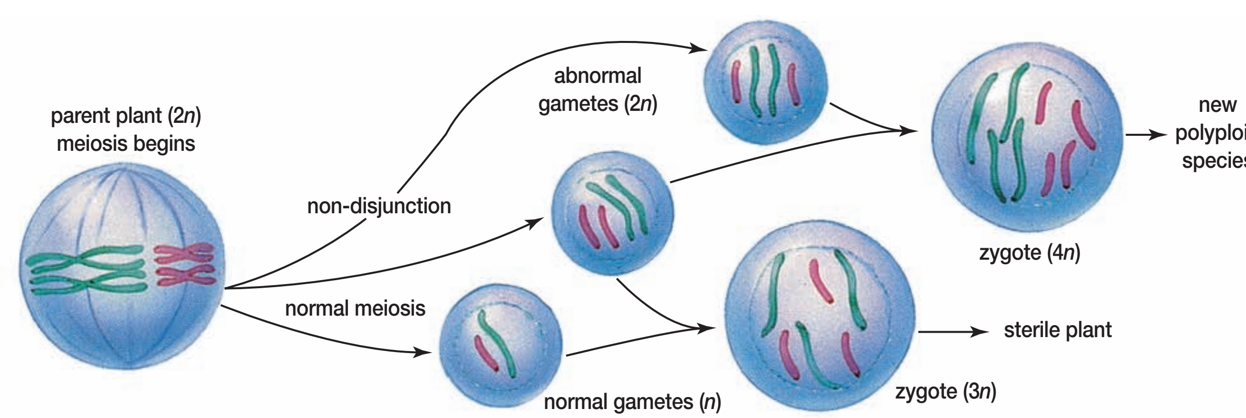


Figure 21.11 Polyploidy can lead to the formation of new species.

BIO FACT

Polyploidy is one way that plant breeders can create seedless fruit, such as watermelon. Plant breeders produce triploid watermelon seeds by crossing a normal diploid parent with a tetraploid parent. (The tetraploid plants are created by genetically manipulating diploid plants to double their chromosome number.) The resulting watermelons are triploid, and thus sterile — they do not have seeds, yet they still produce fruit.

In another model of sympatric speciation, two species can interbreed to produce a sterile offspring. Although the offspring is infertile, it can reproduce asexually — resulting in the formation of a separate population. Through mechanisms such as errors in meiosis, the sterile hybrids can be transformed into fertile polyploids in subsequent generations, thus forming a new, fertile species even though geographical isolation has not occurred. Figure 21.12, for example, shows the evolution of wheat. Chromosome analysis has shown that wheat is the result of two hybridizations of wheat with wild grasses, and two instances of meiotic error. As a result, a new species — the wheat that has been used to make bread for 8000 years — arose. Many other species grown for agriculture, including cotton, oats, and potatoes, are polyploids.

Sympatric speciation may also occur in the evolution of animals, but it is much less common. The mechanisms for sympatric speciation in animals are also different from those in plant populations. Generally, animals will become reproductively isolated within the geographical range of a parent population as they begin to use resources not used by the parent population. This, in turn, will lead to non-random mating and eventual speciation. For example, Lake Victoria in Africa holds almost 500 species of closely related fishes called cichlids (some cichlids are shown in Figure 21.13). Each species has a feature that makes it unique from other species in the lake, and none of these species are found anywhere else on Earth. It is thought that this incredible explosion of diversity happened as small groups of the parent population began to exploit different food sources and habitats in the lake. The speciation of cichlids has resulted in a remarkable variety of cichlids with a fascinating diversity of teeth, jaws, mating behaviours, and coloration. What makes this example even more astounding is that all of this diversity evolved from a single ancestor in less than 14 000 years — a relative blip in the geological time scale.

Figure 21.13 Several species of cichlids. Almost 500 species of cichlids live in Africa's Lake Victoria.

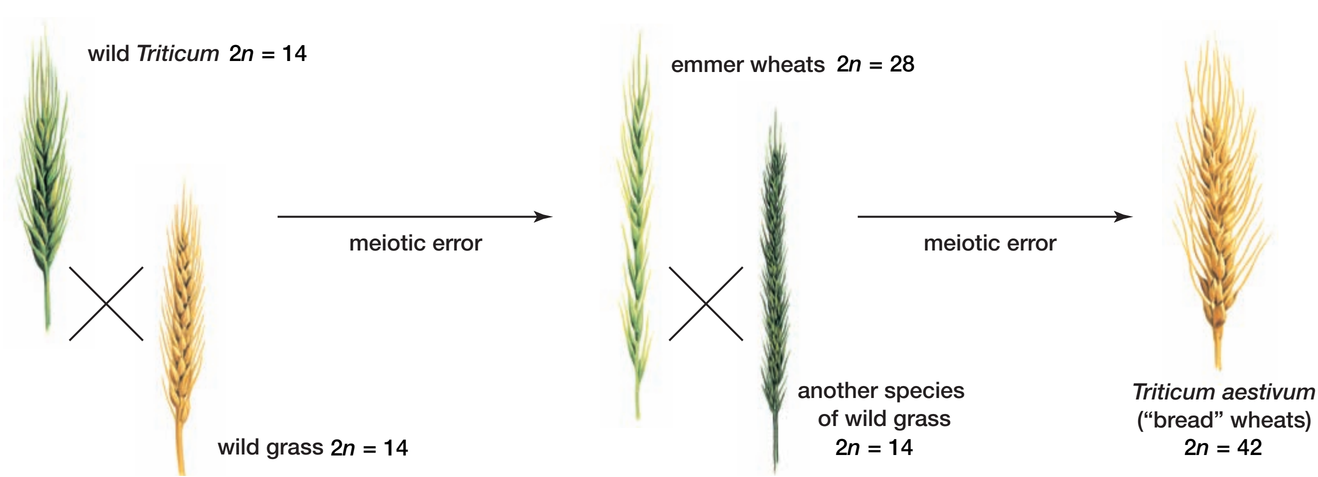


Figure 21.12 Wheat that is used to make bread evolved as a result of two hybridizations and two instances of meiotic error.

Biologists studying the speciation of and genetic differences among cichlids are running out of time. In the 1950s, the Nile perch, a fish that lives in other east African lakes, was introduced as a source of food for people living near Lake Victoria. This huge fish can grow up to two metres long, primarily by preying on cichlids. As well, farming and logging around the lake have resulted in massive soil erosion. The soil erodes into the lake and has turned the once clear waters muddy. Since cichlids cue on the distinct markings of potential mates, they are having difficulty clearly identifying potential mates and, as a result, have been mating with other closely related species. This interbreeding is eroding the reproductive isolation that was leading these fishes into hundreds of new forms.

Allopatric Speciation

Also called geographic speciation, **allopatric speciation** occurs when a population is split into two or more isolated groups by a geographical barrier. (Figure 21.14 illustrates the concept.) Eventually, the gene pool of the split population becomes so distinct that the two groups are unable to interbreed even if they are brought back together. For example, a glacier or lava may isolate populations, fluctuations in ocean levels could turn a peninsula into an island, or a few colonizers may reach a geographically separate habitat. Once populations are reproductively isolated, gene frequencies in the two populations can begin to diverge due to natural selection, mutation, genetic drift, or gene flow. This geographic isolation of a population does not have to be maintained forever for transformation to occur. However, it must be maintained long enough for the populations to become reproductively incompatible before they are rejoined.

The effect of a geographical barrier relates in large part to an organism's ability to disperse. The mobility of animals or the ease with which seeds or plant spores are dispersed limits gene flow, affects the cohesive influence of a common gene pool, and affects the impact of a geographical barrier. For example, while birds easily cross the Grand Canyon, it is impassible to rodents. As a result, the same bird species inhabit either side of the canyon, yet different species of squirrels inhabit opposite sides of the canyon.

Generally, small populations that become isolated from the parent population are more likely to change enough to become a new species. Part of the reason for this is that populations usually become geographically isolated at the periphery, or edges, of their range. It has been shown that groups of individuals at the periphery of a population already have a slightly different gene pool than that of the parent population. So, if this population splinters off, it is subject to the founder effect, since it already has a gene pool not representative of the parent population. As well, until the peripheral population becomes a large population it is subject to the effects of genetic drift. Because of the small population size, new mutations or new combinations of alleles may become fixed in the population simply by chance. This fixing of alleles would cause the genotype and phenotype to diverge from those of the parent population. Finally, because the isolated population may inhabit an environment that is slightly different from that of the parent population, natural selection through selective pressure may change the population in a different way. Note that isolated groups within populations will not automatically survive and thrive when separated into a new population. Many isolated

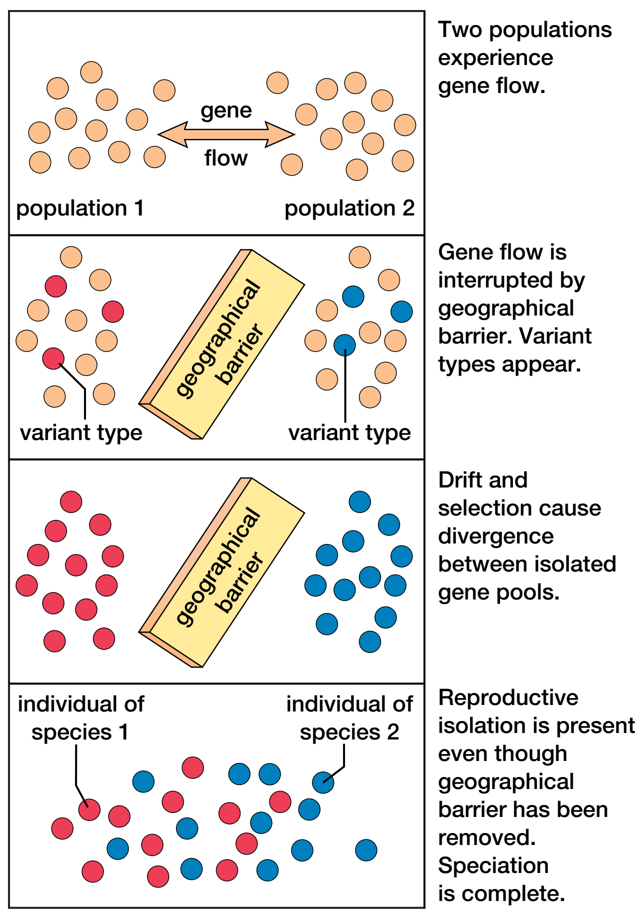


Figure 21.14 Allopatric speciation occurs after a geographical barrier prevents gene flow between populations that originally belonged to a single species.

populations do not last long enough or even change enough to become new species.

The population of finches being studied in the Galápagos is an example of speciation "in action." (You learned about the study of these finches by Peter and Rosemary Grant in Chapter 19.) Members of the ancestral species reached one of the islands in the Galápagos, possibly as a result of being blown off course in a tropical storm. Unable to return to the mainland, the ancestral species evolved differently than their mainland relative. The ancestral birds or their successive generations have since spread through the islands. New species developed as they evolved in response to the unique environments on individual islands.

By observing the finches now present in the islands, measuring features such as beak length, and analyzing the DNA of the birds, the Grants have been able to develop an evolutionary (phylogenetic) tree showing the descent of 14 species from one common ancestor. This phylogenetic tree is shown in Figure 21.15. The length of each branch of the tree reflects how much the DNA of each species has mutated from the group's common ancestor. The figure illustrates how the ancestral population initially gave rise to four lineages of finches. Over time, different lineages began to break off on their own. For example, the first branch to split off were the warbler finches, which used their slender beaks to specialize in eating insects. Next to diverge were the vegetarian finches, which use a stubby beak to eat flower blossoms, buds, and fruit. Finally, two more lineages evolved — tree finches adapted to catching insects in trees and ground finches adapted to eating seeds. Evolutionary biologists

Continued on page 720 ➡

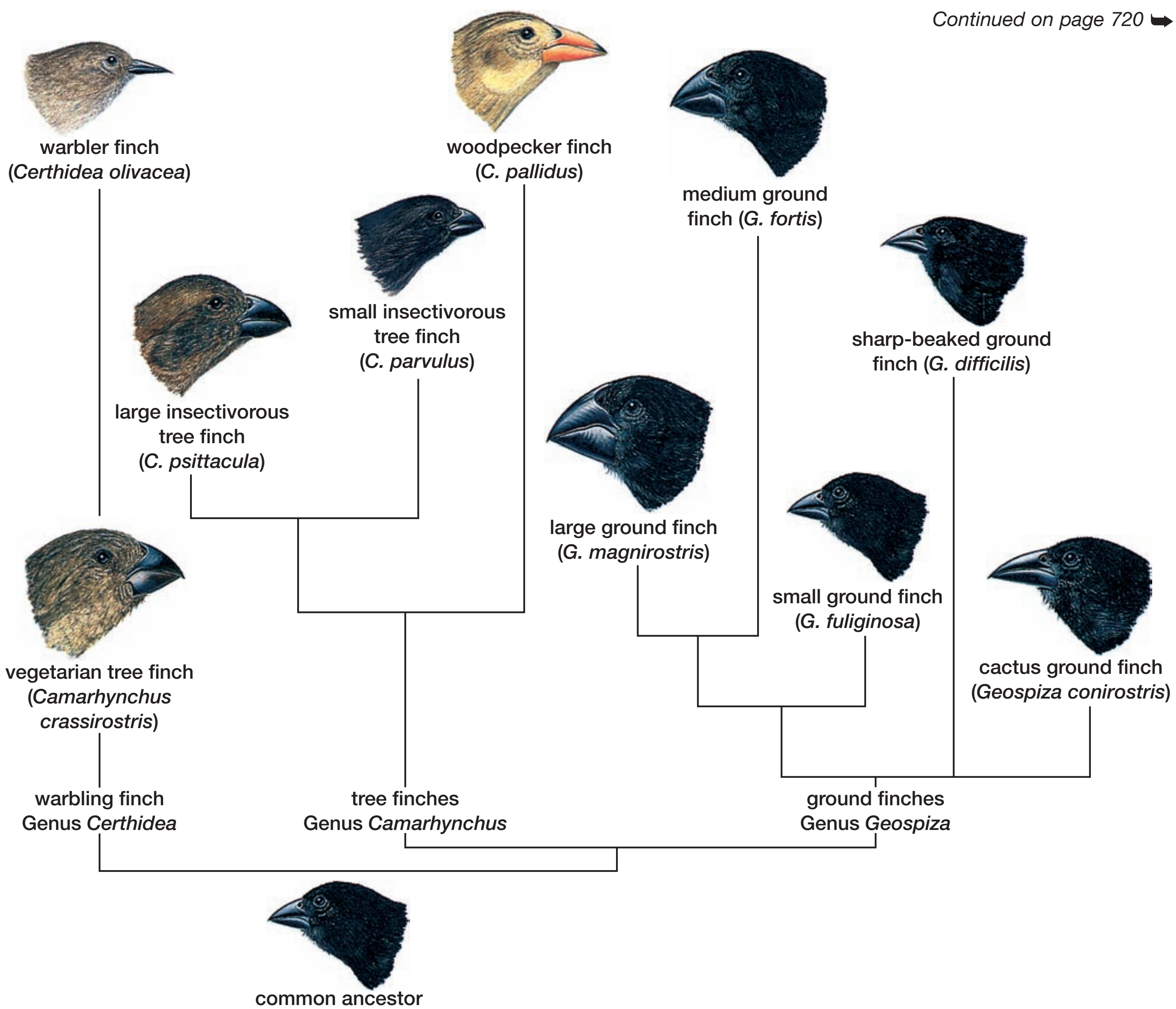


Figure 21.15 A phylogenetic tree for finches from the Galápagos Islands.

Investigation 21 • A

SKILL FOCUS

Performing and recording

Analyzing and interpreting

Communicating results

Skull Differences in Primates

Evolutionary biologists and paleontologists use many techniques, including comparative anatomy and DNA sequence analysis (comparison of nucleic acid sequences), to determine evolutionary relationships between species. In this lab, you will examine primate skulls to determine evolutionary relationships among primates. One of the skulls you will examine is that of *Australopithecus*, an early ancestor of humans. *Australopithecus* is the oldest known example in which the opening in the skull that leads to the spine (called the *foramen magnum*) is found at the bottom of the skull. Early *Australopithecus* species possessed both ape-like and human-like characteristics.

The following information will help you with this investigation:

- The reduced ratio of face area to brain area is a trait of modern human adults.
- An increase in brain size (cranial capacity) is characteristic of more complex organisms. Modern humans have the largest cranial capacity of all closely related primates.
- A jaw angle close to 90° is a trait of modern humans.
- A bony ridge on the skull, called the sagittal crest, is associated with strong muscles that move the lower jaw. The reduced size of the lower jaw in modern humans has resulted in a corresponding reduction in the size of this crest.
- A less prominent brow ridge is a trait of modern humans.

Pre-lab Question

- How can skulls be used to determine evolutionary relationships?

Problem

How do the skulls of primates provide evidence for human evolution?

Prediction

Predict how a modern human skull will differ from the skull of *Australopithecus* and the skull of a gorilla.

Materials

ruler
protractor

Procedure

1. Your teacher will provide you with a copy of the skulls (1/4 natural size) of *Australopithecus africanus*, *Gorilla gorilla*, and *Homo sapiens*.
2. Copy the data table into your notebook.

	Gorilla	Australopithecus	Modern human
face area (cm^2)			
brain area (cm^2)			
ratio of face area to brain area			
cranial capacity (cm^3)			
jaw angle			
sagittal crest			
brow ridge			

3. Measure the face area (lower rectangle), brain area (upper rectangle), and ratio of face area to brain area for each skull. (For example, a skull with a face area of 130 cm^2 and a brain area of 60 cm^2 has a face area to brain area ratio of 1 to 0.46.) Record the data in your table.
4. Determine the cranial capacity (brain volume) of each skull by measuring the diameter of the circle in each skull and multiplying this figure by 200. Record the data in your table.
5. Measure the jaw angle using the two lines drawn on the skull. The jaw angle measures how far the jaw protrudes forward. Record the data in your table.
6. The bony ridge running across the top of a skull is called the sagittal crest. This crest is used for muscle attachment. Record the presence or absence of this crest in each skeleton.
7. Determine the presence or absence of a brow ridge in each skull.

Post-lab Questions

1. Compare the three skulls in terms of the following traits.

(a) face-to-brain area

(b) cranial capacity

(c) jaw angle

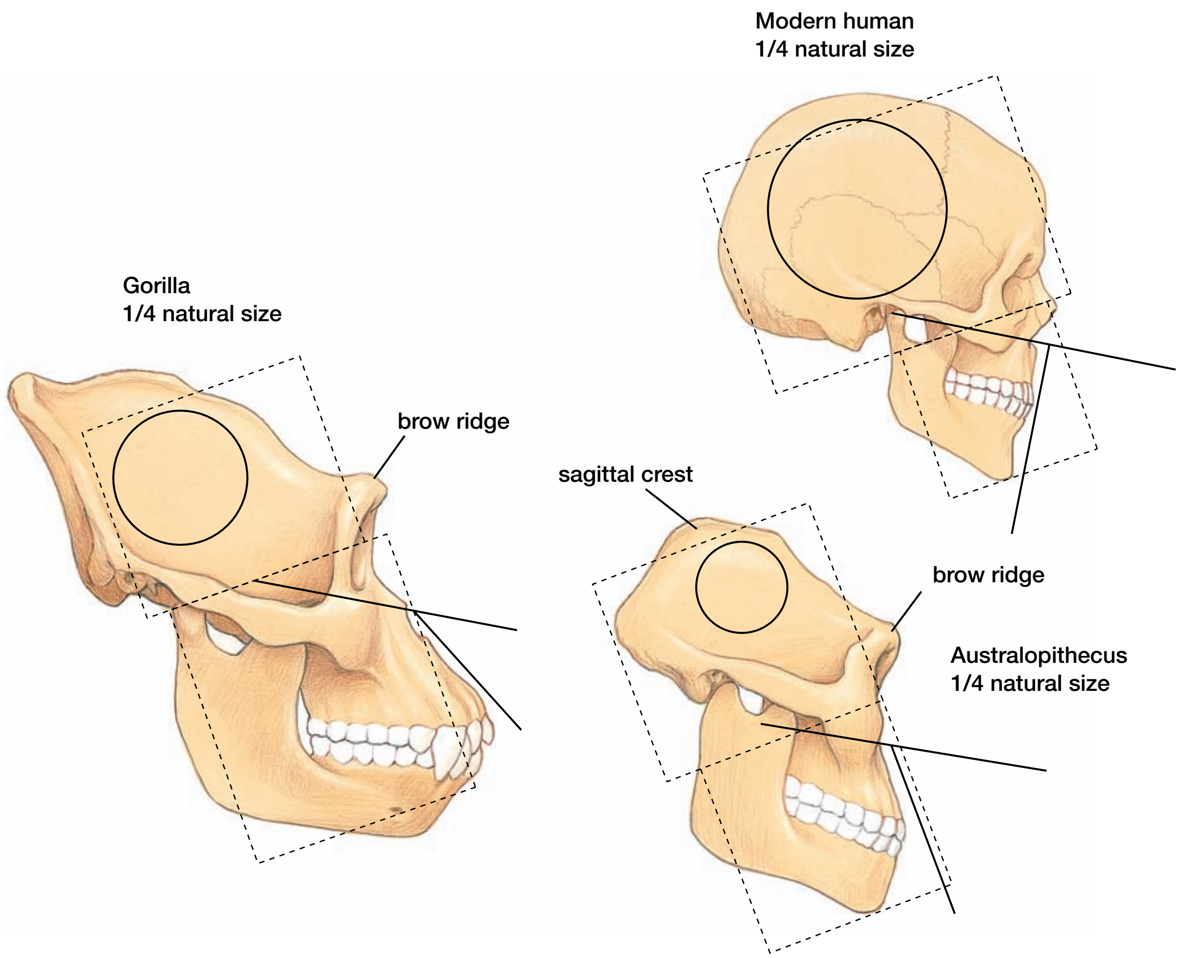
2. Describe other differences in the skulls that you could use to determine evolutionary relationships.

Conclude and Apply

3. Which characteristics of *Australopithecus* appear to be like the ape? Which appear to be like the modern human?

Exploring Further

4. Use library or Internet resources to obtain illustrations of gorilla and *Australopithecus* africanus skeletons. Describe their similarities and differences.



and paleontologists have used similar techniques in trying to determine the evolutionary relationships in primates. You looked at some techniques that are used to determine similarities and differences in primates in Investigation 21-A on pages 718–719.

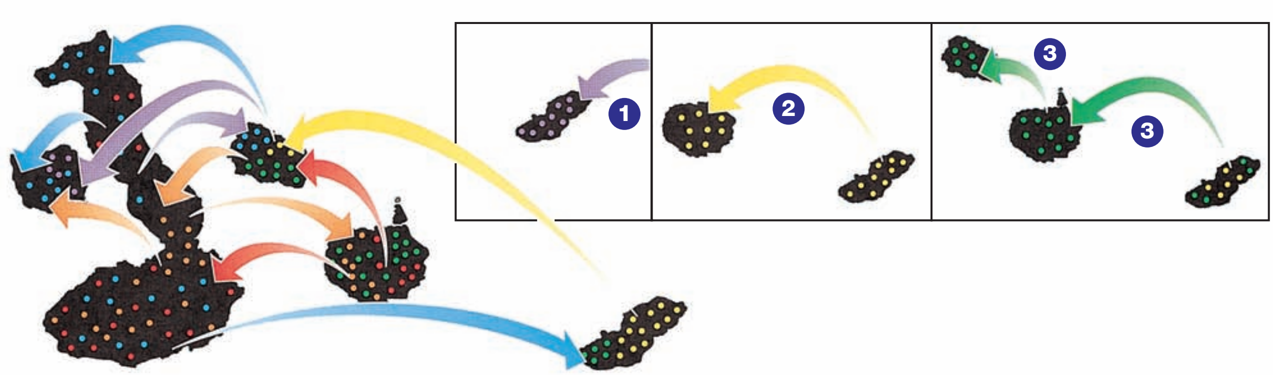
Adaptive Radiation

The diversification of a common ancestral species into a variety of species, all of which are differently adapted, is called **adaptive radiation**. Adaptive radiation is illustrated in Figure 21.16. The speciation of finches throughout the Galápagos Islands is an example of adaptive radiation. As the descendents of the ancestral birds proliferated on the first island they inhabited, individuals began to disperse to other islands. The islands were ecologically different enough to have different selective pressures acting on the individuals, which resulted in the different feeding habits and morphological differences of the finches.

Islands are excellent places to study speciation and biologists sometimes refer to them as living laboratories. Islands give organisms that have dispersed from a parent population the opportunity to change in response to new environmental conditions in relative isolation. The Hawaiian Islands are one of the best places in the world to study evolution and speciation. The archipelago is about 3500 km from the nearest continent, and the islands, which are volcanic, vary in age. The islands were born devoid of living organisms. They were gradually populated by species travelling by ocean currents or by winds. Since each island has different physical characteristics, adaptive radiation has caused an explosion of diversity. Most of the thousands of species of animals and plants that live in the Hawaiian Islands are found nowhere else in the world. Hawaiian honeycreepers (as seen in Figure 20.13 on page 691), for instance, are found only in Hawaii. Approximately 28 species of honeycreepers are believed to have evolved from ancestors that probably crossed the ocean from the American mainland about five million years ago.

Adaptive radiation does not occur solely on islands, however. Two evolutionary biologists at the University of British Columbia studied a particular type of finch, called a red crossbill, which is found throughout southern Canada, to demonstrate speciation (see Figure 21.17 on the next page). There are about 25 species or subspecies of crossbills in North America, Europe, and Asia. The twisted beak of the crossbill allows it to pry open closed conifer cones. Different sized crossbills open different sized cones. Small-beaked crossbills feed primarily on softer larch cones; crossbills with a medium-sized bill feed on harder spruce cones; and heavy-beaked crossbills feed on tightly closed, and very hard, pines cones.

Anna Lindholm and Craig Benkman experimented on seven red crossbills that specialize in eating the cones of western hemlock. (This species lives in coastal forests from Alaska to California.) Lindholm and Benkman "uncrossed" the beaks by trimming them with nail clippers. (This is as painless for the bird as trimming your fingernails is for you.)



1 The ancestral population reached an outer island.

2 The ancestral population adapted to its new home and a new species eventually arose. This species began to spread to other islands in the archipelago.

3 Speciation again occurred as part of this population became adapted to a different habitat and feeding niche.

Figure 21.16 Speciation of the Galápagos finches occurred through adaptive radiation.

The birds with clipped bills were just as effective as those with crossed bills when it came to getting seeds from open cones, but they could no longer open closed cones. As their bills grew back and began to cross again, they became progressively better at opening the tightly closed cones. The experiment demonstrated beautifully how small changes (even those too small to see with the naked eye) can provide a valuable advantage.

The crossed bill did not arise all at once, just as the human eye did not arise at once. The crossed bill changed gradually by selective pressure, one generation after the next, until the birds were quite expert in opening tightly closed cones. The novelty of a crossed bill gave the birds an advantage over others in the same habitat, because it allowed them to eat food no other bird could. The finches with this simple variation were then able to radiate into other habitats, since they had perfected a feeding technique for which they had no competitors.

Figure 21.17 Crossbills use their crossed bill to open tightly closed cones.

Major episodes of adaptive radiation often occur after the evolution of a novel characteristic. For example, the evolution of limbs in vertebrates, and wings in insects, opened up new possibilities for habitat and food supplies. Insect wings resulted in the evolution of hundreds of thousands of variations on the basic insect body plan, making this group the most successful and widespread type of animal on Earth.

Periods of rapid adaptive radiation often occur after **mass extinction** events in Earth's history, too. Extinction is inevitable, and there have been several mass extinctions where life on Earth changed dramatically. For example, the Cretaceous extinction of 65 million years ago marks the boundary between the Mesozoic and Cenozoic eras. During this mass extinction, more than half the existing marine species and many families of terrestrial plants and animals, including the dinosaurs, were exterminated. The climate cooled and sea levels changed. While this event sounded the ultimate death knell for dinosaurs, it was the catalyst for the adaptive radiation of mammals which, up until that time, were probably not much larger than mice.

WEB LINK

www.mcgrawhill.ca/links/atlbiology

Once a species goes extinct, is it gone forever? *Thylacinus cynocephalus*, or the Thylacine (known as the Tasmanian tiger — actually a marsupial wolf) went extinct in 1936. Recently, scientists at the Australian Museum have found well-preserved DNA of the Thylacine. Using modern techniques from biotechnology, a project is underway to clone this animal and bring it back from extinction. Scientists estimate that the process will take from 10–15 years, and success is not certain. To learn more about the efforts to bring the Thylacine back to life, go to the web site above, and click on **Web Links**.

Divergent and Convergent Evolution

The patterns of speciation and adaptive radiation that were discussed in the preceding pages are examples of **divergent evolution**, a pattern of evolution in which species that were once similar to an ancestral species diverge, or become increasingly distinct. Divergent evolution occurs when populations change as they adapt to different environmental conditions. The populations become less and less alike as they adapt, eventually resulting in two different species.

In contrast, in some instances two completely unrelated species share similar traits. For example, both birds and bees have wings, yet they have different ancestors. In **convergent evolution**, similar traits arise because each species has independently adapted to similar environmental conditions, not because they share a common ancestor. Birds and bats evolved independently and at different times, yet natural selection favoured variations suitable for the same environment — air. But since they do not share a common ancestor, birds and bats evolved quite different wings. Similarly, cacti and a group of plants called euphorbs have both independently evolved thick, water-storing stems and modified leaves in response to their desert habitats.

Coevolution

Nature is full of examples of the **coevolution** of organisms. Some organisms are tightly linked with one another and have evolved gradually together, each responding to the changes in the other. Predators and prey, pollinators and plants, and parasites and hosts all influence each other's evolution. Many insects, for example, have extraordinarily long tongues, which they use to drink the nectar from the extraordinarily long tubes in some flowers.

Plants provide many examples of coevolution. Most of the world's 290 000 species of plants rely on animals to spread their pollen, and there are many wonderful strategies to entice insects (and other animals that feed on nectar) to the plants. Plants pollinated by birds usually have bright red petals; they are generally not attractive to insects, because insects are colour-blind. (But insects can see patterns that humans cannot, because of their ability to see some ultraviolet wavelengths.) As well, bird-pollinated plants are usually scentless, since birds have a poor sense of smell. (Insect-pollinated plants, such as the orchid in Figure 21.18, are often scented to attract their pollinator.) Bird-pollinated plants also have their nectar in long, wide tubes to suit the long, stiff beaks of birds.

One specific example of coevolution between an insect and a plant is that of the monarch butterfly and the milkweed. The milkweed species have a toxin in their leaves, which monarchs eat. This toxin also makes monarch butterflies toxic, so most bird species avoid eating them.

Figure 21.18 Many flowers, including orchids, have coevolved with their pollinators.

The relationships between predator and prey also show examples of coevolution. The constant threat of predators can cause prey species to evolve faster legs, stronger shells, or more effective camouflage. As well, prey species can develop an impressive arsenal of poisons. Newts, spiders, and many snakes use venoms to produce powerful toxins. The rough-skinned newt, an amphibian that lives in the wet forests of the northwest coast of North America, produces a poison so strong it can apparently kill 17 adult humans. Since only a small amount of poison would be needed to kill most of its predators, why has this amphibian evolved such a toxic chemical? The answer lies with the newt's predator — the red-sided garter snake. This snake has evolved a genetic resistance to the newt's poison, so it remains a threat. Evolution has driven both the creation of a strong toxin in rough-skinned newts and the enhanced ability to block the poison in red-sided garter snakes.

Plants have been evolving natural pesticides and defences against insects for hundreds of millions of years. Almost since the earliest time when humans began to farm, we have applied poisons to protect crops from insects. In addition, insects are subject to the natural, plant-produced chemical defences. Just as insects coevolved with plants to develop new ways of feeding in response to the plants' development of new defences, insects are also coevolving with human-applied pesticides. And, thanks to evolution, insects seem to be winning this arms race. New pesticides continue to be produced but there is a great deal of concern about how pesticides affect crops, other insects, soil organisms, and the people who produce and apply the poisons. New crops that carry the genes from a bacterium (*Bacillus thuringiensis*, or Bt) have been developed. These bacteria live naturally in the soil and attack insects by producing a protein that destroys an insect's gut. These bacteria have been inserted into the genes of several plants, including cotton, corn, and potatoes; these plants can now produce Bt in their own tissues.

If farmers planted only Bt crops, coevolution would continue and eventually a population of insects resistant to the Bt would develop. Instead, farmers are being asked to plant non-Bt crops on at least 20 percent of their land. The theory is that these patches will become havens for the insects that are not resistant to the Bt crops. While these insects *may* mate with Bt-resistant insects, the fact that there is still a healthy population of non-resistant insects in the fields minimizes the chance of the resistant genes being perpetuated in the population. In order for the idea to work, the farmers must co-operate by giving up part of their fields to insects. If this does not occur and fields are planted solely with Bt-resistant crops, the chance of the insects becoming Bt-resistant is high, which means that new kinds of toxins will probably need to be produced and applied in the future.

The constant struggle between parasites and their hosts is another example of coevolution. Parasites include bacteria, protozoa, fungi, algae, plants, and animals. Since parasites consume their hosts to survive, the hosts must develop ways to defend themselves. The resistance of many bacteria to antibiotics is a clear example of coevolution (see Figure 21.19). Bacteria can divide several times an hour, so they are able to alter the genetic make-up of a population with incredible speed. Unlike insects, which become resistant to pesticides and acquire resistant genes only from their parents, bacteria can also acquire DNA from other bacteria. For example, they can incorporate the genes of dead bacteria into their own DNA. This incorporation is called bacterial transformation. (Note that bacterial transformation, in which non-pathogenic bacteria become pathogenic, is not the same thing as the transformation that occurs when two or more species are formed from one, or when one species is transformed into another.)

Although antibiotics were introduced only in the 1940s, already several strains of bacteria (including *Escherichia coli*, a bacteria that has caused water contamination disasters in Canada) resist most available antibiotics. Pharmaceutical companies are now working on new antibiotics, but there are questions as to how long this new round of drugs will be effective against the incredible rate at which bacteria evolve. When people do not complete the course of antibiotic treatment for bacterial infections, the surviving bacteria (which are more resistant to the medication) proliferate. Over-prescription of antibiotics and their inappropriate use (for example, when antibiotics are taken to fight viral infections) also adds to the problem of rapid bacterial resistance to antibiotics.

There is also concern that the antibiotics fed to livestock may be adding to the problem. For example, since 1994 the use of antibiotics called quinolones has been permitted in chickens to fight an intestinal bacteria called *Campylobacter jejuni*. Since that time, the presence of quinolone-resistant *Campylobacter* cultures in humans has risen from one percent to 17 percent.

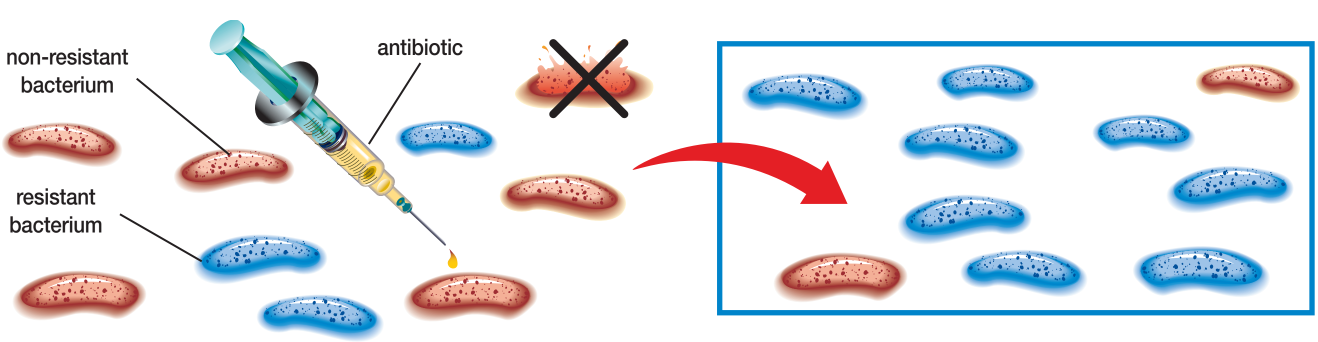
WEB LINK

www.mcgrawhill.ca/links/atlbiology

The resistance of bacteria to many antibiotics is a pressing concern in health care. Several groups have been formed to educate the public about the dangers of antibiotic resistance. To learn more from these groups, go to the web site above, and click on **Web Links** to find out where to go next.

The Pace of Evolution

How fast does evolutionary change happen? There are currently two hypotheses about the pace of evolution. Both models, which are illustrated in Figure 21.20 on page 724, have looked primarily at the fossil record to explain their ideas. Since Darwin's time, evolutionary biologists have supported the model of **gradualism**, which says that change occurs within a lineage, slowly and steadily, before and after a divergence.



A The bacteria in a population vary in their ability to resist antibiotics.

B When the population is exposed to an antibiotic, only the resistant bacteria survive.

C The resistant bacteria live and produce more resistant bacteria.

Figure 21.19 Bacteria can quickly become resistant to antibiotics.

According to this model, big changes occur by the accumulation of many small changes. The fossil record, however, rarely reveals fossils that show this gradual transition. Instead, paleontologists most often find species appearing suddenly in the fossil record, and then disappearing from the record equally as suddenly.

As well, the rate of evolution seems to vary. Paleontologist George Gaylord Simpson, whose work spanned from the 1920s to the 1980s, pointed out that some groups of animals seem to persist relatively unchanged for millions of years. The African lungfish, for example, has experienced few evolutionary changes over the past 150 million years. Simpson noted that other groups, such as mammalian species, were relatively short-lived. An average life for a mammalian species is about 200 000 years.

The different rates of evolution and fossil record evidence of periods of rapid change (for example, periods of rapid adaptive radiation after mass extinctions) led two biologists — Niles Eldredge of the American Museum of Natural History and Stephen Jay Gould of Harvard University — to develop an alternative model called **punctuated equilibrium**. This model proposes that evolutionary history consists of long periods of stasis, or equilibrium, "punctuated" or interrupted by periods of divergence. According to the model of punctuated equilibrium, most species undergo most of their morphological change when they first diverge from the parent species. After that, they change relatively little, even as they give rise to other species. Given this model, the fossil history should consist primarily of fossils from the long periods of time when little or no change occurred, with only a few fossils from the periods of rapid change.

Polyploidy is one mechanism for sudden speciation, as are mutations in genes that regulate the development of embryos. Supporters of the

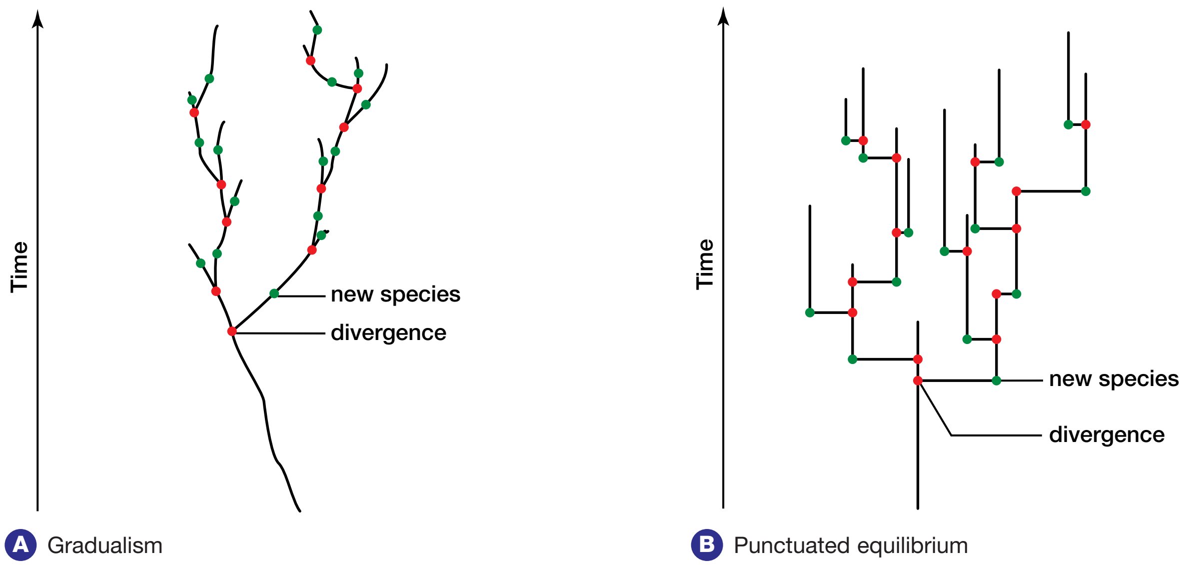


Figure 21.20 Two modes of evolution have been proposed: (A) gradualism and (B) punctuated equilibrium.

THINKING LAB

Partners in Evolution

Background

Plants and their pollinators provide some of the best examples of coevolution. Colours, shapes, scents, and other characteristics of most plants have more than likely evolved in tandem with pollinators; each has shaped the anatomy and/or behaviour of the other over time. For example, the sugar maple is adapted for wind pollination. It has flowers with pistils and stamens but no petals or sepals.

You Try It

1. Choose a plant to investigate. (It is best to choose a species that you can actually see somewhere, such as a garden, park, or flower shop.)
2. Using observation and library and/or Internet resources, learn how this plant is pollinated.
3. Sketch and label a diagram showing the relationship between pollinator and prey.
4. Has this plant coevolved with its pollinator? Explain your answer.

punctuated equilibrium idea note that allopatric speciation can also be very rapid, with genetic drift and natural selection causing dramatic changes in a few thousand, or even a few hundred, years.

Some scientists question the use of the term "sudden" in this context, given that an abrupt episode of speciation may, in fact, take place over 50 000 years or so. If a species survives for five million years, the punctuated equilibrium model says that most of its change would have taken place in the first one percent of its lifetime.

Once a species is created, it may actually remain unchanged if the environment to which it is adapted does not change. (Recall that this is called stabilizing selection.) When stabilizing selection occurs, a population *is* in equilibrium.

The debate surrounding the pace of evolution has stimulated much discussion and research, as all good scientific questions do. More work by both paleontologists and evolutionary biologists will continue to shed light on our understanding of speciation and evolution.

THINKING LAB

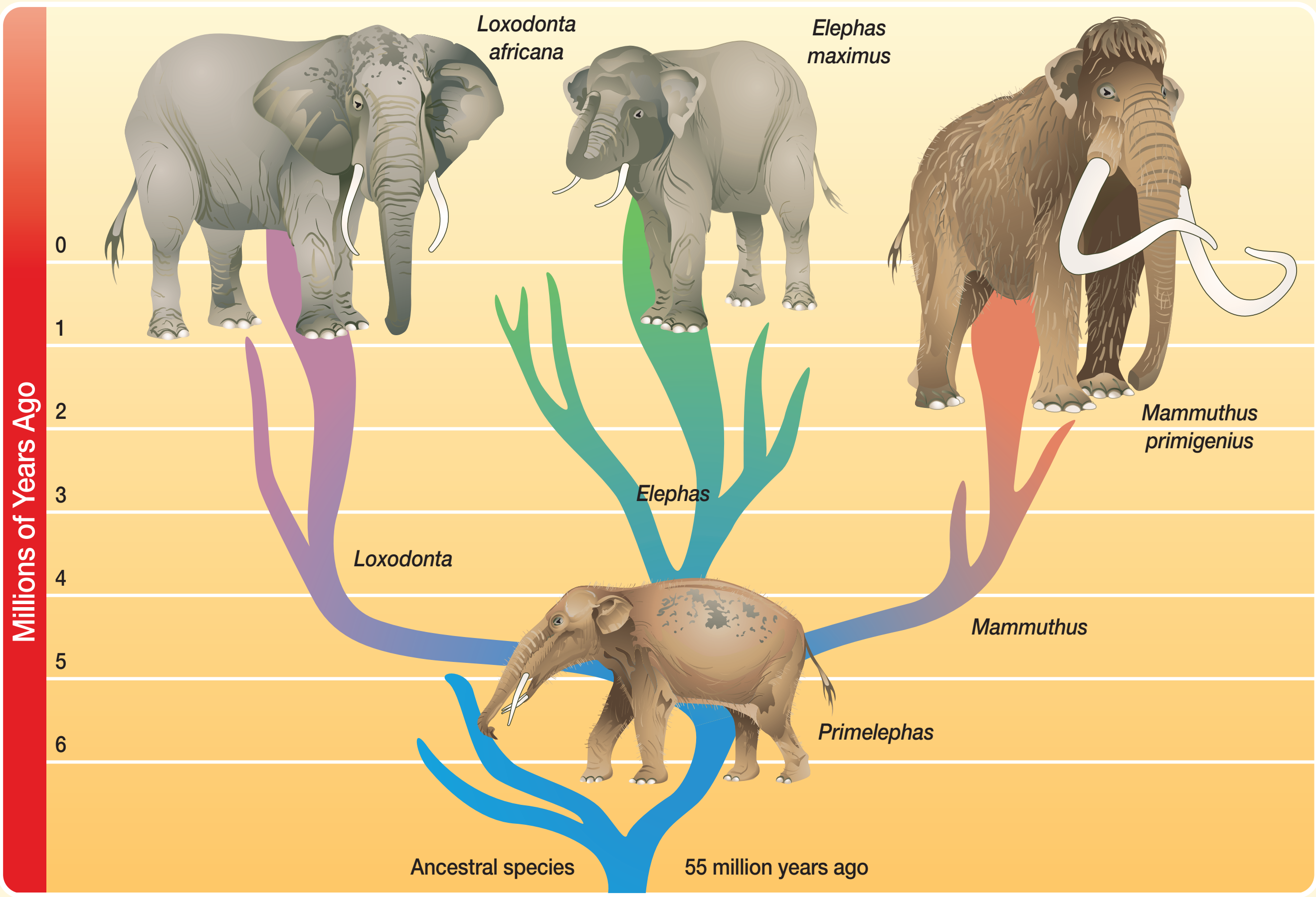
Elephant Evolution

Background

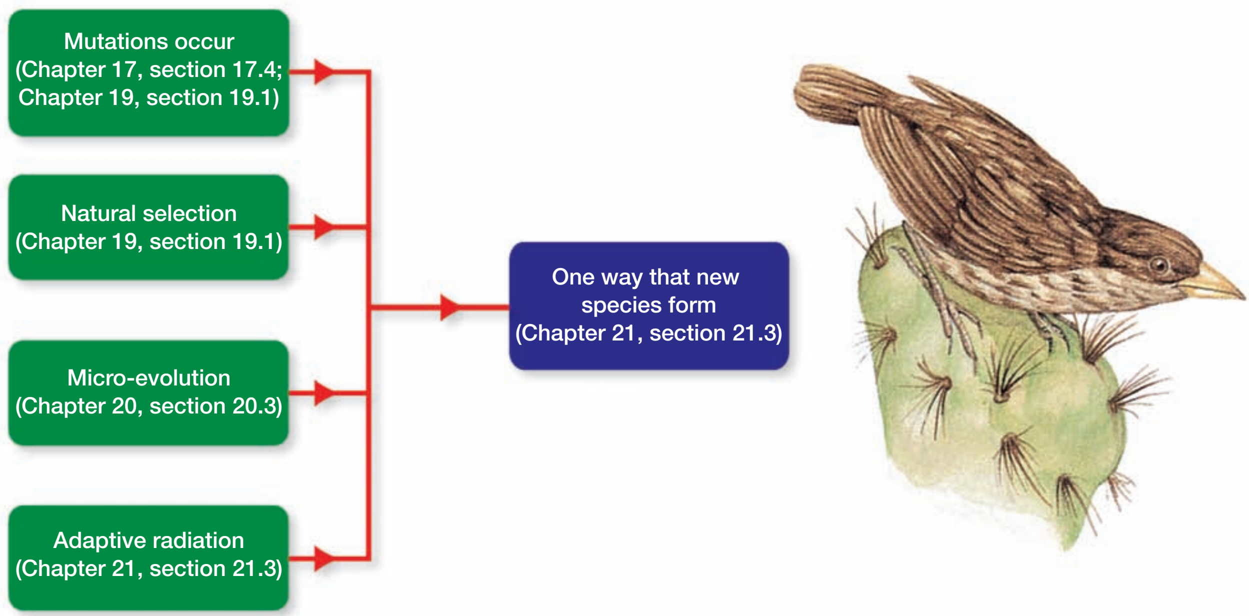
Today only two species of elephants exist — the African elephant and the Asian elephant. The mammoth became extinct only about 5000 years ago. These three elephant species were thought to evolve from an ancestral species, *Primelephas*, that lived about five million years ago.

You Try It

1. Using library and/or Internet resources, investigate the evolutionary history of elephants.
2. Does the evolutionary history of elephants provide better support to the idea of punctuated equilibrium or to the idea of gradualism? Explain your answer.
3. Explain the role of the environment in the pace of speciation.
4. In *Darwin's Ghost: The Origin of Species Updated*, Steve Jones wrote, "When one referee in nature's race is used to a stopwatch and the other to Big Ben, disputes are to be expected. An instant to a paleontologist may appear an infinity to those who study life today." Explain.



CONCEPT ORGANIZER One Way That New Species Are Formed



Individuals from a species of South American finch found their way to the Galápagos Islands, and some survived in their new environment. As these birds foraged on the islands, their ability to survive the environmental conditions of their surroundings resulted in some individuals surviving and reproducing. (Mutations ensure that the genetic make-up of each individual in a species is slightly varied.) Those producing offspring passed on the characteristics that enabled them to survive in the new environment. Through natural selection, the descendants of the ancestral population of finches began to change. Over time, new species arose. As well, as the finches moved to different islands the populations changed further through adaptive radiation.

SECTION REVIEW

1. Shoppers generally prefer food without any blemishes or markings. To achieve this perfect-looking produce, farmers often have to use pesticides. Explain the role that shoppers play in the evolution of insect "pests."
2. If you have ever been given an antibiotic, your doctor probably told you to finish taking all of the medication, even if you were starting to feel better. Explain why this is necessary.
3. There are no indigenous species (that is, no species that are native only to the area) in the Florida Keys, a group of islands close to the U.S. mainland. In contrast, there are a large number of indigenous species in the Hawaiian Islands. Why do you think this is so? Explain your answer based on your understanding of speciation and adaptive radiation.
4. You are asked to catalogue the species of birds living in a remote area that has never been visited by biologists before. What criteria could you use to determine whether the individual birds you observe or collect are of the same or different species?
5. Explain why archipelagos are sometimes referred to as living laboratories.
6. Explain the difference between allopatric and sympatric speciation.
7. Use a diagram and point-form notes to contrast the ideas of gradualism and punctuated equilibrium.
8. Why is rapid evolutionary change more likely to occur in small populations?
9. Describe adaptive radiation as a form of divergent evolution.
10. Colchicine is a chemical that can be used to induce polyploidy. How might plant breeders use such a chemical?

21.4 The Origins of Life on Earth

OUTCOMES

- **Describe the evidence and arguments relating to the origins and development of life on Earth, including the Oparin-Haldane theory, the Miller-Urey theory, the heterotroph hypothesis, and the Serial Endosymbiosis theory.**

Scientists have identified and classified some 1 400 000 species of life on Earth. Many species living have yet to be discovered — it is estimated that the total number of species may be closer to 30 000 000! In the first part of this chapter, you learned how species form through evolution. Yet how did the earliest species develop? How did life begin on our planet in the first place?

Several different explanations for the origins of life on Earth have been put forward. When offering theories and hypotheses concerning the origins of life on Earth, we are speculating: we do not know, and we may never find out exactly how life originated. The best we can do is to propose a possible pathway that makes logical sense, and that takes all available evidence into account.

It is important to realize that science, and particularly this area of science, is not concerned with proving or disproving the existence of God or any other supernatural force. Science is concerned only with what can be observed in nature. Supernatural forces are by definition outside the realm of nature, and therefore science takes no stand on whether there is a God. (Individual scientists, of course, often take very strong stands on this issue.) Whether or not an intelligent force or agent was involved in the formation of life on Earth, this should not affect scientific theories, which are developed by examining the evidence in nature. There are several different theories concerning the origins and development of life on Earth.

Chemical Evolution

The most common scientific theory on the origin of life is called **chemical evolution**. In the 1930s, the Russian scientist Aleksander Oparin and the British scientist John Haldane hypothesized that organic compounds, the building blocks of life, could form spontaneously from the simple inorganic compounds present on the surface of the early Earth.

According to the Oparin-Haldane theory, the early Earth had a *reducing atmosphere* containing little or no oxygen and plenty of hydrogen, ammonia, methane, and water vapour. These gases condensed to form pools (the "primordial soup") on the surface of the Earth. Energy such as lighting and ultraviolet radiation led to the spontaneous development of organic compounds from the simple compounds present in the "soup." Oparin believed that these organic compounds combined and evolved over time, eventually leading to the emergence of an early life form.

In 1953, Stanley Miller, working under Harold Urey, designed an experiment to test the Oparin-Haldane theory. Miller prepared a system, shown in Figure 21.21, that contained a reducing atmosphere similar to that of the early Earth. It contained methane, ammonia, hydrogen, and water vapour. The system circulated the gases from the liquid to the gaseous state, as they would be circulated on Earth's surface. The system also included electric sparks as an energy source, simulating lightning. After running the system for a week, Miller collected

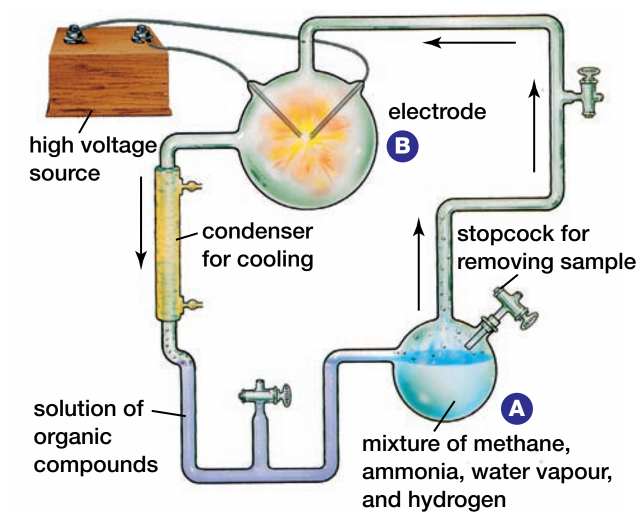


Figure 21.21 This experimental equipment shows how the experiment of Miller and Urey worked. The solution in A, containing ammonia, methane, and hydrogen was circulated as steam, and subjected to electric sparks simulating lightning in B. It is now recognized that the starting conditions Miller and Urey used were probably not as close to the conditions on early Earth as was thought. However, their experiment stands as an indication of how the "molecules of life" might have evolved.

and analyzed the liquid that was produced. He found that several organic compounds were present, including some amino acids. This was an exciting discovery, since amino acids are the building blocks of proteins, which make up the structure of most living things.

Today, scientists think that Earth's atmosphere was only slightly reducing, and was made of carbon dioxide, nitrogen, water vapour, and small amounts of hydrogen and carbon monoxide. Further experiments have shown that organic molecules such as amino acids, nucleotides, and sugars can still develop under these conditions.

Of course, showing that non-living organic compounds could have formed spontaneously still does not explain how life started on Earth. Reproduction is an essential characteristic of living things. Before life could exist, scientists believe that self-replicating molecules must have developed. Scientists diverge on this point, and have identified at least three ways this might have happened:

- amino acids might have polymerized spontaneously to form a special kind of self-replicating protein (it has been shown that dried and heated amino acids can polymerize to form proteins; these proteins cannot self-replicate, however)
- RNA might have developed on its own (under special conditions, RNA has been shown to have the ability to self-replicate); this is called the "RNA world" theory
- both proteins and RNA might have developed at the same time, while being supported by a structure of clay (this would result in a combination of molecules much closer to the contents of a real cell, but it is statistically much less likely)

Either before or after the development of self-replicating macromolecules such as proteins and/or RNA, an external covering (the prototype of the cell membrane) is thought to have developed, which surrounded and protected these fragile organic molecules. This combination of an encapsulating covering and the self-replicating organic macromolecules is called a *protocell*. Scientists believe that the protocell continued to evolve by natural selection, becoming the first living cell.

Other Explanations for Life on Earth

The step from a non-living group of organic molecules to a living cell is an enormous one. In fact, this step has been described as being as large as the evolutionary step from a one-celled organism to a human. (The British astronomer Fred Hoyle estimated the odds of life originating by chance as one in $10^{40\,000}$!) Although many scientists believe these odds are exaggerated, the probability is still heavily weighted against life happening by chance as described in the theory of chemical evolution. In addition, the complexity of life on Earth is thought by some to be beyond the scope of evolution through natural selection and chance. As a result, a minority of scientists support other theories on the origin and development of life on Earth.

- The *panspermia theory* suggests that life originated elsewhere in the universe, and then migrated to our planet. Supporters of this theory disagree on whether life was brought to our planet by intelligent beings (as suggested by Frances Crick, who discovered the structure of DNA), or whether it migrated by chance (for example, living bacterial cells might have travelled on meteorites that hit Earth).

Figure 21.22 Could life on Earth have originated from outer space, and travelled here on meteorites or by other methods?

- The *Gaia theory*, proposed by James Lovelock, views Earth as a living "superorganism," named Gaia, which is maintained and regulated by life on its surface. According to this theory, Earth has systems in place that keep a dynamic balance and regulate the atmosphere and temperature. These systems can be compared to the systems within a living organism that maintain homeostasis. The Gaia theory relies on the theory of chemical evolution to explain the origin of life, and then proposes that Gaia came "alive" and began to regulate Earth processes as life in the form of bacteria multiplied on her surface.

Figure 12.23 The Gaia theory understands life on Earth as many evolving parts, some of them microscopic, which make up a macroscopic organism — Earth itself. How does this relate to Serial Endosymbiosis Theory?

- The *intelligent design theory* suggests that life and the mechanisms of life are too complex to have evolved by chance. According to this theory, the generation and evolution of life must have been directed by an unidentified supernatural intelligence. Supporters of the intelligent design theory include Michael Behe and William Dembski.

Early Forms of Life

Assuming that the first living cell did form on Earth, and did not migrate to our planet, what did it look like, and how did it evolve further? Scientists generally believe that the first cell was a simple prokaryotic bacterium, with no nucleus or organelles. According to the **heterotroph hypothesis**, these first organisms were *heterotrophs*, meaning that they did not manufacture their own food. Instead, they fed on the plentiful organic compounds in the primordial soup.

As these organic compounds were used up, the early bacteria probably consumed each other. Eventually, the increasing lack of food led to the evolution of *autotrophs*, simple bacteria that could manufacture their own food through photosynthesis. As autotrophs carried out photosynthesis, oxygen was produced and began to accumulate in the atmosphere. At around this point, Earth's atmosphere changed from a reducing atmosphere (containing high proportions of hydrogen, both free and in compounds such as methane and ammonia) to an *oxidizing atmosphere* (an atmosphere with a high proportion of oxygen).

Up to this point, the early bacteria were anaerobic (not dependent on oxygen). The accumulation of oxygen in the atmosphere led to the development of yet another type of early organism: the first aerobic (oxygen-breathing) bacteria.

Some scientists believe that these and other early bacteria continued to evolve by Darwinian natural selection, leading to the gradual emergence of the first eukaryotic cell, which contained a nucleus. Over billions of years, parts of the nucleus in a eukaryotic cell could have pinched off to form useful organelles such as mitochondria and chloroplasts.

Symbiogenesis

A new theory that explains the development of the eukaryotic cell has gained considerable credibility among scientists. As biologist Lynn Margulis knew, the mitochondria and chloroplasts in a eukaryotic cell both have their own genetic material, independent of the cell's nucleus. She was also aware that *symbiosis*, the living together of different organisms, is very common on Earth. For example, your stomach and intestines contain millions of bacterial cells that help you digest food.

Margulis proposed that the development of the eukaryotic cell and its organelles could be a result of **symbiogenesis**, or the development of a new species through symbiosis. This theory is known as the **Serial Endosymbiosis Theory (SET)**. For example, as one step in SET, Margulis proposed that, millions of years ago, an anaerobic bacterium swallowed but did not digest an oxygen-breathing bacterium. The "host" bacterium gained the benefit of being able to breathe oxygen, while the "guest" was protected from the environment by remaining inside the host. Together, the members of this symbiotic partnership had a better chance of survival. Over time, the guest bacterium developed into the mitochondrion. Similarly, Margulis postulated that chloroplasts were at one time free-living photosynthesizing bacteria that had been swallowed but not digested by other bacteria. In this relationship, the host cell gained a food source as the guest performed photosynthesis.

As shown in Table 21.1, theories concerning life on Earth are still under debate. Scientists are continually searching for new evidence to obtain a better understanding of how life originated on Earth.

Table 21.1

Theory	Pros	Cons
Chemical evolution	■ is backed up by evidence from the Miller-Urey experiment, and by further experiments that have shown that all the organic molecules required for life (amino acids, sugars, nucleotides) could have formed on the early Earth ■ experiments have also shown how random proteins can form from amino acids ■ experiments have shown that some forms of RNA can be self-replicating	■ although it seems reasonable that non-living communities of organic molecules could assemble in this way, the jump from non-living organic compounds to a living, self-replicating cell is an enormous one, and is not well understood ■ the odds against life happening in this way have been calculated by some statisticians as being almost impossible within the amount of time estimated for it to have happened (about 1 billion years)
SET	■ explains the fact that mitochondria and chloroplasts have their own genetic material, as would be predicted if they were originally bacteria ■ provides a more statistically reasonable explanation (as compared to natural selection by mutation and chance) of how complex organisms and systems may have developed	■ Margulis' full theory includes the development of cilia through symbiogenesis; she also believes that most large evolutionary changes occur as a result of symbiosis. These suggestions are not accepted by many scientists, since they go against the commonly accepted Darwinian evolution through natural selection.
Panspermia	■ takes into account the large odds against life occurring by chance	■ life must have originated at some point in the universe; does not address this question adequately
Gaia	■ explains the origins of the complex systems on Earth that provide checks and balances, keeping Earth's temperature and atmosphere relatively constant	■ seems to imply *teleology*, or "forecasting" and "planning" on the part of organisms ■ although the regulation of systems on Earth exists, it is only partial, unlike that claimed by the Gaia theory
Intelligent Design (I.D.)	■ takes into account the large odds against life occurring by chance ■ accounts for the existence of enormously complex structures such as the human eye	■ perceived as a religion-based theory, and not counted as serious science by most scientists, since it is too vague, and can cross any gaps in evidence by appealing to "intelligent design" ■ is more concerned with using evidence to back up a preconceived idea or belief, rather than looking at the scientific evidence and building a theory from it

SECTION REVIEW

1. Explain how Stanley Miller's experiment supported the Oparin-Haldane theory.
2. Describe the theory of chemical evolution, including arguments both for and against this theory.
3. The Serial Endosymbiosis Theory suggests that symbiosis was a driving force in the evolution of eukaryotic cells. To which type of symbiosis was Margulis referring? Explain how you came to this conclusion.
4. Why must self-replicating molecules have developed before life could have?
5. Explain how the discovery of both mitochondrial and chloroplast RNA support the Serial Endosymbiosis Theory.
6. Choose another visual design, such as a concept map or Venn diagram, to represent the information in Table 21.1 and create a poster of your design.
7. Lynn Margulis, founder of the Serial Endosymbiosis Theory, has collaborated with James Lovelock, founder of the Gaia theory, for the last twenty-five years. Do research, either in your library or on the Internet, to explore how their theories relate to each other's.
8. What is your personal opinion on the origins of life? On what do you base your arguments or beliefs, and what scientific evidence is needed to support your theory? What scientific evidence might change your opinion?

Chapter Summary

Briefly explain each of the following points.

- Through natural selection, organisms become adapted to their immediate environment over a period of time. (21.1)
- While adaptations are products of evolution by natural selection, variations within a species are the raw material upon which natural selection acts. (21.1)
- Adaptations can be broadly classified as structural (or anatomical), physiological, or behavioural. (21.1)
- A species consists of a reproductively compatible population. (21.2)
- Pre-zygotic (or pre-fertilization) barriers either impede mating between species or prevent fertilization of the ova; post-zygotic barriers prevent hybrid zygotes from developing into normal, fertile individuals. (21.2)
- Alternative concepts recognize some degree of genetic exchange between species. (21.2)
- Sympatric speciation occurs when populations become reproductively isolated without geographical isolation. Allopatric speciation occurs when populations are geographically isolated. (21.3)
- The process of adaptive radiation occurs when there is diversification of a common ancestor into a variety of species. (21.3)
- In convergent evolution, similar traits arise because each species has independently adapted to similar environmental conditions. In divergent evolution, a species that was once similar to an ancestral species diverges or becomes increasingly distinct. (21.3)
- In coevolution, organisms that are closely linked to other species have evolved by responding to the changes in one another. (21.3)
- Two hypotheses that describe the pace of evolution are gradualism and punctuated equilibrium. (21.3)
- The theory of chemical evolution has empirical support to explain the origins of life on Earth. (21.4)
- Serial Endosymbiosis Theory provides a statistically plausible explanation for the development of life, although it is not supported by empirical evidence. (21.4)
- Other explanations for the origins and development of life on Earth include the Gaia theory, the panspermia theory, and the heterotroph hypothesis. (21.4)

Language of Biology

Write a sentence including each of the following words or terms. Use any six terms in a concept map to show your understanding of how they are related.

- adaptation
- exaptation
- structural adaptation
- mimicry
- cryptic coloration
- physiological adaptation
- behavioural adaptation
- biological species
- transformation
- divergence
- speciation
- geographical barrier
- biological barrier
- pre-zygotic barrier
- post-zygotic barrier
- morphological species concept
- sympatric speciation
- polyploidy
- allopatric speciation
- adaptive radiation
- mass extinction
- divergent evolution
- convergent evolution
- coevolution
- gradualism
- punctuated equilibrium
- chemical evolution
- heterotroph hypothesis
- symbiogenesis
- Serial Endosymbiosis Theory (SET)

UNDERSTANDING CONCEPTS

1. Explain the differences between adaptations and variations.
2. Describe exaptation and provide an example.
3. Distinguish between structural, behavioural, and physiological adaptations. Give an example of each.
4. Explain why natural selection does not achieve perfection in organisms.
5. In order for species to remain distinct, they must remain reproductively isolated. Describe a pre-zygotic barrier and a post-zygotic barrier to reproduction.
6. Define and provide an example of:
   (a) habitat isolation
   (b) mechanical isolation
   (c) gametic isolation
7. What are the limitations to defining species using only the concept of biological species?
8. Describe two other ways to define species. Why are these definitions used?

9. Hedgehogs and echidnas both have spiny skins, yet they live in very different environments. Is this an example of convergent or divergent evolution? Explain your answer.

10. Distinguish between sympatric and allopatric speciation.

11. Explain why it is more likely for small populations that have become isolated from a parent population to become a new species than it is for a large population to become a new species.

12. Describe the relationship between adaptive radiation, mass extinction events, and punctuated equilibrium.

13. The coevolution of predator and prey or parasite and host are sometimes portrayed as being an "arms race." Explain why this description is used.

14. Why is it always imperative to consider time scales when discussing evolution, gradualism, and punctuated equilibrium?

15. Suppose bird books published years ago list two birds as different species. However, biologists applying the biological species concept later realized that the two birds are actually the same species. What did the biologists learn that caused them to revise the categorization of these birds?

16. Hummingbird moths are night-flying insects that look similar to hummingbirds. Explain how these two organisms demonstrate the concept of convergent evolution.

17. What are some of the factors that prevent hybrids of two species from developing viable offspring?

18. In both plants and animals, successful matings may occur between different species. In those matings, what are some reasons that gametes are prevented from fusing?

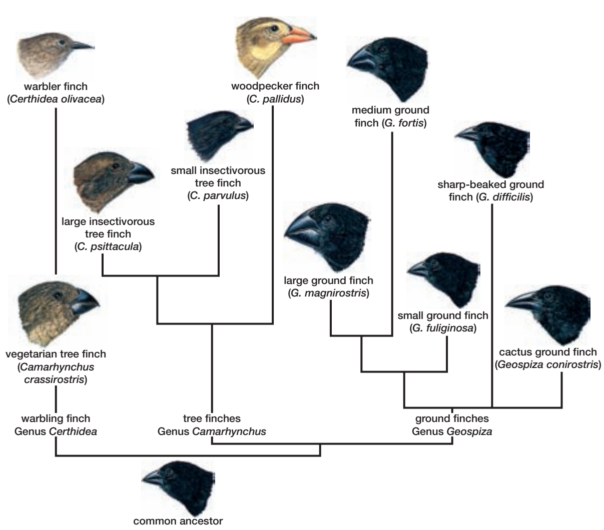
19. Contrast the basic ideas of gradualism and punctuated equilibrium with regard to speciation.

20. Explain how the Earth's atmosphere may have changed over time, and what led to these changes. What effect did this change have on life on Earth?

21. What experimental evidence supports the Oparin-Haldane theory? What flaws are there with this evidence?

INQUIRY

22. Interpret the evolutionary history of 10 species of finch in the Galápagos Islands using this phylogenetic tree.



23. Scientists compare differences in protein amino-acid sequences to determine the relationships among organisms. Compare the short sequences of amino acids of these proteins to determine evolutionary relationships.

Baboon	Chimp	Lemur	Human
ASN	SER	ALA	SER
THR	THR	THR	THR
THR	ALA	SER	ALA
GLY	GLY	GLY	GLY
ASP	ASP	GLU	ASP
GLU	GLU	LYS	GLU
VAL	VAL	VAL	VAL
ASP	GLU	GLU	GLU
ASP	ASP	ASP	ASP
SER	THR	SER	THR
PRO	PRO	PRO	PRO
GLY	GLY	GLY	GLY
GLY	GLY	SER	GLY
ASN	ALA	HIS	ALA
ASN	ASN	ASN	ASN

(a) Calculate how many amino acids in the baboon, chimp, and lemur differ from those in the human sequence. Calculate the percentage differences as well.

(b) Which primate appears to be most closely related to humans? Which appears to be the least closely related?

(c) Construct a phylogenetic tree that shows the relationships among the primates in this table.

24. What tools and techniques can biologists use to determine whether two populations that look quite similar are one species or two?

COMMUNICATING

25. Draw an illustrated time line or flowchart that shows how a complex adaptation such as an eye might have evolved.

26. Use a concept organizer to illustrate the relationships between variations, adaptations, and natural selection.

27. Use a diagram to show the two general pathways that can lead to the formation of new species. Indicate which pathway promotes biological diversity.

28. Use a labelled diagram to show how polyploidy can lead to speciation.

29. You have been asked by a group of health-care professionals to write a short newspaper article explaining to the general public the dangers of misusing antibiotics. Prepare this article and include references to evolution.

30. This animal was called *Ichthyostega*, a tetrapod that was one of the first amphibians with limbs efficient enough to crawl on land. Many of its characteristics were still quite fish-like. Explain how scientists might use the term "exaptation" when discussing this animal's ability to walk on land.

MAKING CONNECTIONS

31. Investigate how plant breeders use the chromosomal condition of polyploidy in their work.

32. There are many antibiotic soaps and sprays currently available over-the-counter. Why might an evolutionary biologist suggest that you avoid buying (or restrict your use of) these products?

33. Today, individuals and populations of the giant panda are being isolated in many small reserves in China. What are the genetic implications of having so many small reserves rather than one large reserve? If the giant panda were to become extinct in the wild, what might some of the economic, political, and social implications be for China?

34. In Canada, individuals and populations of grizzly bear are being isolated as human populations expand their use of the land previously used by the bears. If the grizzly bear were to become extinct in the wild, what might some of the economic, political, and social implications be for Canada? How might the wildlife corridors (designed to help animals cross busy highways in Canada's mountain parks safely) help the situation?

35. In the past, scientists considered gorillas to be the closest primate relative to humans. How have new technologies contributed to our changing phylogenetic tree?

36. As humans have populated remote islands throughout the world, some people have been isolated from other populations for long periods of time. Despite the geographical barrier, speciation has not occurred. Explain.

37. Some scientists, such as Michael Behe and William Dembski, argue that life on Earth is too complex to have evolved by chance. They posit that the origins of life had to have been directed by a supernatural intelligence. Do their arguments contradict other explanations for life on Earth, or can viewpoints which seem contradictory be reconciled?

UNIT 7 REVIEW

UNDERSTANDING CONCEPTS

True/False

In your notebook, indicate whether each statement is true or false. Correct each false statement.

1. If evolution occurs, we would expect different biogeographical regions with similar environments to all contain the same mix of plants and animals.
2. Absolute dating uses the unique properties of radioactive isotopes to date fossils.
3. Artificial selection is not an evolutionary mechanism.
4. Darwin was the only scientist of his time to formulate the theory of natural selection.
5. The Hardy-Weinberg principle states that in large populations, genotype proportions will vary considerably from generation to generation.
6. The effects of mutations on the evolutionary success of organisms are always unfavourable.
7. Exaptations are evolutionary adaptations of one species that are mimicked by a competing species.
8. Hybrid breakdown is a post-zygotic barrier.
9. In divergent evolution, two or more species grow closer together in behaviour or other traits.
10. The theory of punctuated equilibrium is accepted as the correct explanation for the pace of evolutionary change.

Multiple Choice

In your notebook, write the letter of the best answer for each of the following questions.

11. The fossil record provides direct evidence for common descent because you can
    - **(a)** see that types of fossils have changed over time
    - **(b)** sometimes find common ancestors
    - **(c)** trace the ancestry of a particular group
    - **(d)** sometimes find arrangements of bones similar in common ancestors
    - **(e)** all of the above
12. Assuming a Hardy-Weinberg equilibrium, 21% of a population is homozygous dominant, 50% is heterozygous, and 29% is homozygous recessive. What percentage of the next generation is predicted to be homozygous recessive?
    - **(a)** 21%
    - **(b)** 50%
    - **(c)** 29%
    - **(d)** 25%
    - **(e)** 42%
13. In a population of diploid individuals that is in Hardy-Weinberg equilibrium, the frequency of a dominant allele for a certain hereditary trait is 0.3. What percentage of individuals in the next generation would be expected to be homozygous for the dominant trait?
    - **(a)** 9%
    - **(b)** 14%
    - **(c)** 42%
    - **(d)** 49%
    - **(e)** 90%
14. From which of the following areas of study did Darwin and Wallace derive *most* of their evidence for evolution?
    - **(a)** mechanisms of heredity
    - **(b)** comparing the anatomy of different species
    - **(c)** geographic distribution of organisms
    - **(d)** embryology
    - **(e)** animal behaviour
15. Genetic equilibrium occurs when
    - **(a)** populations are small
    - **(b)** there is no immigration to or emigration from a population
    - **(c)** natural selection acts on particular phenotypes
    - **(d)** mutations arise in a population
    - **(e)** individuals that are related or live in close proximity to one another mate
16. A human population has a higher-than-usual percentage of individuals with a genetic disease. The most likely explanation is
    - **(a)** gene flow
    - **(b)** stabilizing selection
    - **(c)** directional selection
    - **(d)** genetic drift
    - **(e)** all of the above are possible
17. Which of these is/are necessary in order for natural selection to occur?
    - **(a)** variation
    - **(b)** differential success at reproduction
    - **(c)** inheritance of difference
    - **(d)** all of the above
    - **(e)** only (b) and (c)
18. Which of the following is a pre-zygotic barrier?
    - **(a)** habitat isolation
    - **(b)** temporal isolation
    - **(c)** hybrid inviability
    - **(d)** hybrid sterility
    - **(e)** (a) and (b)

19. The many species of Galápagos finches were each adapted to eating different foods. This is an example of
   (a) gene flow
   (b) adaptive radiation
   (c) sympatric speciation
   (d) all of the above
   (e) (b) and (c)

20. The Oparin-Haldane Theory posited that
   (a) life on Earth originated from outer space
   (b) the odds of life on Earth forming by chance are $10^{40\,000}$
   (c) life on Earth cannot be explained scientifically
   (d) early Earth had a reducing atmosphere
   (e) (a) and (d)

Short Answer

In your notebook, write a sentence or a short paragraph to answer each of the following questions.

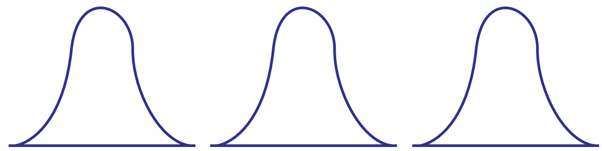
21. Explain the difference between a fact and a theory. Give an example of each.
22. Explain the difference between analogous structures and homologous structures.
23. Distinguish between mutations and variations.
24. Give an example of each of the following types of mutations: one that would be beneficial to an individual; one that would be detrimental to an individual; and one that would have no effect on an individual.
25. "Evolution can occur without new species arising." Do you agree with this statement? Explain your answer.
26. Explain why diversity within a population is necessary for evolution.
27. Artificial selection can sometimes perpetuate traits that are not desired, such as respiratory problems in some breeds of dogs. Does the same thing happen in natural selection? Explain your answer.
28. Does the process of natural selection always improve the design of organisms? Explain your answer.
29. How might (a) Lamarck and (b) Darwin have explained the elephant's long trunk?
30. Insects reproduce fast enough that they could quickly populate and "overrun" Earth. Explain why this does not occur. How was this significant to Wallace and Darwin?
31. Explain how the ability to sequence DNA furthered the understanding of evolution.
32. Distinguish between macro-evolution and micro-evolution.
33. How do heterozygous individuals and polymorphic populations contribute to variation within a population?
34. In the past, ideas of natural selection have been used to justify injustice and prejudice. Explain why this is a scientifically incorrect use of the idea of natural selection.
35. Explain why the effects of genetic drift are more significant in small populations.
36. Outline the limitations to defining species purely on the basis of reproductive isolation.
37. Distinguish between allopatric and sympatric speciation.
38. Describe how adaptive radiation helps colonize volcanic islands.
39. Describe an example of (a) convergent evolution and (b) coevolution.
40. Give an example of (a) structural adaptation, (b) physiological adaptation, and (c) behavioural adaptation.
41. Explain why most species would not be in Hardy-Weinberg equilibrium.
42. Explain why the evolution of resistance to antibiotics in bacteria is an example of directional selection.
43. If a human population has a higher-than-usual percentage of individuals with a genetic disease, is the most likely explanation gene flow or genetic drift? Explain your answer.
44. In a sample taken for radiocarbon dating, tests determine that 1.56% of the original carbon-14 remains. How old is the sample?
45. How does the GAIA theory view the origins and continuance of life on Earth?
46. How does the theory of symbiogenesis relate to evolutionary theory?

INQUIRY

47. Madagascar separated from the African continent about 50 million years ago. The Canary Islands are volcanic in origin and are about 10 to 15 million years old. Discuss the types of organisms you would expect to find on these islands and why this information supports the theory of evolution.

48. Calculate the genetic structure of a population of flowers in which 150 individuals are homozygous dominant, 130 are heterozygous, and 58 are homozygous recessive. Assuming that the allele for pink is dominant to the allele for white, describe the population's phenotype as well.

49. The following diagrams represent a distribution of genotypes in a population. Copy the diagrams into your notebook and draw and label: (a) another line to show that disruptive selection has occurred; (b) another line to show that stabilizing selection has occurred; and (c) another line to show that directional selection has occurred.



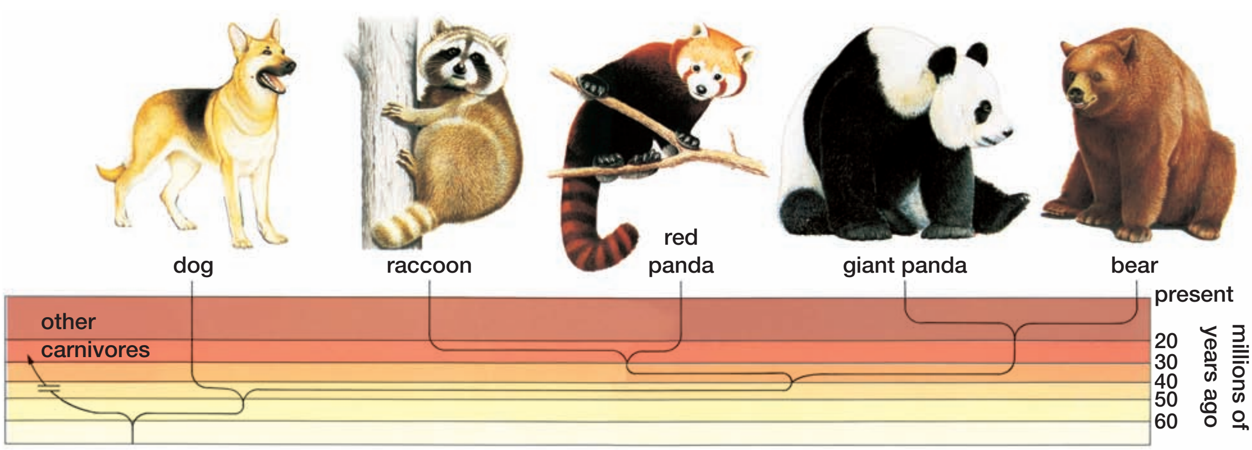
50. You are an investigator studying the frequency of certain traits in a population. You find that 73% of the individuals in the population has freckles. The presence of freckles is controlled by a dominant allele. Calculate the genotype and allele frequencies for the population.

51. Are pandas more closely related to bears or raccoons? This has been a long-standing question for biologists. A biologist determined in the 1950s that, based on behavioural traits, red pandas and giant pandas were closely related to each other and that both more closely resemble bears than raccoons. However, in the 1980s, molecule analysis (including DNA comparison) led to the determination of the evolutionary characteristics shown below. Use this illustration to answer the following questions.

(a) Is the raccoon or the bear more closely related to the red panda?

(b) Is the raccoon or the bear more closely related to the giant panda?

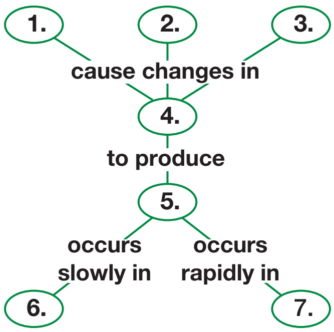
(c) Approximately how long ago did raccoons and bears split into two lineages?



Is the panda a bear or a raccoon?

COMMUNICATING

52. Complete this concept map by using the following vocabulary terms: frequency of alleles, speciation, gradualism, natural selection, geographical isolation, reproductive isolation, punctuated equilibrium.



53. Create a time line or use another graphic organizer to outline the major events and ideas that have led to the current theory of evolution.

54. Use a labelled diagram to show natural selection at work in a population as environmental conditions change.

55. A person tells you that evolution is a hoax because it is "just a theory." Explain to the person what a theory means in a scientific sense and provide five facts that support the theory of evolution.

56. There is concern within a community about the outbreak of a dangerous species of bacterium. As a precaution, people begin to purchase and administer their own antibiotics, without the advice of physicians. Prepare a communications brief that explains why this practice could worsen the situation.

57. You are organizing a debate on gradualism vs. punctuated equilibrium. Develop an information brief for each debating team.

MAKING CONNECTIONS

58. You discover the remains of an extinct animal that has a small amount of brain tissue preserved in its skull. Outline the scientific techniques you might use to learn more about the evolutionary history of this animal.

59. You are a biologist heading a team of scientists trying to bring whooping cranes back from the brink of extinction. At its smallest, the population had six to eight individuals. Develop a brief presentation that explains to funding officials why this population is still in peril even though it now numbers over 200. Outline the steps you would take to help save this population.

60. A scientist observes that members of a particular plant species are shorter at the top of a mountain than at the bottom. Give an explanation based on natural selection.

61. Several articles published recently in a scientific journal call for the reduced use of antibiotics in the feed given to animals (such as chickens and cattle). Based on your understanding of coevolution, explain why scientists are calling for this change.

62. Explain why zoos exchange animals of one species. How does this benefit society? How does it benefit the environment? What are some of the economic issues?

63. You are a gardening expert who runs a local nursery. A gardener calls you and explains that she had an insect infestation in her garden. When she applied an insecticide, 99 percent of the insects were killed. However, when she applied the insecticide again six weeks later, only 50 percent of the insects were killed. How would you explain why the insecticide did not work as well the second time it was applied?

64. In Canada, Atlantic salmon are farmed on both the Pacific and Atlantic coasts. Some people are concerned about the introduction of domestic salmon to the oceans, fearing that Atlantic salmon that escape from fish farms might affect the genetics of wild salmon if they begin to interbreed and hybridize. Biologists point to the selectional forces that are at play in the two populations. Farmed salmon, for example, are artificially selected and bred for increased growth rate and larger size, among other characteristics. In populations of wild salmon, however, natural selection is at play. Describe the selectional forces that might affect wild salmon populations and note whether the type of selection in farmed and wild salmon populations is directional, stabilizing, or disruptive.