UNIT

7

Evolution

Unit Preview

In this Unit, you will discover

- the scientific evidence that supports the theory of evolution,
- the mechanisms that result in evolution, and
- how the science of evolution is related to current biological research.

Unit Contents

Dive into the water off one of Canada's coasts and you will be surrounded by a myriad of life. Life in the ocean, and in all habitats on Earth, is rich and varied. Species differ from one another, but individual members of a single species also differ. These sea stars are all the same species but they exhibit different colours. The diversity within a species can be obvious (such as variations in size or colour) or "hidden" (such as differences in DNA sequencing). This diversity is a cornerstone of evolutionary biology.

When *Hallucigenia* (inset photo) swam in the sea over 500 million years ago, there was a *greater* diversity of life forms than there is today. *Hallucigenia* was found in the Burgess Shale — a rich fossil bed in the Rocky Mountains in Yoho National Park, British Columbia. The fossils there provide a piece of the puzzle that has helped shape our current ideas about evolution — the process by which organisms alive today descended from ancient forms of life and have been modified over time. Using fossil evidence, observation of species over time, and modern techniques such as genetic analysis, scientists are adding to our understanding of life on Earth. How has life on Earth changed over the millennia? What are the mechanisms that give rise to new species? In this unit, you will explore the fascinating science of evolution. You will learn how early studies and observations of life shaped early theories of evolution. As well, you will see how new discoveries and scientific techniques and technologies contribute to our understanding of evolution.

Why did some species, such as *Hallucigenia*, become extinct, while others survived?

CHAPTER 19

Introducing Evolution

Reflecting Questions

- What ideas and observations helped develop the current theory of evolution?
- What is some of the evidence that helps explain evolution?
- What are the roles of genetics and the environment in evolution?

Living organisms are constantly faced with challenges in their environment. Severe weather, drought, famine, and competition for food and space are all struggles living organisms may or may not overcome. Severe weather such as snowstorms and freezing temperatures are some of the challenges that animals, such as the wolf, face in northern environments. Animals that survive have the opportunity to reproduce and pass along to their offspring the traits that helped them survive. The diversity within species and the interactions of organisms with their environment help explain how populations can change over time and why some organisms survive while others become extinct.

The millions of species on Earth today are only a small fraction of the species that have ever lived. In fact, it is estimated that 99 percent of all species that have ever lived are now extinct. While some of the fossilized animals are ancestors of animals that are common today, others have long been extinct and are unlike anything in our modern oceans. Fossils help to show that there was a *greater* diversity of basic animal forms half a billion years ago than there is today. The animals like the fossils unearthed in the Burgess Shale lived during the Cambrian Explosion (over 500 million years ago), a time when there was a stunning burst of biodiversity that is now recorded in the fossil record.

What factors affect which organisms survive and pass on their genes to the next generation? How do environmental conditions affect survival and reproductive ability of organisms? Species diversity and environmental conditions are crucial factors when discussing evolution.

In this chapter, you will learn how changes in the environment and diversity within a *species* can result in changes in *populations* of particular species, and even the formation of new species. You will also learn how the early observations and ideas of naturalists and biologists helped provide a foundation for our current understanding of evolution.

Why is variation within a species necessary for evolution to occur?

Chapter Contents

19.1 Diversity of Life

OUTCOMES

- **Explain the process of adaptation of individual organisms to their environment.**
- **Analyze evolutionary mechanisms and their effects on biodiversity and extinction.**

The word "evolution" is commonly used in English but its meaning is often misunderstood or misused. In biology, **evolution** refers to the relative change in the characteristics of populations that occurs over successive generations. As you read through this unit, you will begin to better understand evolution and this definition will become clearer.

The grouse in Figure 19.1 lives in the boreal forest of northern Canada. Its brown, white, and black mottled feathers help it blend in with its environment. How do scientists explain that the grouse, and so many other living things, are so well suited to where they live? Recall what you have learned previously about adaptations and heredity. An **adaptation** is a particular structure, physiology, or behaviour that helps an organism survive and reproduce in a particular environment. Camouflage is one adaptation. The superb sense of smell of a shark or the bill shape of a shore bird are also adaptations.

Figure 19.1 This grouse is well-camouflaged in its forest environment. How could the coloration of *individuals* help the survival of a *population*?

Since adaptations help an organism survive, that organism will have a better chance of passing on to its offspring the particular characteristics that were advantageous to its survival. It is important to remember that although some differences between individuals are not outwardly evident, they do exist. For example, slight variations in bill size or shape, or mutations in a gene, are not immediately visible.

Meanwhile, environments can change: climates change over time, and droughts, floods, and famines occur. Thus, a characteristic that may not give an individual organism a particular advantage *now* may become critical for survival *later* if the environment inhabited by that species changes. This was demonstrated beautifully in the story of the English peppered moth.

The Peppered Moth Story

The story of the English peppered moth, *Biston betularia*, is often cited as an example of how the proportions of some inherited characteristics in a population change in response to changes in the environment. The peppered moth has two colour variations: greyish-white flecked with black dots (that resemble pepper) and black (see Figure 19.2 on page 645). In the past, the black variety was extremely rare. The first known black moth was caught in 1848 by lepidopterist R.S. Edleston. At that time, it was estimated that black moths made up less than two percent of the peppered moth population near Manchester, England. Yet 50 years later, in 1898, 95 percent of the moths in Manchester were of the black type. In rural areas, however, black moths were less frequent. What caused the sudden increase of black moths in Manchester? The answer lies in the behaviour and genetic makeup of the moths *and* the environment in which they lived.

Peppered moths are active at night. During the day, when they rest on the trunks of trees, they are

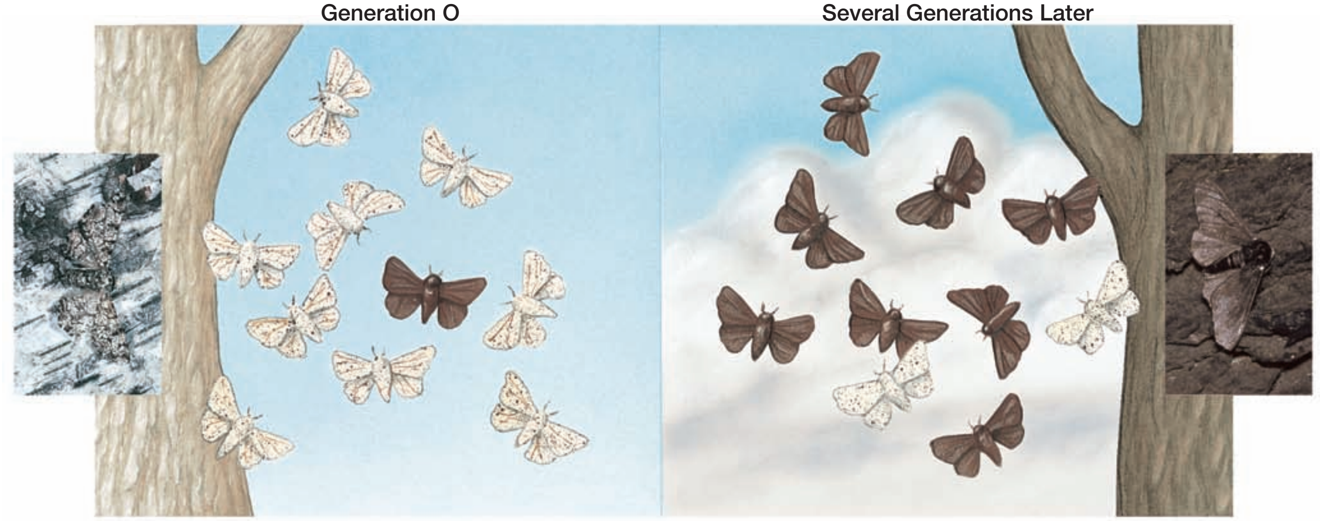


Figure 19.2 The frequency of flecked and black moths in this population of peppered moths changed in response to changes in the environment.

potential prey for birds. Until the mid-nineteenth century, the flecked moths in Manchester were camouflaged when they rested against the light-coloured lichens on tree trunks. The black moths, however, were easily seen and therefore easily preyed upon. The 50 years in which the black moths gradually became much more common in Manchester coincided with the Industrial Revolution in England. The air pollution from all the new factories killed the lichens, and soot began to cover Manchester's trees. As a result, the flecked moths were seen and eaten by birds and more black moths survived long enough to reproduce and pass on their genes to their offspring. Figure 19.2 shows how the peppered moth population evolved — that is, changed over the course of several generations.

The difference between the flecked and black forms of the peppered moth is caused by a single

THINKING LAB

Changes in Peppered Moth Populations

Background

The peppered moth story shows how genetic variety within a species can result in changes in the characteristics of a population when the environment changes. Since insects have a relatively short life cycle, this shift can happen quite quickly. In the 1950s, English biologist H.B. Kettlewell studied the camouflage adaptations in a population of flecked and black peppered moths.

Kettlewell raised over 3000 caterpillars to provide the adult moths. In a series of trials in the country and the city, he released and recaptured the moths. The number of moths recaptured in each trial indicated how well the moths survived in the environment.

You Try It

1. Examine the table on the right. Calculate the percentage of moths recaptured in each experiment.
2. Explain the differences in survival rates in the unpolluted and polluted environments.
3. Based on this lab, the information that has been presented so far in this chapter, and your understanding of genetics and evolution, discuss the following statements in a small group: Genes mutate. Individuals are selected. Populations evolve.
4. Discuss any other factors that may have influenced data in this study and the conclusions based on these data.

Numbers of peppered moths released and recaptured in polluted and unpolluted areas in England

Location		Number of flecked moths	Number of dark moths
Dorset (unpolluted)	released	496	488
	recaptured	62	34
Birmingham (polluted)	released	137	493
	recaptured	18	136

gene. Before the Industrial Revolution, more flecked moths survived and therefore passed on the gene for flecked-colouring in the **gene pool**. A gene pool is the total of all the genes in a population at any one time. However, when air pollution increased, more black moths survived with each successive generation and the ratio of flecked and black moths in the population essentially reversed. It is important to understand that the ratio of flecked to black moths in the *population* changed over successive generations. Individual moths were not transformed from flecked to black. A population is the smallest unit that can evolve.

In the 1950s, England started to enact clean-air legislation and lichens began to grow on trees again. As you might predict, the frequency of flecked moths increased in industrial areas such as Manchester. In these areas, nine out of 10 peppered moths were black in 1959. By 1985, five out of 10 were black, and the number dropped to three out of 10 by 1989. It is estimated that by 2010 the black peppered moth will again be as rare in Manchester as it was before the Industrial Revolution.

BIO FACT

The records and collections of lepidopterists were used by biologists to trace the spread of the black variety of peppered moth across England. Since the black moths were initially extremely rare, they created a frenzy among collectors in the mid-nineteenth century. The subsequent increase in the number of black moths collected from certain areas allowed historians and biologists to track colour changes in the populations of peppered moths.

Revisiting the Definition of Evolution

The peppered moth story demonstrates how a gene pool shifted from a population in which a particular gene coded for one expression of the characteristic (light, flecked colouring) in most individuals to a population in which the gene coded for a different expression of the characteristic (black colouring) in most individuals. Although no new species was formed, this *is* an example of evolution because there was a change in the gene pool of the population over successive generations. *Any shift in a gene pool is also used to*

Investigation 19 • A

SKILL FOCUS

- Predicting
- Performing and recording
- Communicating results

Diversity Within a Species

You have learned how diversity (also called variability) within a species can help populations survive environmental changes. Diversity within a species can be monitored genetically, or it can be demonstrated by measuring individuals within a population. In this investigation, you will measure a particular characteristic in each of three populations to determine variability within each population.

Pre-lab Question

- What would be the evolutionary advantage to a plant of having a larger seed?

Problem

How can variability among individuals be measured?

Prediction

Predict whether measurements of a particular characteristic (for example, length of bean seed) in a population would be evenly distributed throughout a population or whether most individuals would be the same length, with only a few individuals being longer or shorter than the norm.

Materials

10 kidney beans
callipers
string
10 lima beans
ruler
graph paper

Procedure

Part A

1. Use the callipers to measure the length of each of the 10 kidney beans.
2. Record your measurements.
3. Pool your measurements with other students in the class so you have between 50 and 100 measurements.
4. Calculate the average length of this population of kidney beans and prepare a bar graph of the class data.

define evolution. In fact, many scientists consider such a shift to be the most accurate and specific definition of evolution. This idea will be discussed in more detail in Chapter 21.

Natural Selection

The story of the peppered moths is an example of **natural selection**. Natural selection is a process whereby the characteristics of a population of organisms change because individuals with certain heritable traits survive specific local environmental conditions and pass on their traits to their offspring. You will learn more about natural selection later in this unit. For natural selection to occur there must be diversity *within* a species. Look around your classroom. You are all the same species but clearly there is a great deal of variety among you and your classmates. Without the extensive variability within a population, there would be no possibility for selection to occur. In the populations of peppered moths, the moths that survived were *selected*. In other words, *they survived the change in the environment around them*, and thus could reproduce and pass on the genes that coded for black. *Individuals* did not change colours during their lifetime; rather, the *populations* shifted in colour over time. The environment exerts a **selective pressure** on a population. In other words, an environmental condition can *select for* certain characteristics of individuals and *select against* those of others.

Artificial Selection

In the peppered moth story, change occurred naturally in the population in response to changes in the environment. However, people have been artificially selecting organisms for particular traits for centuries. Artificial selection for desirable traits has resulted in plants that are disease-resistant, cows that produce more milk, and racehorses that run faster. In **artificial selection**, a plant or animal breeder selects individuals to breed for the desired characteristics he or she wishes to see in the next generation. Figure 19.3 on the next page shows some of the varieties of dogs that have been produced by artificial selection. As another example, a rose

Part B

1. Repeat the steps from Part A using lima beans.

Part C

1. Use the string to measure the length of your partner's forearm, from the crease inside the elbow to the wrist. Use the ruler to determine forearm length.
2. Record your data and pool your data with that of the rest of the class.

3. Calculate the average forearm length of students in your class and prepare a bar graph of the class data.

Post-lab Questions

1. How are your three graphs similar?
2. From your graphs, what can you conclude about the variability within a population? For example, is there a "typical" size, or is the distribution of individuals spread evenly from small to large?

Conclude and Apply

3. What advantage would large size have to a newly germinated seed? (Recall that a seed is stored food.)
4. What environmental pressures might favour small seeds?
5. Predict a situation (actual or imagined) in the environment in which having a longer forearm might be advantageous to a person's survival.

Exploring Further

6. Create a breeding strategy to favour the production of large seeds.

breeder could select the seeds from roses with a strong scent to produce generations of roses with an equally strong fragrance.

Artificial selection can also perpetuate characteristics that are not particularly desirable. For example, Pekinese and British bulldogs are bred for their flat faces, but this characteristic also results in severe respiratory problems. Hip dysplasia, a type of arthritis common in German shepherds, is also an unfortunate consequence of artificial selection.

Overhunting can result in future generations that have a higher proportion of individuals *without* the favourable trait. For example, in the 1970s and 1980s, between 10 and 20 percent of all wild elephants in Africa were being killed by ivory poachers each year. Since poachers preferred elephants with large tusks, elephants with smaller tusks were less likely to be killed. Elephants with no tusks were not shot at all. Since that period, elephant watchers and biologists have noticed more and more tuskless elephants in the areas that experienced the most intense poaching pressure.

The key difference between natural and artificial selection is that in natural selection, the environment plays the role that humans play in artificial selection. In natural selection, the environmental conditions determine which individuals in a population are most fit to survive in the current conditions. This, in turn, affects the proportion of genes among individuals of future populations because the genes from the surviving individuals are passed on to their offspring. When discussing natural selection and evolution, the word "fit" or "fitness" is often used. **Fitness** in this sense refers to how well an organism fits with its environment. A high degree of fitness means that an organism will survive and reproduce, thereby passing on its advantageous genes to its offspring.

Natural Selection Is Situational

It is important to note that natural selection does not anticipate change in the environment. Instead, natural selection is situational. It is essentially by chance that a trait that might at one time have no particular relevance to survival (for example, black coloration in moths) becomes the trait that helps a population survive. This trait then persists within a population in response to changes in the environment via subsequent inheritance of the trait by the offspring of survivors. Adaptations that are beneficial in one situation may be useless or detrimental in another. This has been demonstrated in the work of Peter and Rosemary Grant in their study of finches in the Galápagos Islands.

For over 20 years, the Grants have been studying medium ground finches (*Geospiza fortis*), one of the 13 species of finches in the Galápagos Islands.

Figure 19.3 All dogs are members of the same species, *Canis familiaris*, yet artificial selection has resulted in a wide variety of breeds.

These birds use their strong beaks to crush seeds, and tend to prefer small seeds that are produced in profusion during the wet years in the islands. Fewer small seeds are produced during dry years, and the Grants found that during these times the finches also have to eat larger seeds, which are harder to crush. As part of their study, the Grants measured the depth (dimension from top to bottom) of the finches' beaks. They found that the average beak depth in the population changes over the years. During droughts, the population's average beak depth increases. During wet periods, the average beak depth in the population decreases again. The Grants' study demonstrates a change in the finch population in response to the environmental conditions. During dry periods, birds with stronger (that is, slightly larger) beaks have an advantage because they are better able to crack large seeds. Since these birds have a feeding advantage, they survive in greater numbers and have greater potential to pass the gene for a larger beak on to their offspring.

This difference in ability to crack larger seeds within the finch population can only happen because there is variety within the population. As you found when you did the investigation on page 646, not all kidney beans are identical in length, nor are the forearms of all Grade 12 students. *It is the variety that is already present within a population that allows change to occur in response to local environmental conditions*. Natural selection acts like an editor; it only works with what is already present in a population.

The finches reproduce once a year. The Grants have been able to monitor morphological changes in the population only by measuring and monitoring the birds year after year as part of their multi-year study. In other organisms that reproduce more quickly, such as insects and bacteria, the change in a population in response to local environmental conditions can be observed in a much shorter time. How do you think natural selection is involved in insects becoming resistant to pesticides or in bacteria becoming resistant to antibiotics? This idea will be discussed further in subsequent chapters.

BIO FACT

As part of their study, the Grants needed to measure the force required to open seeds. Peter Grant designed a unique device with the help of an engineer from McGill University in Montréal. The "McGill nutcracker" looks like pliers with a scale attached. When a seed is squeezed with the pliers, a scale measures the force required to crack the seed.

SECTION REVIEW

1. Can individuals evolve? Explain your answer.
2. Give two definitions of evolution.
3. How are adaptations and evolution related to each other?
4. Describe how the study of peppered moths by Kettlewell demonstrates evolution in action.
5. Define the term "gene pool."
6. Explain the term "selective pressure" as it relates to the study of evolution.
7. In a population of sparrows, most birds have a bill that is about 10 mm long. Some birds, however, have bills that are slightly longer or slightly shorter than the average. Explain why this variation within the population is important when discussing evolution.
8. Give one example of artificial selection and one example of natural selection. What is the major difference between the two types of selection?
9. Give some examples of how people have used artificial selection to create new varieties of plants or animals. Describe the possible economic and environmental impacts of these new varieties.
10. How would you test the hypothesis that larger finches on the Galápagos Islands had a greater survival rate in wet years than in dry years? What factors would you measure?
11. With a partner, discuss what your understanding of evolution was before you read this section. Has your understanding changed in any way now that you have completed this section? If so, how has your definition of evolution changed?
12. Explain what is meant by the statement "natural selection is situational."

19.2 Developing the Theory of Evolution

OUTCOMES

- **Describe, and put in historical context, some scientists' contributions that have changed evolutionary concepts.**
- **Evaluate the scientific evidence that supports the theory of evolution.**
- **Describe the role of peer review in the development of scientific knowledge.**
- **Compare the evolutionary theories of Darwin and Lamarck.**

Ideas about natural selection and evolution began to be discussed in earnest in the early nineteenth century. Although the name Charles Darwin is often mentioned synonymously with the theory of evolution, in fact the work and ideas of many others helped to shape our current understanding of evolution. Indeed, as our technological and scientific techniques improve and our knowledge of the principles of evolution grows, our understanding of the processes of evolution also improves.

A Historical Context

The English naturalist Charles Darwin was by no means the first (or only) person to influence thought on what is commonly referred to as the theory of evolution. Several Greek philosophers believed that life gradually evolved. However, two of the most influential philosophers in Western culture, Plato and Aristotle, did not support ideas that organisms could change. For example, Aristotle thought that all organisms that ever would exist were already created. He also believed that these organisms were permanent and perfect and would not change. Religious beliefs of Darwin's time said that all organisms and their individual structures resulted from the direct actions of a Creator who formed the entire universe. It was thought that all species were created during a single week and that they remained unchanged over the course of time. The predominant belief that Earth was only a few thousand years old fortified the idea of a single act of creation.

In the nineteenth century, however, some scholars began to present new ideas. Some thinkers proposed that living things did change during the course of the history of Earth, and that the organisms that exist now might be different from the organisms that existed previously in history. Others said that populations of organisms perhaps even changed from one generation to the next. They observed variations in populations and saw that populations could adapt to particular situations. Although these ideas were discussed, especially in scholarly circles, they were contrary to the religious teachings of the time and as such were often dismissed as heresy. As well, no one could propose a plausible mechanism that explained these phenomena. Darwin's name is so closely associated with the theory of evolution because he linked all of the prevailing knowledge from paleontology, geology, geography, and biology with his own observations. In doing so, he developed a theory describing a mechanism that showed convincingly that life could change over time. (Another English naturalist, Alfred Russel Wallace, also came to the same conclusion as Darwin.)

Cuvier's Fossils

The science of **paleontology**, which is the study of fossils, provided important clues that helped to develop the theory of evolution. French scientist Georges Cuvier (1769–1832) is largely credited with developing the science of paleontology. Cuvier realized that the history of life was recorded in Earth's layers of rocks, which contained fossils. Cuvier found that each of the layers, or strata, of rock is characterized by a unique group of fossil species and that the deeper (older) the stratum, the more dissimilar the plant and animal life are from modern life (see Figure 19.4 on page 651). Cuvier also recognized that extinction of species was a fairly common occurrence in the history of life on Earth. As he worked from stratum to stratum, he found evidence that new species appeared and others disappeared over the course of millions of years.

Cuvier's work showed that something was causing species to appear and disappear, but he was strongly opposed to the ideas of evolution being suggested at the time. Instead, he proposed the idea of **catastrophism**. According to this idea,

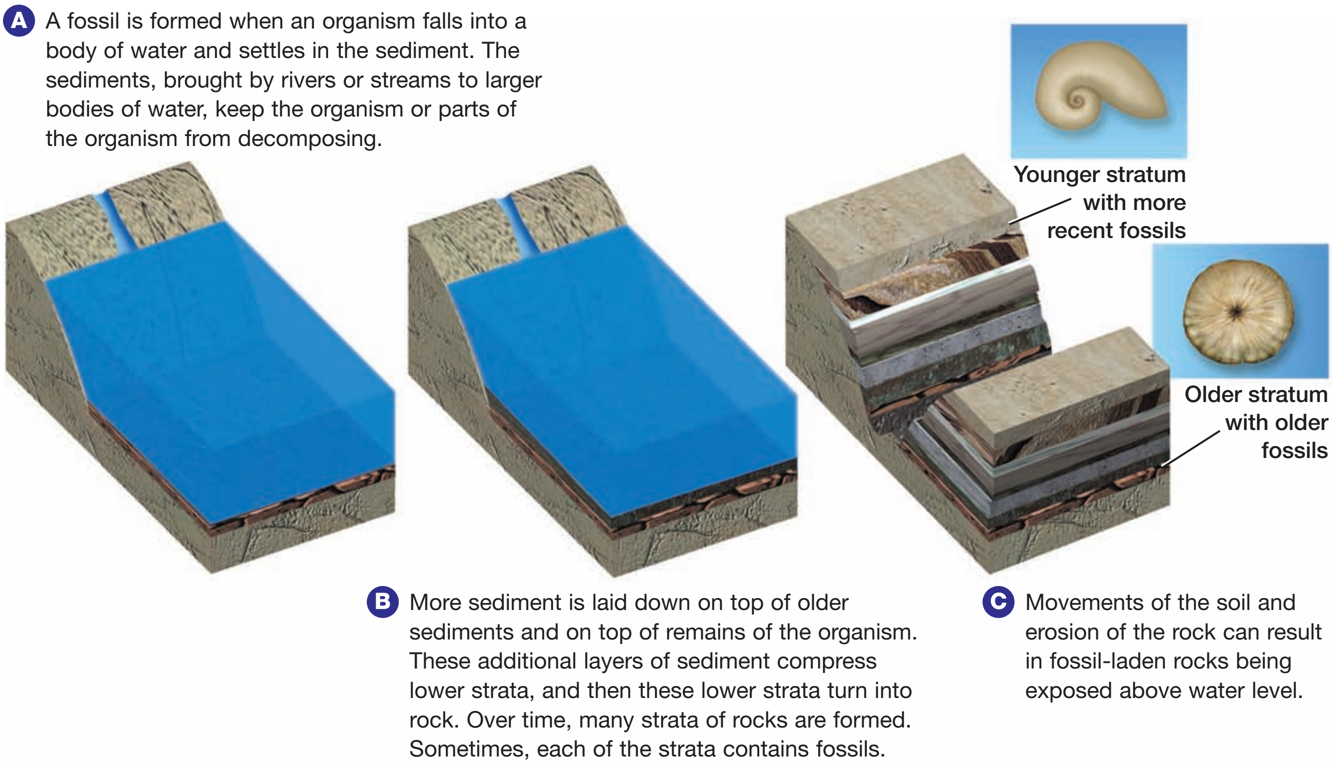


Figure 19.4 **Layers of sedimentary rocks are of different ages and contain different groups of fossils.**

catastrophes (such as floods, diseases, or droughts) had periodically destroyed species that were living in a particular region. He hypothesized that these catastrophes corresponded to the boundaries between each stratum in his studies. Cuvier proposed that these catastrophes were limited to local geographical regions, and that the area would be repopulated by species from nearby unaffected areas. This is how he explained the appearance of "new" species in the fossil record.

Lamarck's Theory of Inheritance of Acquired Characteristics

French naturalist Jean-Baptiste Lamarck published a theory of evolution in 1809, the year Charles Darwin was born and 50 years before Darwin would finally publish his own ideas on evolution. While working at the Natural History Museum in Paris, where he was in charge of the invertebrate collections, Lamarck compared current species of animals with fossil forms. He could see that there appeared to be a "line of descent" where the fossil record showed a series of fossils (from older to more recent) that led to a modern species. Lamarck proposed that microscopic organisms arose continually and spontaneously from non-living sources. He thought that species were initially very primitive, and that they increased in complexity over time until they achieved a sort of perfection. Lamarck believed that the organisms would become progressively better and better adapted to their environments. It was thought at the time that body parts that were used extensively to cope with conditions in the environment would become larger and stronger (the idea of "use and disuse"). Lamarck's idea fit with this line of reasoning. For example, he proposed that a blacksmith would develop a larger biceps in the arm in which he holds his hammer.

Lamarck further proposed that characteristics acquired during an organism's lifetime, such as large size, short hair, or large muscles, could then be passed on to its offspring. Following this reasoning, Lamarck claimed that the large biceps of a blacksmith would then be passed on to his offspring. He called this the **inheritance of acquired characteristics**. Lamarck's proposed mechanism of evolution is now known to be incorrect, but his ideas provoked thought and discussion. They also influenced the thoughts of others, including Charles Darwin. Although controversial for the time, Lamarck's thinking was visionary, especially his idea that adaptations to the environment result in the evolution of species.

BIO FACT

Recent understanding of the immune system has shown that, in some instances, characteristics acquired throughout one's lifetime *may* be passed on to offspring. For example, antibodies acquired during a mother's lifetime can be passed from mother to child during breastfeeding. This boosts the infant's immune system. Scientists Edward Steele and Reginald Gorczynski conducted an experiment that supported Lamarck's basic tenet when they were working at the Ontario Cancer Institute in Toronto in the 1970s. The researchers injected infant male mice with cells from different groups of mice and found that the infants' immune systems developed a tolerance to the foreign cells. They then observed that the offspring of these mice had the same tolerance. Other scientists who have tried and failed to replicate the experiment of Steele and Gorczynski refute the scientists' findings. Nevertheless, this work has sparked interest and critical scientific debate.

Darwin's Evidence

In 1831, a young man left England on the HMS *Beagle*, a British survey ship used for voyages of scientific discovery. No one, including 22-year-old Charles Darwin himself, knew what the voyage would mean to Darwin and the study of biology as he stepped aboard. The expedition had a primary mission to survey the coast of South America, yet it provided Darwin with an opportunity to travel much of the world with ample time to explore the natural history in various locations. Figure 19.5 shows the voyage of the *Beagle*. While the crew surveyed the coastline, Darwin spent hours on shore observing and collecting thousands of specimens in the diverse environments that the ship visited, from the towering Andes Mountains to the Brazilian jungle.

Darwin gathered evidence and made many important observations that led him to realize how life forms change over time and vary from place to place. First, he noted that the flora and fauna of the different regions he visited were distinct from those he had explored in England, Europe, and elsewhere. For example, the rodents in South America were structurally similar to one another but were quite different from rodents he had observed on other continents. Of particular importance was Darwin's observation that species living in the cooler, temperate regions of South America were more closely related to species living in the tropical regions of that continent than to the species in the temperate regions of Europe or elsewhere in the world. He noted that lands that have similar climates seemed to have unrelated plants and animals. Darwin and many others in his time wondered why it was that if all organisms originated from a single act of creation, there existed this distinctive

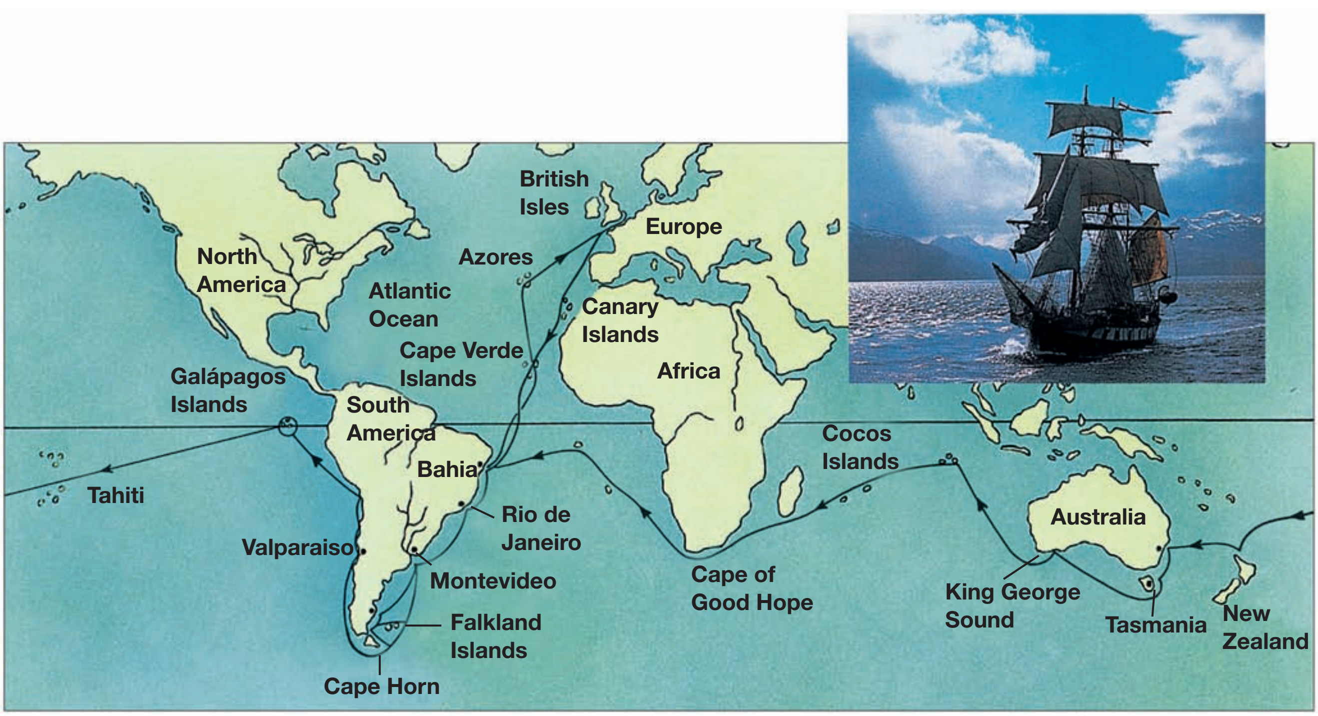


Figure 19.5 The five-year voyage of the HMS *Beagle* took Darwin around the world. Most of his time, however, was spent exploring the coast and coastal islands of South America.

clustering of similar organisms in different regions of the world. Why weren't organisms randomly distributed across Earth?

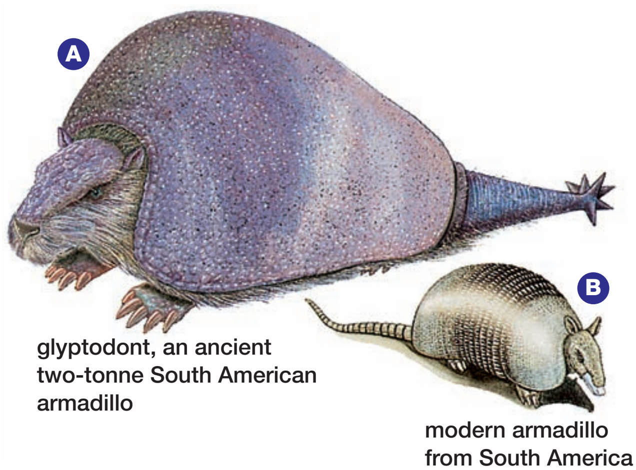


Figure 19.6 Comparison of the extinct glyptodont and a modern armadillo

Darwin also found several important fossil remains, including that of a glyptodont, an extinct armadillo-like animal. He wondered if this fossil was somehow related to the living forms of armadillos that lived in the same region (see Figure 19.6). Why would there be living and fossilized organisms that were directly related to one another in the same region? Could one have risen from the other?

Although it was not entirely evident to Darwin at the time, the *Beagle*'s five-week stop in the Galápagos Islands was particularly important in helping Darwin formulate his ideas on evolution. The Galápagos Islands are a group of over 20 small volcanic islands located in the Pacific Ocean approximately 1000 km off the coast of Ecuador. Darwin noted that the islands in the Galápagos supported relatively few animal species. (There was only one land mammal, for instance, and no frogs or other amphibians.) The species that were there, however, closely resembled animals of the west coast of South America, the nearest continental land mass. Darwin wondered: if these organisms had been created independently and placed in the Galápagos Islands (as the prevailing ideas of the time suggested), why did they so closely resemble organisms on the adjacent South American coastline? A single act of creation did not seem to support the trend Darwin was observing.

In the Galápagos, Darwin observed many new species, including huge land tortoises and giant cactus trees like those shown in Figure 19.7. These species were unique to the Galápagos, and were fairly common in the islands. Some of the species, such as the Galápagos tortoise, were slightly different from island to island. Darwin did not

BIO FACT

Although Darwin is often identified as being the naturalist on the *Beagle*, in fact he was not. Rather, he was welcomed aboard as a "gentleman's companion" to Captain Robert FitzRoy. At that time, captains did not socialize with their crew. Since the voyage was a long one, FitzRoy decided that he needed a companion and selected Darwin. The *Beagle*'s "official" naturalist was the ship's surgeon, Robert McKormick. At that time it was very common for the job of ship's surgeon to be combined with ship's naturalist.

A Galápagos tortoise

B Cactus trees

Figure 19.7 Unique species of the Galápagos observe this himself. Rather, he was told by the vice-governor of the Galápagos that local residents could tell which island captured tortoises came from, just by looking at them. At the time Darwin dismissed this, later writing, "I did not for some time pay attention to this statement … I have never dreamed that islands, about fifty or sixty miles apart, and most of them in sight of each other, formed of precisely the same rocks, placed under a quite similar climate, rising to a nearly equal height, would have been differently tenanted." As it turns out, this fact became a critical piece of information that helped Darwin develop his theory.

Darwin also collected a variety of birds while in the Galápagos Islands, including 13 species of finches (as shown in Figure 19.8). "Darwin's finches" have since become well known in the history of evolutionary thought and, like the information on tortoises, they also became a key to the formulation of Darwin's final theory. While he was in the Galápagos Islands, Darwin scarcely gave the finches much thought, however. He collected several dozen birds but assumed they were similar to birds on the coast of South America or on other Galápagos islands.

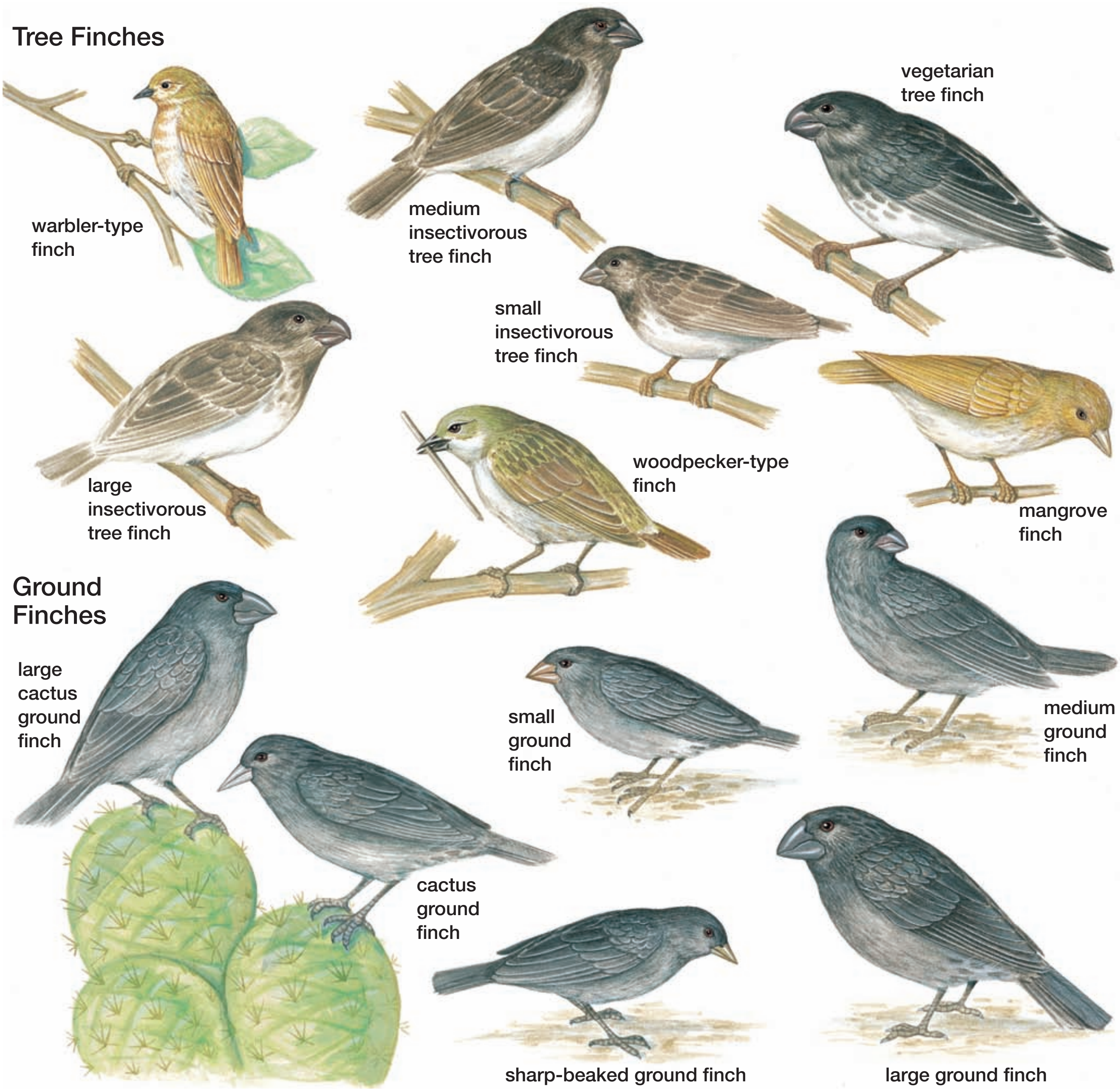


Figure 19.8 Galápagos finches are adapted to gathering and eating different types of food.

Darwin *did* wonder why there was such a diversity of species in such a small area. Each type of Galápagos finch (see Figure 19.8) is adapted to gathering and eating a different type of food based on the size and shape of its beak. Tree finches, for example, have beaks largely adapted to eating insects and, at times, plants. Ground finches have beaks adapted to eating cactus or different-sized seeds. The woodpecker-type finch uses a tool, a cactus spine or twig, to probe in the bark of trees for insects.

In Britain, a colleague catalogued the birds for Darwin and became particularly excited about Darwin's finches. All of the birds were new species that had never been described before. On reflection, Darwin could now see that although the finches were somewhat similar to finches on the coast of South America, they were clearly distinct species. This suggested that they had been modified from an ancestral form of the bird that was blown by chance into the newly formed Galápagos Islands. In the *Voyage of the Beagle* Darwin wrote, "…in the thirteen species of ground-finches, a nearly perfect gradation may be traced, from a beak extraordinarily thick, to one so fine, that it may be compared to that of a warbler. I very much suspect, that certain members of the series are confined to different islands. …" He continued, "Seeing this gradation and diversity of structure in one small, intimately related group of birds, one might really fancy that, from an original scarcity of birds in this archipelago, one species had been taken and modified for different ends."

In summary, Darwin's experience in the Galápagos Islands, particularly the information gathered on tortoises and finches, demonstrated a mechanism for how new species could arise from ancestral ones in response to the local environment.

While on the voyage, Darwin also read *Principles of Geology* by the geologist Charles Lyell. Lyell expanded on ideas first proposed in 1795 by another geologist, James Hutton. Hutton said that Earth's geological features were in a slow, continuous cycle of change. For example, the slow action of rivers eroding through rocks eventually forms canyons. This is called **gradualism**. Lyell expanded on Hutton's ideas to develop a theory known as **uniformitarianism**. Lyell said that geological processes operated at the same rates in the past as they do today. He rejected the idea of irregular, unpredictable, catastrophic events shaping Earth's history.

Lyell's work was significant and a strong influence on Darwin. If geological changes were indeed slow and continuous rather than catastrophic, then Earth was certainly older than the 6000 or so years espoused by biblical scholars. As well, Lyell's work showed that slow, subtle processes happening over a long period of time could result in substantial changes. Darwin, and others searching to explain the changes they saw in the organisms around them, applied Hutton's and Lyell's ideas to biology. Darwin hypothesized that slow, subtle changes in populations of organisms could translate into substantial changes over time.

Summarizing Darwin's Evidence

1. Plants and animals observed in the temperate regions of South America were more similar to plants and animals in the South American tropics than to plants and animals in other temperate regions in the world.
2. Darwin found fossils of extinct animals (such as the glyptodont) that looked very similar to animals presently living in the same region (for example, the armadillo).
3. Plants and animals living in the Galápagos Islands closely resembled plants and animals living on the nearest continental coast (the west coast of South America).
4. Species of animals (such as tortoises) that at first looked identical actually varied slightly from island to island in the Galápagos.
5. Finches collected in the Galápagos looked similar to finches from South America but were, in fact, different species. Finch species also varied from island to island.
6. After reading Lyell's work, Darwin understood that geological processes that are slow and subtle can result in substantial changes. As well, forces that affect change are the same now as in the past.

WEB LINK

www.mcgrawhill.ca/links/atlbiology

Upon his return to England, Charles Darwin wrote the memoirs of his journey and published *The Voyage of the Beagle* in 1839. This book, along with Darwin's other works, is still widely available today. To read some of the original text, go to the web site above, and click on **Web Links**. Read an entry that Darwin made about his time in the Galápagos Islands and the observations he made there.

WEB LINK

www.mcgrawhill.ca/links/atlbiology
Today, the Galápagos Islands continue to be an important site for scientific research in many subject areas, including evolutionary biology. The islands have been recognized by the United Nations and have been designated a Biosphere Reserve, World Heritage Site, and national park. To find out more about current scientific research in the Galápagos Islands, go to the web site above, and click on **Web Links**.

Darwin's Theory of Evolution by Natural Selection

After returning to England, Darwin compiled his memoirs of the voyage. He then devoted eight years to a study of barnacles, in which he filled four volumes on their classification and natural history. Darwin continued to develop his ideas and collect evidence to support his conclusion that species could and did change over time. He investigated variations in species by breeding pigeons and studying breeds of dogs and varieties of flowers. From this work he knew it was possible for traits to be passed on from parent to offspring, so it was clear that species could change over time. He could not explain, however, exactly *how* it happened.

In 1838, Darwin read *Essay on the Principles of Population*, which was written by English economist Thomas Malthus in 1798. In Malthus's paper Darwin found the key idea he had been searching for to explain his observation of changes in species over time. This idea was that plant and animal populations grew faster than their food supply and eventually a population is reduced by starvation, disease, or (as in the case of humans) war. How did this idea help Darwin's thinking?

Malthus's idea helped Darwin refine his thoughts. Darwin knew that many species produce large numbers of offspring, but he also knew that population levels tended to remain unchanged. Malthus's vision of struggle and crowding helped Darwin realize that individuals had to struggle somehow to survive. This struggle was the force that constantly prevents a population explosion. A struggle could be competition for food, shelter, or a mate, for example. Only some individuals survive the struggle and produce offspring. Darwin recognized that the struggle between individuals of the same species competing for limited resources *selected for* individuals with the traits that would increase their chances of surviving. Then, the survivors could potentially pass this favourable trait on to their offspring. He realized this was similar to humans selecting for favourable traits when breeding dogs, horses, or plants.

BIO FACT

Erasmus Darwin (1731–1802), Charles Darwin's grandfather, also proposed that competition between individuals could result in changes in species. Erasmus Darwin was a physician, naturalist, and influential intellectual in eighteenth century England. He formulated one of the first formal theories on evolution, and published his ideas in papers and in a poem, *The Temple of Nature*.

WEB LINK

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

THINKING LAB

Could Pumpkins Rule Earth?

Background

Charles Darwin applied Malthus's ideas to various organisms. For example, he calculated that a single pair of elephants could have 19 million descendents in 750 years. He knew, of course, this could not be true and began to think about the mechanism that must be controlling populations of all species on Earth. The largest number of offspring produced by the members of a population is known as the **biotic potential** of a species.

You Try It

1. Assume there are 70 seeds in one pumpkin. These 70 seeds are planted and each seed grows into a plant that produces two pumpkins. Calculate the number of seeds produced by this generation.
2. If you plant all of the seeds from step 1, how many seeds are available at the end of the next generation?
3. Why is the maximum biotic potential never actually reached in nature?

WEB LINK

www.mcgrawhill.ca/links/atlbiology

Many scientists have contributed to our current understanding of evolutionary biology, and exciting work continues today. To learn more about the various contributions of scientists and philosophers, go to the web site above, and click on **Web Links**. Choose one of the individuals on the list and summarize his/her contribution to evolutionary biology.

Darwin's thinking was catalyzed by Malthus's ideas, his experience with pigeon breeding and artificial selection, and the observations he made during and after the voyage of the *Beagle*. He gradually synthesized his ideas to show that individuals that possess physical, behavioural, or other traits that help them to survive in the local environment are more likely to pass these traits on to offspring than those that do not have such advantageous traits. These favourable characteristics then begin to increase in the population and, over time, the nature of the population as a whole changes. Darwin called this process natural selection. Darwin drafted his initial ideas in two manuscripts shown only to trusted friends in 1842 and 1844. We know he realized their importance because he asked his wife to ensure they would be published in the event of his untimely death. Curiously, however, Darwin did not present his ideas publicly until 1859, when he released *On the Origin of Species by Means of Natural Selection*. (In this text we will refer to this book as *The Origin of Species*.)

Why did Darwin wait so long to publish his ideas? Thinking and discussions about evolutionary theory were becoming more and more commonplace in the mid-nineteenth century, but the discussions were inevitably heated. The subject was controversial, since it was perceived as being contrary to the religious teachings of the time. Perhaps Darwin was reluctant to publish because he anticipated the response and possible uproar it would cause. His friend Lyell, whose book on fossils had influenced Darwin, encouraged him to publish on the subject before someone else did, even though Lyell himself was not convinced of evolution.

Lyell's prediction came true in June 1858, when Darwin received a paper from British naturalist Alfred Russel Wallace. As a result of his studies in a group of islands near Indonesia, Wallace had reached a conclusion similar to Darwin's. In the paper, Wallace outlined an essentially identical theory of evolution by natural selection. With Wallace's paper was a letter asking Darwin to evaluate the paper and pass it on to Lyell if he thought it should be published. Darwin did as Wallace asked and in a letter to Lyell he wrote, "Your words have come true with a vengeance… I never saw a more striking coincidence… so all my originality, whatever it may amount to, will be smashed." Lyell presented Wallace's paper and parts of Darwin's unpublished 1844 essay to the scientific community on July 1, 1858. Darwin quickly went to work and wrote *The Origin of Species*, which was published in 1859. With *The Origin of Species*, Darwin was the first to gather an array of facts related to evolution and present them cohesively.

Descent with Modification

Darwin did not use the word "evolution" in the original edition of *The Origin of Species*. ("Evolved" is used once — it is the final word in the book.) Instead, Darwin spoke of **descent with modification**. One reason he did not use the word "evolution" is that he felt it implied progress — that each generation was somehow getting better (that is, was improving in some way). Natural selection does *not* demonstrate progress; it has no set direction. It results purely from an ability to survive local environmental conditions, thereby giving the survivors the opportunity to pass on the trait that helped them survive in the first place.

Darwin proposed two main ideas in *The Origin of Species*: present forms of life have arisen by descent and modification from an ancestral species; and the mechanism for modification is natural selection working continuously for long periods of time. Darwin said that all organisms descended from some unknown organism. As descendants of that organism spread out over different habitats over the millennia, they developed modifications, or adaptations, that helped them fit in their local environment. Darwin's theory of natural selection showed how populations of individual species became better adapted to their local environments. These ideas are summarized in the text box on the following page.

As Darwin anticipated, *The Origin of Species* created a sensation, since the ideas outlined in the work were deeply disturbing to many. Within a few years, however, his view was widely accepted by most scholars. This was partly because the gap between religious viewpoints and the idea of natural selection narrowed, and because Darwin supported his ideas logically with a great deal of evidence. *The Origin of Species* continues to be one of the most famous and influential books of all time.

Summary of Darwin's Ideas

Natural selection means that organisms with traits best suited to their environment are more likely to survive and reproduce. The factors Darwin identified that govern natural selection are:

1. Organisms produce more offspring than can survive, and therefore organisms compete for limited resources.
2. Individuals of a population vary extensively, and much of this variation is heritable.
3. Those individuals that are better suited to local conditions survive to produce offspring.
4. Processes for change are slow and gradual.

The work of Darwin, Lyell, Lamarck, and Cuvier helped shape the understanding of evolution. Many other people also helped advance these ideas. For example, Darwin was influenced by reading a work by Lyell on geology. Darwin supported his ideas with evidence of natural selection. In the next section, you will study some of the scientific evidence that supports the theory of evolution.

BIO FACT

Unfortunately, Alfred Russel Wallace, co-discoverer with Darwin of the idea of natural selection, is not well known by the general public. Wallace was an accomplished naturalist and contributed a great deal of knowledge to biological sciences, geography, and other disciplines. During his long life Wallace published over 150 works (including essays, books, and letters) and travelled and lectured widely. He did not, however, agree with all of the contents of Darwin's *The Origin of Species*. In fact, Wallace eventually became a "spiritualist" and could not extend the idea of natural selection to apply fully to humans. He believed that while natural selection worked at a biological level, there was a spiritual process that operated at the level of human consciousness. Humanity, he felt, had a special connection with God.

SECTION REVIEW

1. An athlete breaks her leg. Years later she has a child who walks with a limp. Is this an example of evolution? Explain your answer.
2. Describe the contributions of the following people to the understanding of evolution:
   (a) Cuvier
   (b) Malthus
   (c) Wallace
   (d) Lyell
3. Charles Darwin was not the only person to discuss the idea of evolution. Why is his name most often mentioned synonymously with the idea of evolution?
4. Write a brief presentation that explains the difference between catastrophism and uniformitarianism and how these ideas related to the development of the theory of evolution.
5. Explain the idea of use and disuse as it relates to the theory of evolution by the inheritance of acquired characteristics.
6. Summarize some of the observations Darwin made while on the voyage of the *Beagle* that he later incorporated into his theory of evolution by natural selection.
7. Nature writer Wallace Stegner once wrote of a population of trout in a mountain lake that were in a "Malthusian dilemma." Explain what Stegner meant.
8. Describe what is meant by the term "biotic potential."
9. Explain why Darwin referred to "descent with modification" rather than "evolution."
10. At the site of a fossil bed, you come across fossils in a number of layers in the sediment. Which layers would have the oldest fossils and which would have the youngest fossils? On what evidence would you base your response?

19.3 Evidence of Evolution

OUTCOMES

- **Evaluate the scientific evidence that supports the theory of evolution.**
- **Analyze how technological development has extended support for the modern theory of evolution.**
- **Explain how nucleic acid sequences provide evidence for evolutionary relationships.**

Charles Darwin assembled a group of facts that had previously seemed unrelated in *The Origin of Species*. However, before and after publication of this book, biologists, geologists, geographers, paleontologists, and other scientists provided a wealth of information that supported and strengthened the theory of evolution. Evidence in support of evolution has come from the fossil record, the sciences of genetics and molecular biology, the geographic distribution of organisms on Earth, and studies comparing the anatomy of adult and embryonic animals.

The Fossil Record

Fossils are made when organisms become buried in sediment that is eventually converted into rock. Sedimentary rocks with fossils reveal a **fossil record** of the history of life on Earth and show the kind of organisms that were alive in the past. While some fossils look similar to species we see today, most are very different. For example, the animals alive during the Cambrian period that were preserved in the Burgess Shale fossil beds in British Columbia had never been seen in the fossil record before. The animals unearthed in the Burgess Shale lived during the Cambrian Explosion (about 500 million years ago), a time during which a stunning burst of biodiversity occurred, much of which is now preserved as fossils. While some of the animals found in the Burgess Shale are ancestors of animals that are common today, others have long been extinct and are unlike anything in our modern oceans. An artist's representation of how the ocean might have looked when the Burgess Shale animals were alive is shown in Figure 19.9.

Fossils from more recent geological periods are much more similar to species alive today. This also supports the idea that life has evolved over time. Those species that were alive long ago have had a longer time to change, whereas those living only a few million years ago would have had comparatively little time to change. The geological time scale (Figure 19.10 on the following page) shows when organisms first appear in the fossil record.

Figure 19.9 An artist's representation of the habitat and animals now fossilized in the Burgess Shale

Another way in which the fossil record supports the idea of evolution is that fossils appear in chronological order — that is, probable ancestors appear earlier (in older rock strata) in the fossil record. The oldest fossils discovered thus far are of stromatolites that lived over 3.8 billion years ago. Stromatolites are unusual rings formed by cyanobacteria (blue-green algae). The stromatolite formation on the shore of Lake Superior (as shown in Figure 19.11) is approximately 1.9 billion years old. As Figure 19.10 shows, other organisms, from simple invertebrates to mammals, then appear sequentially in the fossil record through time.

The fact that organisms do not all appear in the fossil record simultaneously supports the idea that organisms have slowly evolved from ancestral forms. As an example, the fossil history of vertebrates shows that fossilized fishes are the oldest vertebrate fossils. Next to appear in the vertebrate fossil record are amphibians, followed by reptiles, and then birds and mammals (see Figure 19.10). Biologists and paleontologists have gathered evidence that shows that amphibians evolved from ancestral fish, reptiles from ancestral amphibians, and so on, up through the vertebrate groups.

It is important to keep in mind the vast amounts of time that the history of life covers. Changes are slow and can take millions of years, yet the fossil record gives us a "snapshot" of ancestral forms. Figure 19.12 on page 000 shows the evolution of oyster shells.

Figure 19.11 These stromatolites are among the earliest known organisms preserved in the fossil record.

About 200 million years ago, oyster shells were small and curved. The fossil record shows that the shells of later generations evolved into a larger, flatter shape over a period of about 12 million years. Oysters live on the ocean floor, and the larger, flatter shell shape may have proved a more stable shape to prevent shifting as water moved over the oysters.

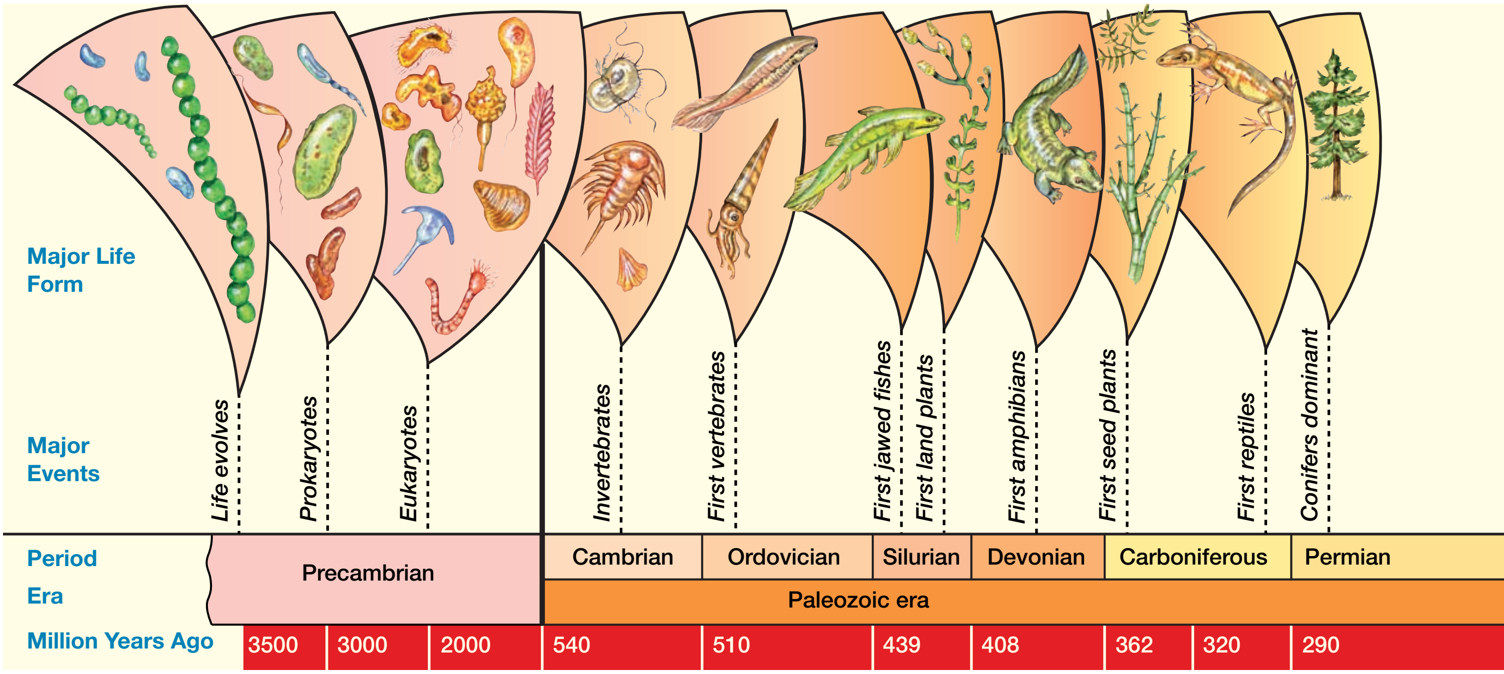


Figure 19.10 The geological time scale shows when organisms first appear in the fossil record.

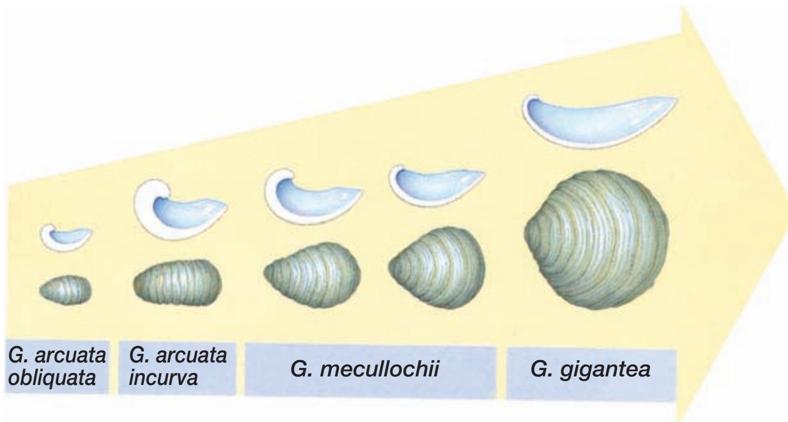
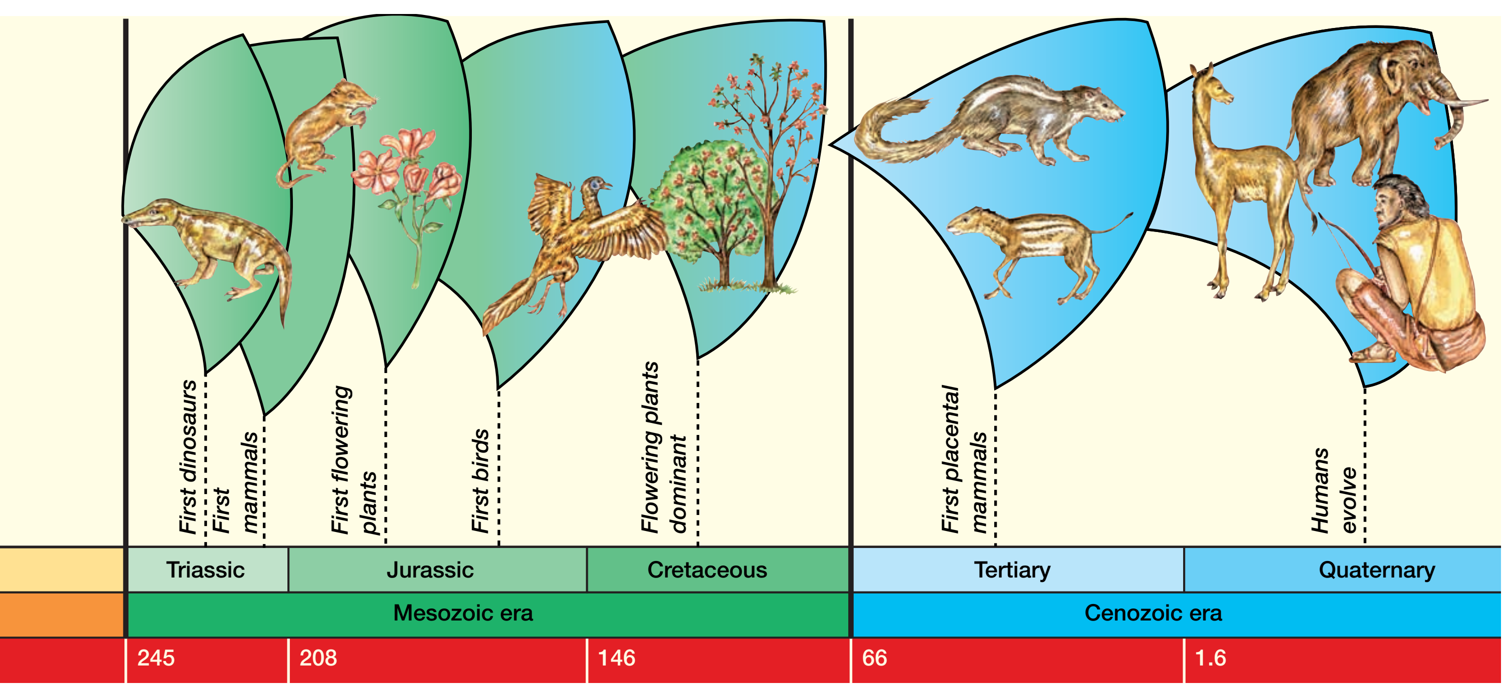


Figure 19.12 Evolution of the oyster shell

How did scientists begin to understand the links between fishes and reptiles or between reptiles and amphibians? What evidence was there to support the main ideas of natural selection — that organisms could slowly adapt and change (even into new species) given vast amounts of time? This idea has been supported by the discovery of hundreds of **transitional fossils**. These fossils show intermediary links between groups of organisms, and share characteristics common to two separate groups.

Archaeopteryx (see Figure 19.13A), for example, lived about 150 million years ago. Fossils of this species reveal characteristics of both reptiles and birds. This creature had feathers, but unlike any modern bird, *Archaeopteryx* had teeth, claws on its wings, and a bony tail. *Archaeopteryx* resembles certain dinosaurs more than any modern bird. This fossil, along with other types of evidence, supports the hypothesis that birds evolved from dinosaurs. (Indeed, if it had not been for the preservation of *Archaeopteryx* feathers, *Archaeopteryx* would have been placed in a group of small, carnivorous, bipedal (two-footed) dinosaurs called theropods.) Several other dinosaurs with feathers have since been unearthed, but *Archaeopteryx* is the first known true-flier and is considered to be the earliest bird.

Figure 19.13A Fossil of *Archaeopteryx*, which shows a link between birds and reptiles



Acanthostega is a fossil that shows the link between fish and amphibians. *Acanthostega* lived about 360 million years ago (see Figure 19.13B). It had gills *and* lungs, stumpy legs, limbs and toes, a long tail almost the length of its body, a crocodile-like snout, and a jaw filled with teeth. Paleontologists do not think *Acanthostega* walked on land. Rather, they believe it used its limbs and toes to grab onto vegetation and pull itself through plant-choked swamps.

Figure 19.13B *Acanthostega* lived in swamps and used limbs and toes to maneuver in swampy waters.

There are two ways to date fossils. **Relative dating** judges the age of fossils by their position in rock layers. Rocks closest to the Earth's surface are considered to be younger than rocks found deeper below the surface. This method, however, only provides a rough estimate of a fossil's age. **Absolute dating** provides a much more accurate way to determine a fossil's age, using radioactive dating techniques. As you learned in Chapter 4, radioactive isotopes have a **half-life**, the time that it takes for half of the radioactive isotope (the *radioactive parent*) to change into another, stable element (the *stable daughter*). In the Thinking Lab below, you will use known decay rates of radioactive isotopes to date samples.

Paleontologists continue to add to our understanding of evolution. For example, researchers have recently found fossilized whales that link these aquatic mammals to their terrestrial ancestors. The *Basilosaurus* was an ancient whale that had hind limbs but led an entirely aquatic life (see Figure 19.13C on the next page). An earlier transitional form, *Ambolucetus*, had heavier leg bones and was thought to live both on land and in water.

THINKING LAB

Rocks of Ages

Background

By examining percentages or ratios of radioactive parent isotopes to stable daughters, fossils can be dated with better accuracy than relative dating can provide. In a hypothetical sample, 25% $\left(\frac{1}{2} \text{ of } \frac{1}{2}\right)$ of the original C^{14} was found. Thus, the sample is two half-lives of 5 730 years, or approximately 11 460 years old. C^{14} dating only works with fossils that contain organic matter, and that are 50 000 years old (ten half-lives or less). Study the table below, and use the data to answer the following questions.

Radioactive parent	Stable daughter	Half life (years)
C^{14}	N^{14}	5 730
U^{235}	Pb^{207}	713 000 000
K^{40}	Ar^{40}	1 250 000 000
Rb^{87}	Sr^{87}	48 800 000 000

You Try It

1. A well preserved human corpse is found in a bog, clutching a primitive looking spear. Tests determine that 6.25% of the original C^{14} remains in the sample. How long ago did this person die?
2. An undetermined fossil is found on a paleontological expedition. The sample contains 1 part U^{235} to every 32 parts Pb^{207}. How old is this fossil? How could knowledge of its age help classify it?
3. If a rock contains 6.25% K^{40} to 93.75% Ar^{40}, how old was the rock when it first crystallized?
4. In groups of two, write additional questions for this Thinking Lab, using the data from the table and inventing hypothetical, but plausible, scenarios. Solve the questions first, then exchange questions with another group and try to solve their questions.

Figure 19.13C Fossilized leg bones of *Basilosaurus*, an ancient whale that provides evidence that whales evolved from terrestrial animals

Geographical Distribution of Species

Biogeography is the study of the geographical distribution of species. Darwin's thinking was influenced by the distribution of animals. Recall that he wondered why the birds in the Galápagos Islands so closely resembled those on the closest continent, South America. This suggests that animals on islands have evolved from mainland migrants, with populations adapting over time to adjust to the environmental conditions of their new home. This idea has since been supported in many studies. Geographically close environments (for example, desert and forest habitats in South America) are more likely to be populated by related species than are locations that are geographically separate but environmentally similar (for example, a desert in Africa and a desert in Australia).

The biogeographical evidence for evolution also points to places such as Australia. Why would so many marsupials but relatively few placental animals live there? (Marsupials such as the kangaroo bear live young, but part of the offspring's development occurs outside the uterus in a pouch. Young develop in the uterus until birth in placental animals.) Australia can clearly support placental mammals; populations of introduced rabbits and mice have certainly increased! The unique marsupials of Australia evolved in isolation from places where the ancestors of placental mammals lived.

Neighbouring New Zealand also has a variety of animals found nowhere else, specifically a variety of flightless birds including the kiwi, the takahe, and the extinct moa, the largest bird to ever live (see Figure 19.14). New Zealand is a country comprised of two large and several small islands. Originally, New Zealand and Australia were part of the supercontinent Gondwana. As these countries drifted away from Gondwana, due to the shifting of the continental plates, they became isolated from other land masses. Once isolated, populations unique, or **endemic**, to these islands evolved.

Islands can have a volcanic origin (such as the Galápagos) or they may have broken off adjacent continental land masses (such as New Zealand). Islands can be colonized by species that swam, flew, or floated from the nearest mainland. Islands with nonvolcanic origins can also be populated by

Figure 19.14 Birds found only in New Zealand include the kiwi (A), the takahe (B), and the moa (C), which is now extinct.

species that remained on the island as it broke away from the mainland. Once isolated on the island, these species begin to evolve in different ways from their ancestors on the mainland. The degree of difference from their ancestors depends on the age of the islands. This can be demonstrated by looking at Madagascar and the Canary Islands, both of which are off the coast of Africa.

Madagascar is an island off the east coast of Africa that was originally connected to the African mainland. Madagascar is thought to have split from the African continent about 150 million years ago, although periodic fluctuations in ocean levels may have reconnected the two on a few occasions up until about 50 million years ago. Today, the channel between Africa and Madagascar is about 400 km wide, so species dispersing to the island during the last 50 million years would have had to cross this channel. Madagascar has 184 species of birds, 125 of which are endemic to Madagascar. Larger birds such as ducks, which can easily cross the water between the two countries, are found in both Africa and Madagascar. However, 90 percent of the land birds in Madagascar are found only there.

Madagascar is also the only place in the world where lemurs are found. However, the fossil record shows that lemurs were once widespread throughout Africa. Lemurs first appear in the fossil record about 65 million years ago; therefore, they were either present on Madagascar when it separated from the African continent or they floated to Madagascar when the channel was narrow. So why are lemurs no longer present in Africa? When Madagascar permanently separated from Africa 50 million years ago, monkeys had not yet evolved. Monkeys do not appear in the fossil record until about 35 million years ago, so they had no way of reaching the island of Madagascar (because the channel between Africa and Madagascar was too wide at that time). However, monkeys eventually took over the niche that lemurs had on the African continent and drove lemurs to extinction there.

The Canary Islands, off the northwest coast of Africa, are about 10 to 15 million years old. They were formed by volcanoes — they were never attached to the African continent. Therefore, unlike Madagascar, the Canary Islands have been colonized only by those animals and plants able to disperse from the adjacent coastline of Africa. Of the 53 bird species known to breed there, only two are endemic. As well, the Canary Islands have no snakes or land mammals (except bats). The eight species of lizards on the islands are thought to have drifted on pieces of wood from the adjacent coastline. They are similar to west African species, yet are sufficiently different to show that natural selection has created some change in the populations. In fact, some of the lizards are now recognized as new species.

Anatomy

When the anatomy of various animals is examined, more evidence for evolution of animals from common ancestors is revealed. Figure 19.15 shows the forelimbs and individual bones of five vertebrates. All of the limbs have the same basic arrangement of bones, yet they are modified into wings, arms, legs, and fins. The present arrangements of bones in the animals shown in Figure 19.15 are variations on a common structural theme. As these animals descended from common ancestors, the same bones were put to different uses. The bones have the same origin yet they now differ in structure and function. Such anatomical signs of evolution are called **homologous structures**. Homologous structures have not only similar numbers of bones but also similar numbers of muscles, ligaments, tendons, and blood vessels. They also have the same developmental origin.

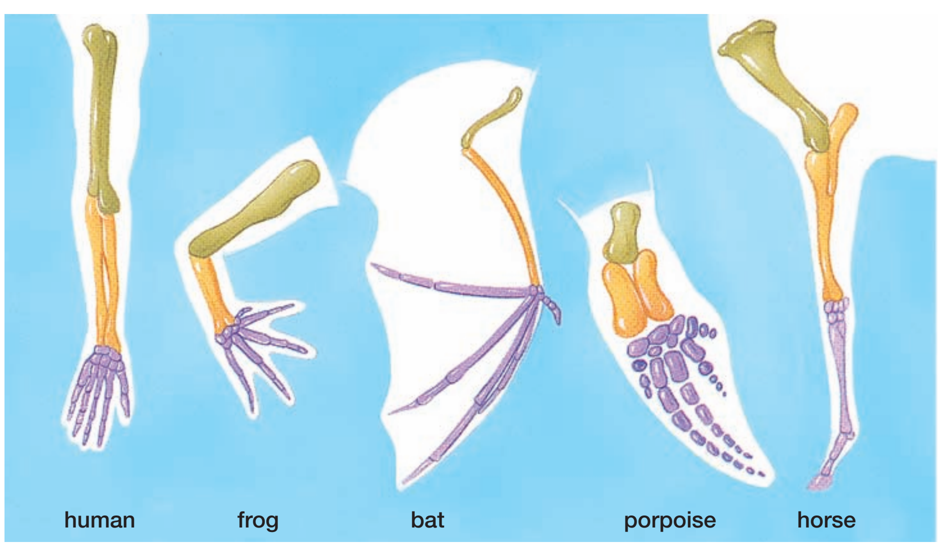


Figure 19.15 These vertebrates have the same basic arrangement of bones, but the bones have been put to different uses.

Homologous structures can be similar in structure, function, or both. For example, the limbs in Figure 19.15 are structurally similar. Also, the limbs of the human, frog, and horse perform the same function: they are designed for walking on land. Functional similarity, however, does not necessarily mean that species are closely related. For example, insect and bird wings are similar in function but not in structure. The wings of these types of animals evolved independently and have very different structures. Bird wings are supported by bones, whereas a tough material called chitin makes up insect wings. Body parts of organisms that do not have a common evolutionary origin but perform similar functions are called **analogous structures**.

Even though analogous structures do not show evolutionary relationships between animals, they do support the idea of natural selection. Bird and insect wings evolved separately when the ancestors of today's species adapted independently to a life that included flight.

Many organisms also possess **vestigial structures**. These are structures that were functional in the organism's ancestors yet have no current function. For example, the baleen whale in Figure 19.16 has vestigial pelvic bones. Pelvic bones perform no function in modern whales since they have no hind limbs. Their presence in modern whales points to the terrestrial origins of ancestral whales. The vestigial pelvic bones are artifacts from the whales' evolutionary history.

The forelimbs of the flightless ostrich are another example of a vestigial structure. The ancestors of modern ostriches were probably able to fly, but they likely foraged and nested on the ground. As a result, over time these animals became quite large and unable to fly, and the forelimbs became unnecessary.

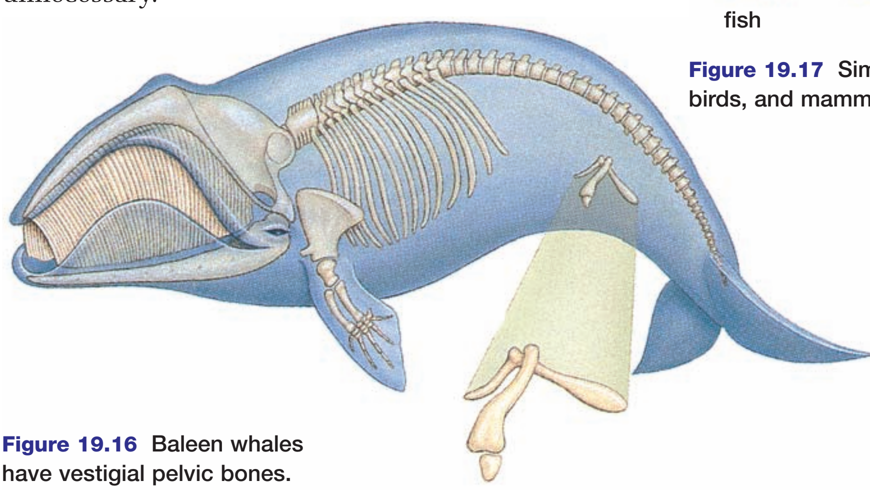


Figure 19.16 Baleen whales have vestigial pelvic bones.

Embryology

Embryology has also been used to determine evolutionary relationships among animals. When the embryos of organisms are examined, similar stages of embryonic development are evident. For example, all vertebrate embryos (including humans) go through a stage in which they have gill pouches (as shown in Figure 19.17). At certain stages in the development of the embryo, the similarities among fish, birds, humans, and all other vertebrates are more apparent than their differences. In Figure 19.17 for example, the early stages of development of fish, reptile, bird, and mammal embryos each have a tail and gill pouches. Gill pouches form gills in fish. In terrestrial vertebrates, the gill pouches are modified for other uses, such as the Eustachian tube in humans. The tail in a human embryo becomes the coccyx at the end of the spine.

These similarities between embryos in related groups (such as vertebrates) point to a common ancestral origin. It follows that related species would share both adult features (such as the number of arm bones, as discussed earlier) and embryonic features (such as the presence of gill pouches).

Figure 19.17 Similarities in the embryos of fish, reptiles, birds, and mammals show evidence of evolution.

Heredity

When Darwin published *The Origin of Species*, the science of genetics and an understanding of heredity was not yet established. This meant that Darwin could not completely explain the mechanism that drove natural selection. Today, since the laws of inheritance and the science of genetics are more clearly understood, the variations in organisms required for natural selection to occur can be explained. This will be discussed in further detail in Chapter 20.

Molecular Biology

The evolutionary relationships among species are reflected in their DNA and proteins. Since DNA carries genetic information, how closely related two organisms are can be determined by comparing their DNA. If two species have similar patterns in their DNA, this similarity indicates that these sequences must have been inherited from a common ancestor. For example, by studying gene sequences, scientists have determined that dogs are related to bears and that whales and dolphins are related to ungulates (hoofed animals such as cows and deer).

The degree to which DNA sequences are similar between species determines how closely related those species are. For example, humans and chimpanzees have an approximately 2.5 percent difference between their DNA sequences, while humans and lemurs have a 42 percent difference.

The science of molecular biology has also helped show that all forms of life are related to the earliest organisms to some extent. Even organisms that are

Biology At Work

Paleontologist

Douglas Boyce

Douglas Boyce's interest in paleontology began at an early age, during a primary school trip to the New Brunswick Museum. "Paleontology is a multifaceted branch of geology," he says. "It has applications as mundane as ecotourism on Earth, and as exotic as the search for extraterrestrial life."

In a 1989 monograph, Douglas Boyce named and described three new genera and 14 new species of trilobites. Although his research focuses on trilobites, Doug also works on other types of fossils, including bivalves, brachiopods, cephalopods, corals, fish, and plants. Although Doug collected his first fossil when he was twelve years old, his official geological education began in 1973 at the University of New Brunswick (Saint John). In 1975, he transferred to Memorial University of Newfoundland (St. John's), where he obtained his B.Sc. Honours degree and his M.Sc. degree.

As an undergraduate in 1976, Douglas Boyce began a continuing collaboration with Dr. Ian Knight on the rocks and fossils of western Newfoundland. "The province of Newfoundland and Labrador has a rich fossil history going back two billion years," Doug points out. Since June 1984, he has been the Provincial Paleontologist for the Geological Survey of Newfoundland and Labrador.

At the Geological Survey, paleontology is an integral part of systematic bedrock mapping. One of the most important applications is the relative age dating of rock sequences (biostratigraphy). "Paleontologists have long recognized that fossil assemblages occur in a particular order in the sedimentary rock record," Doug notes. "These assemblages have been used to define biostratigraphic zones. The zone is the fundamental building block of the Phanerozoic portion of the geological time scale." Doug was able to consistently recognize many different fossil zones over broad areas. "Rocks of different ages can strongly resemble each other, particularly when the original sediments were deposited in similar environments," he says. "Similarly, the strata of one rock formation may be repeated by faulting. Fossils, therefore, provide an elegant way to quickly distinguish between various rock units or different levels within a single unit; this facilitates oil and gas exploration."

Recently, Douglas Boyce was a local collaborator on three National Geographic studies — dealing with west Newfoundland Ordovician snails. During the summers of 2000 and 2001, he was a member of a multidisciplinary international field project that studied Cambrian and Ordovician limestones in northeast Greenland. In May 2002, he was elected Chair of the Geological Association of Canada's Paleontology Division. But paleontology is not the only field in which Douglas Boyce excels. He's a longtime computer enthusiast, harmonica player, amateur actor, and prize-winning Karaoke singer.

Career Tips

1. Select a university, museum, or private company where paleontologists work and describe the various kinds of work they do there.
2. Research and report on the ways in which the work of paleontologists facilitates oil and gas exploration in Canada.

only remotely related have some proteins in common. One example is **cytochrome c**, a protein involved in cellular respiration that is found in the mitochondria. The amino acid sequence of cytochrome c is so similar among organisms that it can be used to indicate relatedness. The length of the cytochrome c enzyme varies from 103 to 112 amino acids, depending on the organism. The amino acid sequence of the cytochrome c in chimpanzees and rhesus monkeys (both primates) differs by only one amino acid; the sequence in chimpanzees and horses (both mammals) differs by 11 amino acids; and the sequence of the chimpanzee and dogfish (both vertebrates) differs by 24 amino acids.

Scientists have also tracked the evolution of cytochrome c itself. Figure 19.18 shows that the longer the time since an organism evolved from a simple ancestor, the greater the number of differences in nucleotide sequences in the gene for cytochrome c. This also points to the evolutionary idea of organisms having common ancestors. While mutations have substituted amino acids in various places in the protein cytochrome c during the long period of evolution, cytochrome c still has a similar structure and function in all species.

Scientists can also study the evolutionary history of a gene using DNA sequencing. The gene for the protein hemoglobin has been well studied. The pattern of descent, or the **phylogenetic tree**, of the hemoglobin gene is shown in Figure 19.19 on the following page. (A phylogenetic tree shows the pattern of descent. A phylogenetic tree is similar to

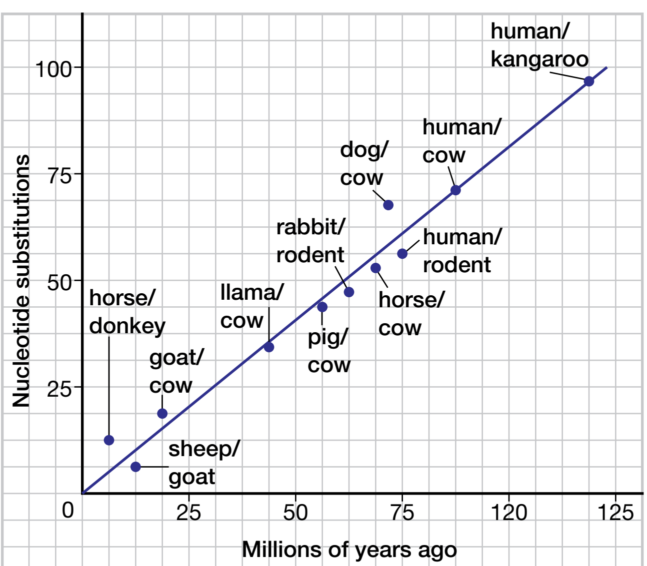


Figure 19.18 Evolution of cytochrome c. The longer an animal diverged from a common ancestor, the greater the difference in genetic sequence.

an evolutionary family tree for an organism.) The progressive changes in the hemoglobin molecule have produced a tree that shows the evolutionary relationships between organisms — the shorter the line in the tree, the more amino acids in common and the closer the evolutionary relationship.

In the early 1800s, when scientists first used microscopes to look at cell mitochondria, they were amazed at how much they resembled bacteria. The same was true with the chloroplasts in plant cells. Today we know that there is a very strong evolutionary link among these structures. In fact, the DNA in chloroplasts is the same as the DNA in cyanobacteria.

Scientists now know that chloroplasts are descendants of cyanobacteria, and mitrochondria are descendants of aerobic prokaryotes. Both began by living symbiotically in host eukaryote cells. Scientists, including W. Ford Doolittle of Dalhousie University, examined the DNA in the chloroplasts of some species of algae and compared it to the DNA in the algae's nucleus. The DNA was different. This proved that the chloroplast originated outside of the algae cell and, through evolution, became a symbiont in the algae.

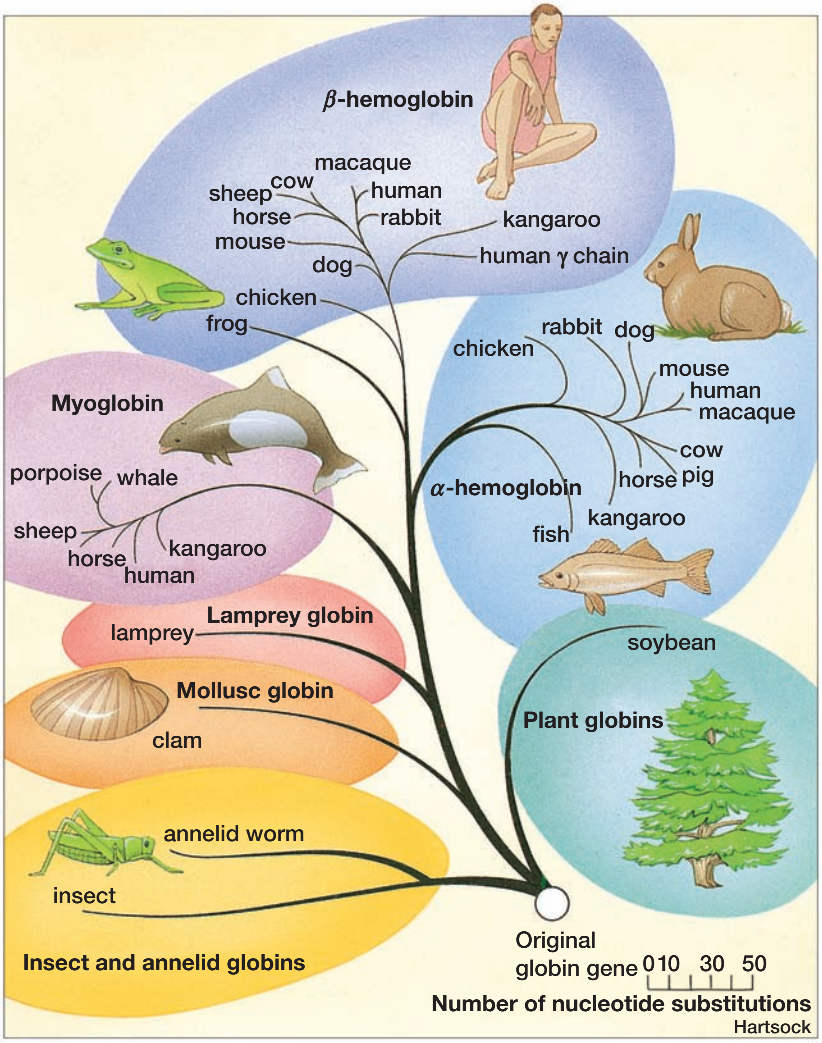
Defining a Theory

Current understanding of the theory of evolution is dismissed by some as being "just a theory." This implies that somehow a theory is just a guess and therefore is easy to refute. It is important to clarify the use of the words "theory" and "fact" in the realm of science. Scientific facts are the data that have been collected. For example, homologous structures, the fossil record, the DNA sequencing in individual organisms, and the other information presented in this chapter are scientific facts. Scientific theories attempt to explain facts and tie them together in a comprehensive way. For example, the facts

WEB LINK

www.mcgrawhill.ca/links/atlbiology

Canadian fossil sites, including Mistaken Point in Newfoundland, the Burgess Shale in British Columbia, the rich fossil sites near Drumheller, Alberta, and the Joggins Fossil Cliffs in Nova Scotia, have revealed fascinating information on the evolution of life. To learn more about these sites, go to the web site above, and click on **Web Links**. Choose one fossil site and prepare a short oral presentation or one-page summary on the significance of the site and how it contributed to our understanding of the evolution of life.



gathered by Darwin and people before and after him show that evolution is happening. Darwin's theory of evolution by natural selection is the theory that attempts to tie these facts together.

This chapter has outlined the development of the theory of evolution and the facts from various disciplines, including geography, paleontology, and molecular biology, that all support this theory. The study of evolution continues to spark debate even today. Although there are still lively debates in the scientific community over specific details of exactly *how* life evolved, biologists do not refute the idea of evolution itself.

Figure 19.19 Evolution of the globin gene

SECTION REVIEW

1. How does the discovery of so-called missing links in the fossil record help us to understand evolutionary events of the past?
2. How do the number of endemic species differ between Madagascar and the Canary Islands? Explain why these differences exist.
3. Describe how the anatomy of animals is used to explain evolution.
4. Baleen whales, such as grey and humpback whales, have teeth and body hair while they are embryos, but they lack these features as adults. What does this tell us about the evolutionary history of these animals?
5. When human organs are transplanted, the rate of success is higher in cases where the donor and recipient are close relatives. Why do you think this is so?
6. Explain how the differences in the sequence of amino acids that make up cytochrome c in different kinds of organisms help us understand evolution.
7. Biologist Stephen Jay Gould wrote, "The fact of evolution is as well established as anything in science (as secure as the revolution of the earth around the sun) … Theories, or statements about the causes of documented evolutionary change, are now in a period of intense debate — a good mark of science in its healthiest state. Facts don't disappear while scientists debate theories." Explain the difference between fact and theory as they relate to science.
8. Make a hypothesis concerning what species changes and what environmental changes you would expect to see on Madagascar if it were to become reconnected to the mainland of Africa. How might a scientist test your hypothesis?

Chapter Summary

Briefly explain each of the following points.

- Variety within a population and the environment in which organisms live allow natural selection to happen. (19.1)
- Genetics and environment can affect evolution. (19.1)
- The ideas and observations of many people helped develop the current theory of evolution. (19.1)
- Natural selection is the process whereby a population of organisms changes because individuals who inherit certain traits can survive the local environmental conditions and pass on these traits to their offspring. (19.1)
- Artificial selection is the process whereby humans artificially select organisms with certain traits and these organisms pass on these traits to their offspring. (19.1)
- Observations of Charles Darwin led him to develop a theory of evolution. (19.2)
- Contributions of Cuvier, Lamarck, Malthus, Hutton, Lyell, and Wallace helped develop the theory of evolution. (19.2)
- Darwin's theory of evolution by natural selection is compared with Lamarck's theory of evolution by the inheritance of acquired characteristics. (19.2)
- Technology, such as DNA sequencing and amino acid sequencing, has provided more evidence for evolution. (19.3)
- Fossils, biogeography, anatomy, and molecular biology all provide evidence for evolution. (19.3)
- A scientific fact is data or information that have been collected, and a theory attempts to explain facts. (19.3)

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.

- evolution
- adaptation
- gene pool
- natural selection
- selective pressure
- artificial selection
- fitness
- paleontology
- catastrophism
- inheritance of acquired characteristics
- gradualism
- uniformitarianism
- biotic potential
- descent with modification
- fossil record
- transitional fossil
- relative dating
- absolute dating
- half-life
- biogeography
- endemic
- homologous structures
- analogous structures
- vestigial structure
- embryology
- cytochrome c
- phylogenetic tree

UNDERSTANDING CONCEPTS

1. If you teach children to look both ways before they cross the street, this action will help them survive. Is this an example of natural selection at work? Explain your answer.

2. Compare the controlling factors for artificial selection and natural selection.

3. How might the colour of a field mouse affect its survival?

4. Some caves contain fish that are blind. These fish have eye sockets and vestigial eyes. Explain how (a) Lamarck and (b) Darwin would account for the origin of sightlessness in these fish and other blind cave-dwellers.

5. How do vestigial structures provide evidence for evolution?

6. Summarize the main points of Darwin's theory of evolution by natural selection.

7. Explain, in the context of evolution and natural selection, common misunderstandings and misinterpretations about the following words: (a) evolution; (b) fitness; (c) theory.

8. Although Lamarck and Darwin explained evolution in different ways, their theories had some similarities. Describe these similarities.

9. Does evolution mean that organisms are becoming progressively better with each generation? Explain your answer.

10. Are a bird wing and an insect wing homologous structures? Explain your answer.

11. How does the study of embryology support evolution?

12. Why is it more accurate to speak of the evolution of populations rather than of individual organisms?

13. Explain why DNA is a useful tool for determining possible relationships among species of organisms. Give an example.

14. Distinguish between fact and theory.

15. Describe how the following items contributed to Darwin's thinking on evolution:
   (a) his experiences on the voyage of the *Beagle*;
   (b) Lyell's *Principles of Geology*;
   (c) the experience of plant and animal breeders; and
   (d) Malthus's essay on population.

16. Much of the theory of evolution has been developed by interpreting certain observations or making inferences about these observations. For each observation below, outline the inferences that Darwin, other scientists, and other naturalists made from this information.
   (a) Populations tend to remain stable in size.
   (b) No two individuals are exactly alike.
   (c) Resources such as food are limited.

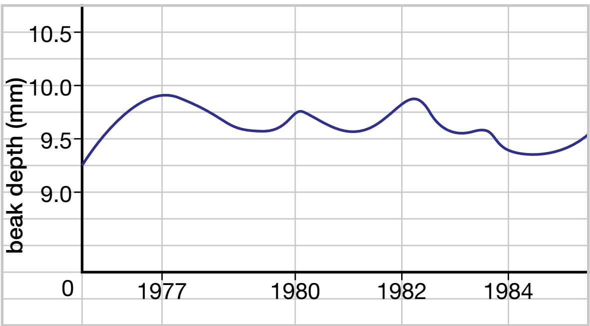
INQUIRY

17. Outline a breeding program that would help you develop a cow that produces more milk. Is your cow a new species? Explain your answer.

18. Design an experiment that would demonstrate variation within a population.

19. Examine the fossils found in the sedimentary rocks shown below. The rocks are older as you go deeper into the rock strata. Explain what these rock strata and the fossils within them can tell you about evolution.

20. You are analyzing the amino acids in the hemoglobin of various species. You find that this protein in rhesus monkeys differs by about eight amino acids from the protein in humans. The difference in this protein between mice and humans is about 26 amino acids, and the difference between lampreys (a primitive fish) and humans is about 125 amino acids. Interpret these data and explain how they relate to our understanding of evolution.



21. This graph shows how the average beak size (depth) in a population of ground finch shifted during particularly wet and dry years. 1977, 1980, and 1982 were all drought years; 1984 was a wet year.
   (a) Interpret these data and explain how they relate to natural selection and the definition of evolution.
   (b) An observer suggested that during drought years all the seeds were large and tough to open. This meant that birds exercised their beaks more, making the beaks stronger. Is this a plausible explanation for these data? Explain your answer.

22. Lamarck's idea of inheritance of acquired characteristics has recently gained support by some scientists. Search the Internet for information on renewed interest in Lamarck's idea as it relates to the immune system. The new ideas suggest that in some instances, characteristics acquired during one's lifetime may be passed on to offspring. Summarize these ideas.

COMMUNICATING

23. Red Island and Blue Island are hypothetical islands 500 km off the coast of South America. Red Island is volcanic in origin and is only five million years old. Blue Island separated from South America over 80 million years ago. Describe the origin of the animals on these islands and how they may be similar to or different from those of South America.

24. Create a time line showing the various individuals whose contributions eventually led to the development of the theory of evolution by natural selection. State their contributions.

25. Richard Dawkins, a popular writer and evolutionary biologist, refers to natural selection as the "blind watchmaker," meaning that natural selection is totally blind to the future. Explain what Dawkins means by this statement.

26. Explain how the examination of proteins can demonstrate relatedness among species.

27. A population of fish in which 95 percent of individuals are light-green and 5 percent are mottled grey lives primarily among kelp that grows on the ocean bottom. A disease kills the kelp, leaving the population without cover. Use a diagram or objects (such as poker chips) to describe how the population might change over several generations.

28. You are a biologist working with a student to make a collection of plants found in Hawaii. You notice that your assistant did not label the island that one of the plants was collected on. When asked, he explained that he did not think this was necessary as this particular plant was found on all of the Hawaiian islands. Write a memo clearly explaining why it is necessary to label the exact island and location where the plant was found.

MAKING CONNECTIONS

29. A tan-coloured insect lives in a sandy area. Some insects in the population show some green in their coloration. The climate begins to cool and become moister; slowly the habitat is covered by green plants. Use Darwin's theory of evolution by natural selection to explain how the insect population might evolve to be green. Use a diagram.

30. Darwin recognized that variation occurred within populations and that these variations could be inherited. He could see the results but could not explain the mechanism. Explain the advances in science and technology that would eventually make Darwin's theory of evolution even more convincing and would help fill in this missing piece of the puzzle.

31. Given your understanding of diversity within species and natural selection, explain why it is important to maintain biodiversity.

32. Two populations of flowers of the same species are found in nearby meadows. There are slight differences in the plants between the two populations, such as flower colour and leaf shape. How might Darwin have interpreted these facts?

33. A farmer sprays an insecticide on a field to combat a beetle that is destroying the crops. The spray works very well the first year it is used. However, after five years of spraying on an annual basis, the insecticide does not seem to be effective any longer and the beetles are still present. Explain how this illustrates natural selection.

34. Analyze the following data. The proteins present in four organisms are shown below. (Each letter represents a protein.) Determine which of the organisms are closely related. Explain your answer.

Organism 1	A, G, T, C, L, E, S, H
Organism 2	A, G, T, C, L, D, H
Organism 3	A, G, T, C, L, D, P, U, S, R, I, V
Organism 4	A, G, T, C, L, D, U

35. Evolutionary biologist Stephen Jay Gould said "Local environments change constantly. They get colder or hotter, wetter or drier, more grassy or more forested. Evolution by natural selection is no more than a tracking of these environments by differential preservation of organisms better designed to live in them: hair on a mammoth is not progressive in any cosmic sense." Explain what is meant by this statement.

36. Recommend ways that would help ensure that non-native plants and animals would not be accidentally brought to islands such as the Galápagos Islands or the Hawaiian Islands. What can be done once non-native plants and animals invade these types of islands?