16.4

Welcome to Lesson 16.4, "Evidence of Evolution." In this lesson, we'll explain how geologic distribution of species relates to their evolutionary history; we'll explain how fossils and the fossil record document the descent of modern species from ancient ancestors; we'll describe what homologous structures and embryology suggest about the process of evolutionary change; we'll explain how molecular evidence can be used to trace the process of evolution; and we'll explain the results of the Grants' investigation of adaptation in Galápagos finches. Charles Darwin's theory depended on assumptions involving many scientific fields. Scientists working in geology, physics, paleontology, chemistry, and embryology did not have the technology or understanding to test Darwin's assumptions during his lifetime. Other fields that are important in evolutionary theory, like genetics and molecular biology, didn't exist yet.

During the 150 years since Darwin published *On the Origin of Species*, research in all these fields has provided independent tests that could have supported or refuted Darwin's work. Darwin recognized the importance of patterns in the distribution of life--the subject of the field called *biogeography*. **Biogeography** is the study of where organisms live now and where they and their ancestors lived in the past. Patterns in the distribution of living and fossil species, combined with information from geology, tell us how modern organisms evolved from their ancestors. Two potential difficulties for Charles Darwin's theory involved the age of Earth and gaps in the fossil record. Data collected since Darwin's time have addressed those difficulties and have provided dramatic support for an evolutionary view of life.

Although James Hutton and Charles Lyell argued that Earth was old, technology in their day couldn't determine just how old. Half a century after Darwin published his theory, physicists discovered radioactivity. Geologists now use radioactivity to establish the age of certain rocks and fossils. If these data had shown that Earth was young, Darwin's ideas would have been refuted and abandoned. Darwin also struggled with what he called the "imperfection of the geological record." Darwin's study of fossils had convinced him and other scientists that life evolved. But paleontologists in 1859 hadn't found enough fossils of intermediate forms of life to document the evolution of modern species from their ancestors. Many recently discovered fossils form series that trace the evolution of modern species from extinct ancestors.

Since Darwin, paleontologists have discovered hundreds of fossils that document intermediate stages in the evolution of many different groups of modern species. Recent fossil finds connect the dots between dinosaurs and birds--and between fish and four-legged land animals. In fact, so many intermediate forms have been found that it is often hard to tell where one group begins and another ends. All historical records are incomplete, and the history of life is no exception. The evidence we do have, however, tells an unmistakable story of evolutionary change. Recently, researchers have found more than 20 related fossils that document the evolution of modern whales from ancestors that walked on land. Several reconstructions based on fossil evidence are shown. This image shows the continuation of the evolution of whales. These organisms spend their entire lives swimming in the ocean.

Modern whales retain reduced pelvic bones and, in some cases, upper and lower limb bones. However, these structures no longer play a role in locomotion. Since Charles Darwin puzzled over how this transition occurred, some presume that missing intermediate fossils disprove Charles Darwin's theory of evolution by natural selection. Consider how rare it is for fossils to form in the first place, let alone to be found by paleontologists.

Many intermediate fossils have been found since Darwin's time, such as fossils showing that land animals descended from aquatic animals, that whales descended from land-living ancestors, and birds descended from nonflying dinosaurs.

By Charles Darwin's time, scientists had noted that all vertebrate limbs had the same basic bone structure. Yet, some were used for crawling, some for climbing, some for running, and others for flying. Darwin proposed that animals with similar structures evolved from a common ancestor with basic versions of that structure. Similar structures that are shared by related species and that have been inherited from a common ancestor are called **homologous structures**. Evolutionary theory explains the existence of homologous structures adapted to different purposes as the result of descent with modification from a common ancestor. Biologists test whether structures are homologous by studying anatomical details, the way structures develop in embryos, and the pattern in which they appeared over evolutionary history. Similarities and differences among homologous structures help determine how recently species shared a common ancestor.

For example, many bones of reptiles and birds are more similar to one another in structure and development than they are to similar bones of mammals. These similarities indicate that the common ancestor of reptiles and birds lived more recently than the common ancestor of reptiles, birds, and mammals. So, birds are more closely related to crocodiles than they are to bats. The key to identifying homology is common structure and origin during development--not common function. A bird's wing and a horse's front limb (which are homologous structures) have similar structures and development but different functions. Biologists have identified homologous structures in many other organisms. Certain groups of plants, for example, share homologous stems, roots, and flowers.

Body parts of organisms that share common functions--but not common structure and development--are called **analogous structures**. The wing of a bee and the wing of a bird are analogous structures. Not all homologous structures have important functions. **Vestigial structures** are inherited from ancestors but have lost much of their original size and function due to different selection pressures acting on the descendant. For example, the hipbones of the bottlenose dolphin are vestigial structures. In their ancestors, hipbones played a role in terrestrial locomotion. However, as the dolphin lineage adapted to life at sea, this function was lost. Why do organisms retain structures that are just vestiges, or traces, of the original? One possibility is that the presence of the structure does not affect the organism's fitness, and so natural selection does not act to eliminate it.

The term *vestigial* is not synonymous with "useless." Sometimes a vestigial structure can have a nonobvious function. For example, the vestigial hipbones of large whales seem to play a role in male reproduction. This is an image of a cat embryo. Development researchers noticed a long time ago that the early developmental stages of many animals with backbones (called vertebrates) look very similar. Recent observations make clear that the same groups of embryonic cells develop in the same order and in similar patterns to produce many homologous tissues and organs. For example, despite the very different adult shapes and functions of the limb bones, all those bones develop from the same clumps of embryonic cells. Evolutionary theory offers the most logical explanation for these similarities in patterns of development. Similar patterns of embryological development provide further evidence that organisms have descended from a common ancestor.

Darwin realized that similar patterns of development offer important clues to the ancestry of living organisms. He could not have anticipated, however, the incredible amount of evidence for his theory that would come from studying the genes that control development--evidence from the fields of genetics and molecular biology. The most troublesome "missing information" for Charles Darwin had to do with heredity. Darwin had no idea how heredity worked, and he was deeply worried that this lack of knowledge might prove fatal to his theory. Today, genetics provides some of the strongest evidence supporting evolutionary theory. A long series of discoveries, from Gregor Mendel to James Watson and Francis Crick to genomics, helps explain how evolution works. At the molecular level, overwhelming similarities in the genetic code of all organisms, along with clearly homologous molecules, provide evidence of common descent.

Also, we now understand how mutation and gene shuffling during sexual reproduction produce the heritable variation on which natural selection operates. One example of molecular evidence for evolution is so basic that, by this point in your study of biology, you might take it for granted. All living cells use information coded in DNA and RNA to carry information from one generation to the next and to direct protein synthesis. This genetic code is nearly identical in almost all organisms, including bacteria, yeasts, plants, fungi, and animals. This is powerful evidence that all organisms evolved from common ancestors that shared this code. In Darwin's day, biologists could only study similarities and differences in structures they could see. But physical body structures can't be used to compare mice with yeasts or bacteria.

Today, we know that homology resulting from common ancestors shows up at the molecular level, too. Homologous proteins have been found in some surprising places. Homologous proteins share extensive structural and chemical similarities. One homologous protein is cytochrome *c*, which functions in cellular respiration. Remarkably similar versions of cytochrome *c* are found in almost all living cells, from cells of baker's yeast to cells in humans. There are many other kinds of homologies at the molecular level. Genes can be homologous, too, which makes sense given the genetic code that all organisms share. One spectacular example is a set of ancient genes that determine the identities of body parts. Known as Hox genes, they help determine the head-to-tail axis in embryonic development. In vertebrates, sets of homologous Hox genes direct the growth of front and hind limbs.

Small changes in these genes can produce dramatic changes in the structures they control. So, relatively minor changes in an organism's genome can produce major changes in an organism's structure and the structure of its descendants. At least some homologous Hox genes are found in almost all multicellular animals, from fruit flies to humans. Some profound biochemical similarities are best explained by Darwin's conclusion: living organisms evolved through descent with modification from a common ancestor. One way to gather evidence for evolutionary change is to observe natural selection in action. But most examples of evolutionary change discussed so far took place over millions of years--which makes it tough to see change actually happening. Some kinds of evolutionary change, however, have been observed and studied repeatedly in labs and in controlled outdoor environments.

Scientists have designed experiments involving organisms from bacteria to guppies to test Charles Darwin's theories. Each time, the results have supported Darwin's basic ideas. But one of the best examples of natural selection in action comes from observations on animals living in their natural environment. Fittingly, those observations focused on Galápagos finches.

When Darwin first saw the Galápagos finches, he thought they were wrens, warblers, and blackbirds because they looked so different from one another. Once Darwin learned that the birds were all finches, he hypothesized that they had descended from a common ancestor. Darwin noted that several finch species have beaks of very different sizes and shapes. Each species uses its beak like a specialized tool to pick up and handle its food. Darwin proposed that natural selection had shaped the beaks of different bird populations as they became adapted to eat different foods.

This was a reasonable hypothesis, but was there any way to test it? No one thought so until Peter and Rosemary Grant of Princeton University came along. The Grants have spent 40 years studying Galápagos finches. They realized that Darwin's hypothesis rested on two testable assumptions. First, for beak size and shape to evolve, there must be enough heritable variation in those traits to provide raw material for natural selection. Second, differences in beak size and shape must produce differences in fitness. The Grants tested these hypotheses on the medium ground finch on the island of Daphne Major. This island is large enough to support good-sized finch populations, yet small enough to allow the Grants to catch, tag, and identify nearly every bird. During their study, the Grants periodically recapture the birds. They record which individuals are alive and which have died, which have reproduced and which have not.

For each individual, the Grants record wing length, leg length, beak length, beak depth, beak color, feather colors, and total mass. Although most evolutionary changes happen too slowly to be observed directly, there are many examples--including the Grants' research--that show evolution in "real time." Take a look at this graph, which shows the survival rate of one species of ground finch during a drought period. What does the graph indicate? The graph shows that during the drought period, a higher percentage of birds with larger beaks survived than those with smaller beaks. The Grants' data show that there is indeed great variation of heritable traits among Galápagos finches. Their data have also shown that individual finches with different-size beaks have better or worse chances of surviving seasonal droughts and longer dry spells.

When food becomes scarce during dry periods, birds with the largest beaks are more likely to survive. As a result, average beak size in this finch population increases dramatically. The Grants have documented that natural selection takes place in wild finch populations frequently, and sometimes rapidly. Changes in food supply create selection pressure that causes finch populations to evolve within decades. This evolutionary change occurs much faster than many researchers thought possible. This work shows that individual variation causes differential reproductive success during times when environmental resources are limiting. Not only have the Grants documented natural selection in nature, but their data also confirm that the effect of natural selection on a population is related to the existence of inherited variation--variation that doesn't matter much under "normal" environmental conditions, but becomes adaptive as the environment changes during a drought.

The Grants' work shows that variation within a species increases a population's ability to adapt to, and survive, environmental change. Without heritable variation in beak sizes, the medium ground finch would not be able to adapt to feeding on larger, tougher seeds during a drought. Advances in many fields of biology, along with other sciences, have confirmed and expanded most of Darwin's hypotheses. Today, evolutionary theory--which includes natural selection--offers insights that are vital to all branches of biology, from research on infectious diseases to ecology. That's why evolution is also called the grand unifying theory of the life sciences.

Like any scientific theory, evolutionary theory is constantly reviewed as new data are gathered. Researchers still debate important questions, such as precisely how new species arise and why species become extinct.

There is also significant uncertainty about exactly how life began. However, any questions that remain are about how evolution works--not whether evolution occurs. To scientists, evolution is the key to understanding the natural world.