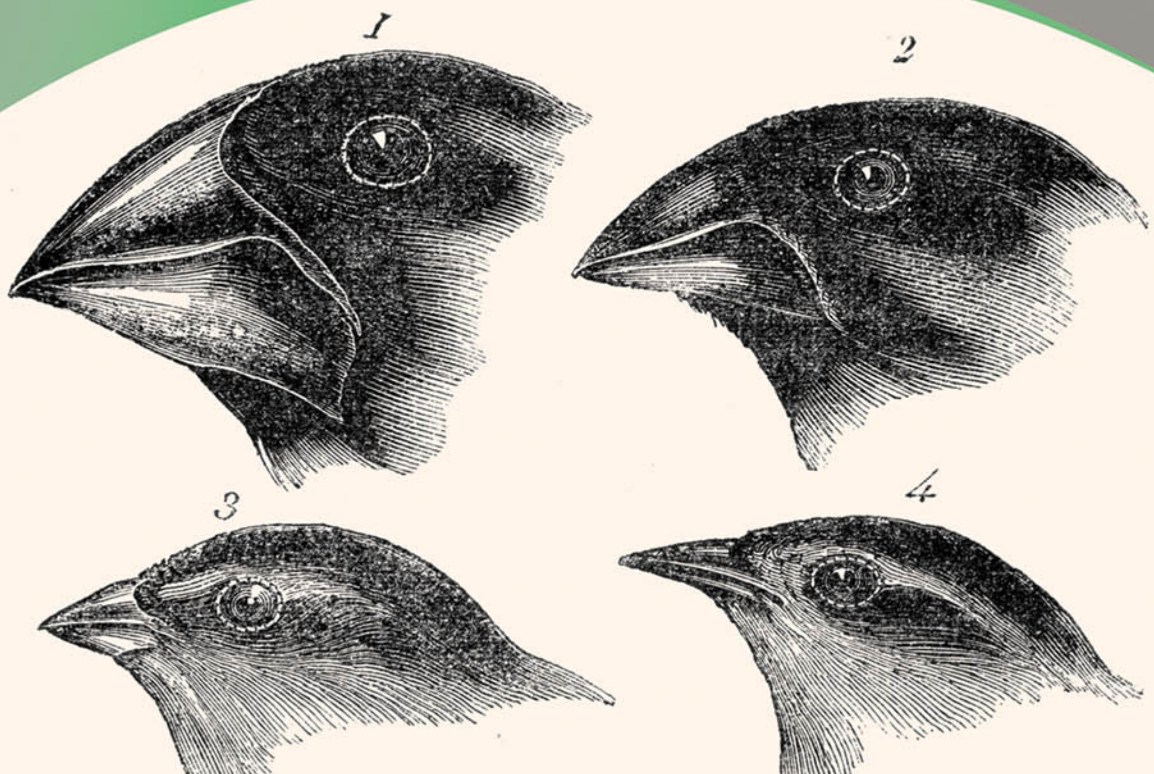
SCIENCE FOUNDATIONS

Evolution

THOM HOLMES



Darwin's Finches

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Evolution

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The Big Bang
Evolution
The Genetic Code
Germ Theory
Gravity
Heredity
Light and Sound
Natural Selection
Planetary Motion
Plate Tectonics
Radioactivity
Vaccines

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CHELSEA HOUSE
PUBLISHERS
An imprint of Infobase Publishing

Science Foundations: Evolution

Chelsea House
An imprint of Infobase Publishing
132 West 31st Street
New York, NY 10001

Library of Congress Cataloging-in-Publication Data
Holmes, Thom.
Evolution / Thom Holmes.
p. cm. — (Science foundations)
Includes bibliographical references and index.
ISBN 978-1-60413-338-7 (hardcover)
ISBN 978-1-4381-3519-9 (e-book)
1. Evolution (Biology)—Juvenile literature. I. Title. II. Series.
QH367.1.H65 2010
576.8—dc22 2010015738

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Text design by Kerry Casey
Cover design by Alicia Post
Composition by EJB Publishing Services
Cover printed by Bang Printing, Brainerd, MN
Book printed and bound by Bang Printing, Brainerd, MN
Date printed: December 2010
Printed in the United States of America

10 9 8 7 6 5 4 3 2 1

This book is printed on acid-free paper.

Contents

1

Building Blocks of Evolution

Evolution is a fact in the same sense that it's a fact that the Earth is round and not flat, [that] the Earth goes round the Sun. Both those are also theories, but they're theories that have never been disproved and never will be disproved.
—Richard Dawkins (b. 1941), British evolutionary biologist

WHAT IS EVOLUTION?

The word ***evolution*** has many meanings. This noun first came into use around the year 1600 and was derived from the Latin word *evolute*, which means "unrolling." The term *evolution* eventually came to mean small changes that took place over a long period of time. The word is used to describe many kinds of things that change in a gradual way: for example, the slowly *evolving* design of the airplane, or the skill of an artist whose work *evolves* year after year from one style to another. Evolution may refer to a gradual and progressive change in society, such as the evolution of religious beliefs or the way in which the government works. Yet, in science, the term evolution has a more specific and precise meaning.

Evolution is a term used in biology. It refers to gradual changes that take place in generation after generation of a species of organism. In scientific terms, evolution is not just a noun with many meanings—it is a **theory**.

The word *theory* is confusing because it, too, has many meanings. When used in ordinary conversation, one may have a theory as to why a football team lost an important game. One might theorize on the outcome of a movie or the reasons why somebody might drink a diet soda with a piece of chocolate cake. These so-called theories are not theories in the scientific sense; they are just opinions and guesswork. Yet, there is nothing speculative about a scientific theory.

In science, a theory is an expression of fact backed by an accumulation of evidence. Although a theory may begin as a suggestion or guess—called a **hypothesis** in science—it attains the status of a theory only after it has been proven with experiments or tests that can be repeated. The proof for a theory can be observed and documented over and over by different people. The theory of evolution is one such theory. It is a fact as surely as Earth rotates on its axis and the Sun rises in the East.

The first life forms on Earth were single-celled organisms that arose in the oceans 3.5 billion years ago. All forms of life on Earth can be traced back to those single-celled beings. The theory of evolution is the only scientifically accepted explanation for how this happened.

Defining evolution is much easier than explaining how it works. This is because evolution comprises more than one simple thread of scientific thought. There are four basic building blocks of evolution:

- biological structures of organisms
- geologic time
- fossils of extinct organisms, and
- microscopic biochemical elements involved in genetics.

Although the study of evolution today involves all of these elements, this was not always the case. There is a rich history of scientific observation and discovery that leads to the modern understanding of evolution.

HISTORY OF EVOLUTIONARY THOUGHT

Early attempts to explain evolution can be found in writings that date back more than 1,000 years. Thinkers in civilizations as diverse as Greece, Persia, and China independently observed clues in the way that organisms adapt to their environments. Although these ideas were not widely understood at the time, these early philosophers were, essentially, inventing the practice of scientific inquiry. They did this by using reason to rise above common superstition and suggest that hidden natural forces were at work in the way that living things developed.

Early Biological Observations

The rise of modern evolutionary theory has roots in Europe. It began during the seventeenth and eighteenth centuries with the work of natural scientists—those who observed and recorded the ways of the natural world. British naturalist John Ray (1627–1705) was a botanist who classified plants and animals according to similarities in their biological structures. His work led to even greater efforts to classify and understand how different organisms are related.

By cataloging the similarities between different organisms, Ray and other early natural scientists helped establish the first building block of evolution: understanding the biological structures of organisms.

Establishing the Geologic Time Scale

The study of geology was the second key building block that led to evolutionary theory. At issue was the age of Earth. Prior to the nineteenth century, most natural scientists held to a literal interpretation of the Christian Bible and believed that God created the universe in six days. They also believed that all living creatures were created by God all at one time. One Irish archbishop, James Ussher (1581–1656), even used the written account of the Bible to calculate the precise date of the creation of Earth. He concluded that creation began at noon on Sunday, October 23, 4004 B.C.E., thus making Earth about 6,000 years old.

However, the work of early geologists suggested that Earth was much older than Ussher's biblical interpretation. Their work indicated that the key to the age of Earth could be found in **sedimentary** rocks—layers in the earth created from the debris of other rocks or the remains of organisms. Geologists observed that such rocks accumulated in layers, with the oldest rocks located on the bottom. These layers of rocks recorded the telltale signs of passing time.

Scottish geologist James Hutton (1726–1797) was one of the first to try and explain the process that created sedimentary rock. He proposed the existence of a natural cycle by which the earth replenished itself. Hutton theorized that rocks first eroded from mountains and were then transported by rivers and streams to the ocean. After settling in the ocean, these rock layers might one day rise to the surface again, slowly forming more mountains. Most importantly, the time needed to complete this natural cycle was enormously long—much longer than human history or any time scale that was in use in the eighteenth century.

Hutton published his innovative ideas in 1785. His idea that the age of Earth could be determined by observing present-day geologic processes was called *uniformitarianism*. Hutton is called the father of geology by many historians, and he can be credited with laying the foundation for modern geology.

Hutton's ideas were innovative but too difficult for most people to understand. The job of communicating Hutton's ideas to a broader audience would fall on the shoulders of another generation of naturalists.

British naturalist Sir Charles Lyell (1797–1875) was born the same year that James Hutton died. Lyell embraced Hutton's theory of uniformitarianism. He traveled widely in search of independent evidence to prove that Hutton's theory was correct. Finally, in 1830, Lyell reduced this complex theory down to a simple guiding principle to explain the age of Earth: *The present is the key to the past.* Lyell's momentous book, *Principles of Geology*, became the bible of geology and was revised twelve times during Lyell's lifetime.

Lyell's seemingly common sense proposition—that observing the present is the key to understanding how geologic features were created over time—was a bold realization in his day. The time needed for layers of Earth to accumulate through erosion, water transport, drought, and other forces has been the same throughout all history. These actions might take thousands, perhaps even millions, of years. Such an idea seemed impossible to people who believed that Earth was only 6,000 years old. Soon, however, many natural scientists and geologists began to support the principle of uniformitarianism through the proof of their own observations.

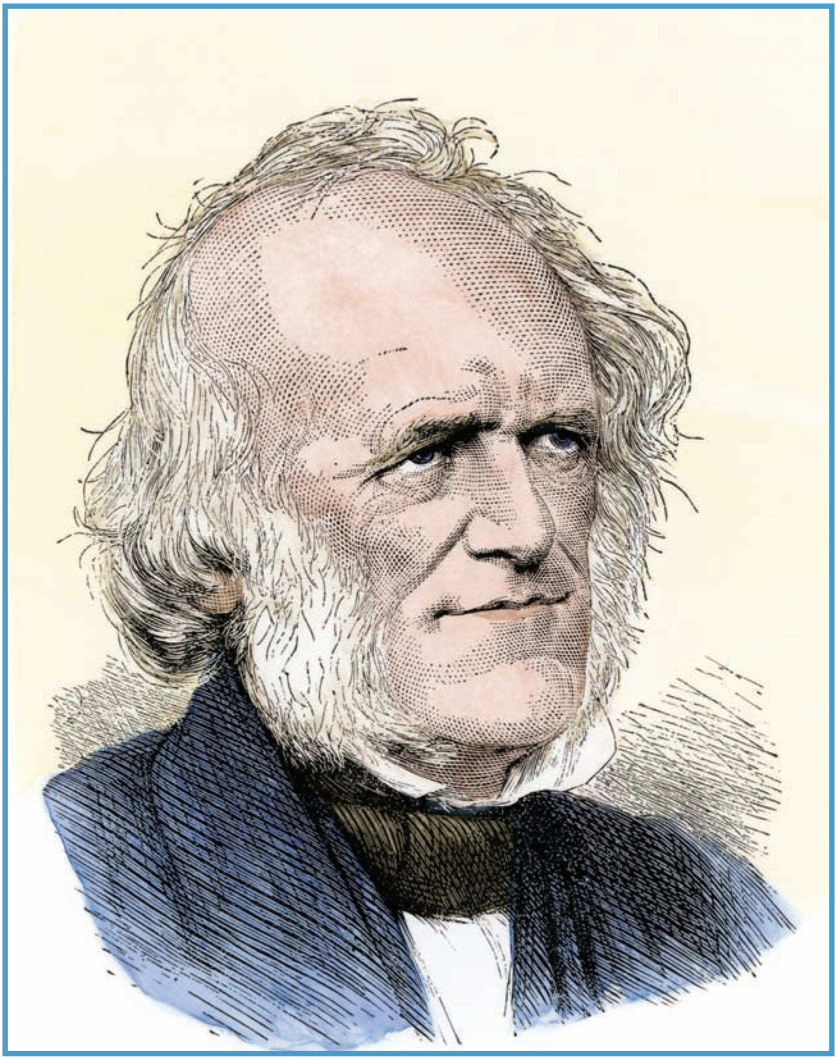

Figure 1.1 Charles Lyell's 1830 book *Principles of Geology* popularized the theory of uniformitarianism, which states that the same natural laws and processes that operate in the universe now have always operated the same way. Lyell was a close friend of famed naturalist Charles Darwin.

Communicating the age of Earth was another challenge. Geologists devised a time scale based on the layers of Earth and how long these layers took to accumulate. This scale is called the **geologic time**

scale and it, too, is another essential building block of evolutionary thought. Without a conception of the great age of Earth, it would be difficult to see how evolution would have time to take place.

By the middle nineteenth century, there was widespread agreement that Earth was many millions of years old. By 1860, Lyell estimated that the planet was a minimum of 200 million years old and perhaps as much as 340 million years old. The measurement of the age of Earth was later improved by the discovery of radioactivity in 1895. Radioactive isotopes found in certain rocks decay at a fixed rate over many millions of years. Measuring the decay signals of these isotopes makes it possible to date layers of Earth with great accuracy. Using such techniques, the age of Earth is currently estimated to be 4.5 billion years.

Fossils of Extinct Organisms

The third important building block in the study of evolution is an understanding of **fossils**. The word *fossil* means "something dug up" in Latin. Fossils are the scientist's key to understanding prehistoric life. A fossil is the trace of any organism—plant or animal—that has been preserved in the layers of the Earth.

Fossils have fascinated people since before the recording of human history. Archaeological evidence shows that early humans living in prehistoric France made primitive jewelry from fossil shells 35,000 years ago. It wasn't until the nineteenth century, however, that a satisfactory scientific explanation was accepted for the origin of fossils.

Prior to the nineteenth century, natural scientists were puzzled by the nature of the organisms seen in fossils. Naturally, fossils appeared to be traces of long-dead organisms. Some of these organisms were familiar, such as fossil leaves and seashells. But many fossils revealed creatures that were wildly different from anything known to still be alive. Early attempts by explorers, natural scientists, and educators to explain fossils seem laughable to us today. In 1663, Otto von Güricke (1602–1686), a physicist and burgomaster of Magdeburg, Germany, cobbled together the incomplete remains of a prehistoric elephant and honestly believed that he had discovered the bones of a unicorn. One of the elephant's tusks was thought to be that mythical creature's horn. Similar cases of mistaken identity were made throughout the eighteenth century in Europe and America.

Advances in geological thought in the early nineteenth century led to the discovery of more and more fossilized organisms. Scientists realized that many kinds of animals that had been alive in the past were no longer alive in the present. This led to the radical idea that species could become extinct.

Extinction is the irreversible elimination of an entire species of plant or animal. Extinction occurs because a species cannot adapt effectively to changes in its environment. These changes may be caused by physical changes to the earth and climate or the rise of better adapted competition, or may have biological causes such as disease.

An understanding of fossils coupled with knowledge of geology provides a view of the deep past that is crucial to the study of evolution. Even though the fossil record is filled with gaps, it provides many examples of extinct organisms that bear anatomical resemblances to other organisms. Understanding the age and structure of extinct organisms helps to piece together trends in evolution.

Putting It All Together: The Emergence of Evolution Science

The individual who is most closely associated with the theory of evolution is British naturalist Charles Darwin (1809–1882). As in most major scientific endeavors, breakthroughs in evolutionary thought were achieved in small steps and by many people, some working before, some during, and some after the time of Darwin. Darwin is so closely associated with evolution because he was perhaps more successful than his contemporaries in illustrating and explaining the processes of evolution in a way that most people could understand.

Darwin had Lyell's work, and he understood uniformitarianism: The present is the key to the past. Not only did Lyell's work provide an appropriately long time for the mechanisms of evolution to take place, but it also inspired Darwin to sharpen his own observation of the present as a window on the past.

Another influence on Darwin was his grandfather, Erasmus Darwin (1731–1802). Among Erasmus Darwin's numerous writings and letters, many of which his grandson Charles is known to have read, were speculations on evolutionary concepts. In a book of verse called

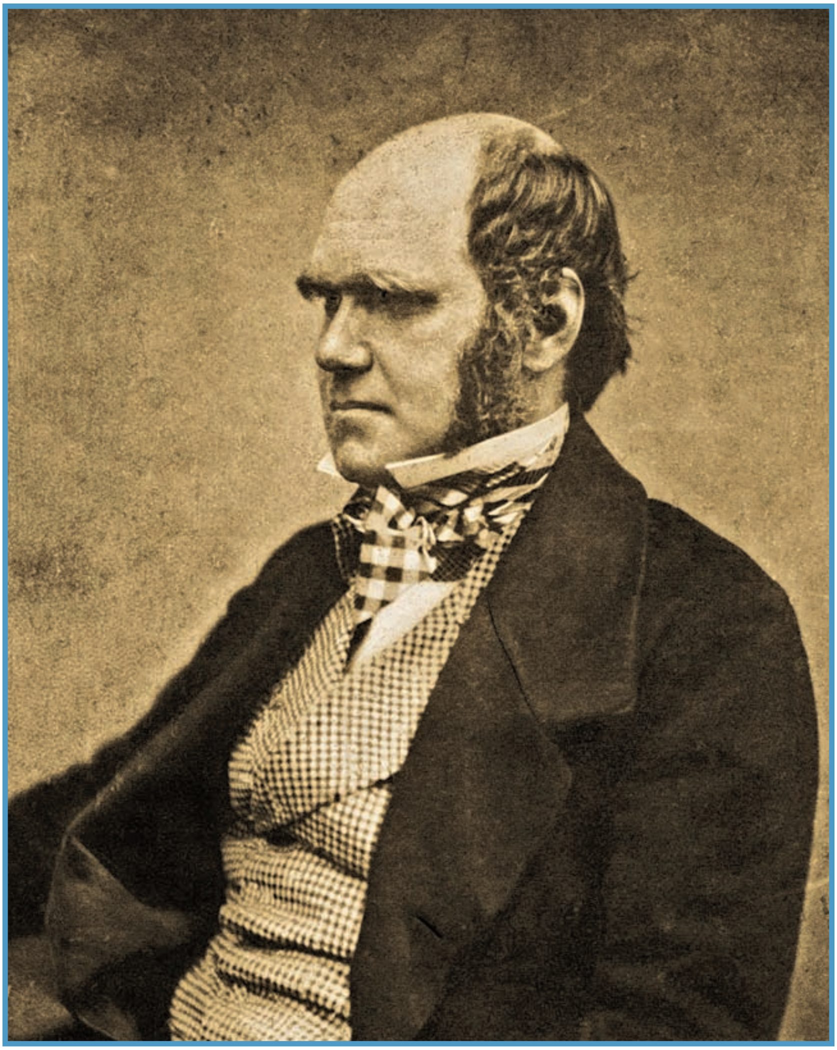

Figure 1.2 Charles Darwin is seen here in 1854 at age 45. At the time, he was working on his book *On the Origin of Species by Means of Natural Selection, or the Preservation of Favoured Races in the Struggle for Life.* For its sixth edition, printed in 1872, the book's title was shortened to *The Origin of Species.*

Zoonomia, published in 1794, Erasmus Darwin wrote that "organic life began beneath the waves," thus suggesting that all animal species had a common ancestry in the oceans.

Before the term *evolution* was widely used, the process of evolution was known by a variety of other names. Most of these names referred back to the observable changes that can be seen in a species from generation to generation. Terms such as *transformism* and *the transmutation of species* or *the transformation of species* often were used to describe this process for which the underlying mechanisms were not yet fully understood.

The most popular theory of evolution before Darwin's time was developed by French scholar Jean-Baptiste Lamarck (1744–1829). Writing long before Darwin, Lamarck thought that an organism could be altered by changes in the environment, and that such alterations could be passed along to offspring. Lamarck's most often cited example was that of the neck of the giraffe. According to Lamarck, giraffes were descended from short-necked ancestors who had to stretch and stretch themselves higher and higher to reach the tree branches where the vegetation they ate was located. Because of this stretching, the neck of the ancestral giraffe became slightly longer, and the length of the neck was passed along to the next generation. Over many generations, giraffes with longer and longer necks came into being.

Lamarck might be given credit for recognizing the important relationship between a species and the environment, but he offered no explanation for how these traits were passed along. His theory met with serious objections based on some simple observations. For example, if an animal could pass along a physical trait such as a longer neck, why didn't it pass along other kinds of physical traits such as a lost tail, a damaged ear, or a lost limb?

Charles Darwin was born into a large, wealthy family and raised in the English countryside. He spent his youth enjoying the outdoors, fishing, hunting, and becoming a keen observer of nature. He was sent to college to study medicine and theology but also was intensely fascinated with the study of geology and Lyell's theories.

In Darwin's time, it was generally accepted that the biological nature of species changed over time but that no scientific mechanism was yet known to explain how this happened. Darwin doubted Lamarckism for a very simple reason: One could observe more variation in living species than could be explained by Lamarck's theory. Darwin's own experience raising domestic pigeons told him that one could selectively breed in and breed out certain desired or undesired traits that were passed along to the next generation, despite the fact that all of the birds were exposed to the same environment. Thus, began Darwin's quest for a theory that would explain how this happened.

At age 22, after graduating from Cambridge University, Darwin joined a scientific expedition on a five-year voyage that circled the globe and provided astonishing opportunities for the young naturalist. During his voyage on the HMS *Beagle* from 1831 to 1836, Darwin immersed himself in geological work and the description of animal species that the expedition encountered. His discovery of fossils of creatures that shared traits with living forms gave him reason to believe that modern animals were descended from long-extinct ancestors.

Of most relevance to Darwin's emerging ideas about species were observations that he made while exploring the Galápagos Islands, which lie in the Pacific Ocean off the coast of Ecuador. Darwin noticed that each of the islands in the system shared many of the same species of animals, but with significant variations from island to island.

The traits of Galápagos finches, for example, were of particular interest. Although it appeared that the island finches were descended from finches on the mainland, each island produced finches with differences in particular physical traits, primarily the shape and size of the beak. Each group of island finches was adapted for a particular kind of food that was most prevalent on a particular island: a heavy beak for crunching big seeds; a thick, short beak for eating leaves, buds, and fruits; or a straight, pointed beak for picking insects from tree bark.

Darwin's theories were based on two important observations: (1) offspring inherit physical traits from their parents; and (2) offspring are never identical to their parents. Each of the offspring includes a unique combination of characteristics that it inherits from its parents. He also observed that a species produces many more offspring than those that will survive long enough to reproduce on their own.

Darwin drew two significant conclusions from these observations. The first was that in our world of many diverse living things, there is an ongoing struggle for survival. Darwin wrote that "many more individuals of each species are born than can survive." He saw that the variation of traits within a given species makes some individuals more likely to survive. The reasons why some individuals survive and others do not led Darwin to his second conclusion.

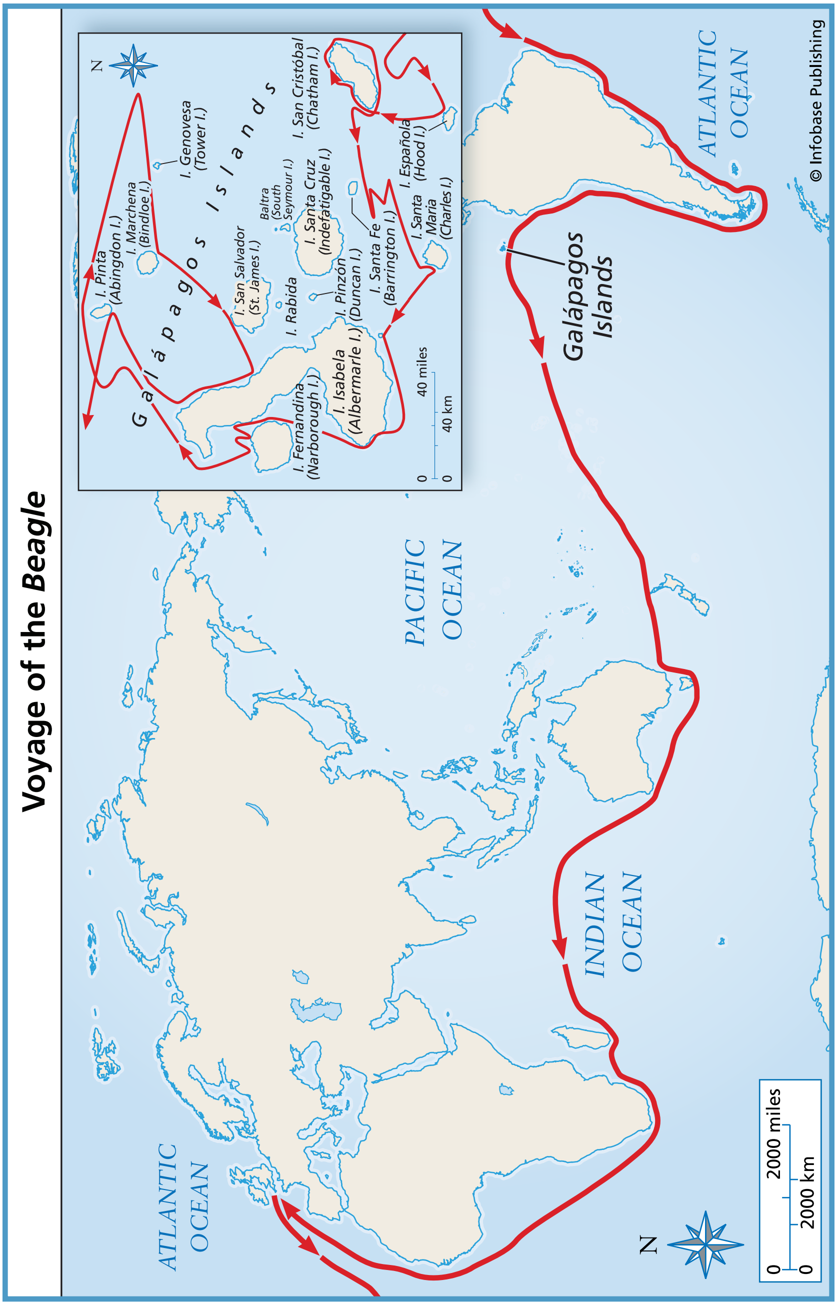

Figure 1.3 At 22 years old, Charles Darwin set sail on the HMS *Beagle* as the ship's naturalist. It sailed around the world, and made a stop at the Galápagos Islands (*inset*), where Darwin made many of the observations that led him to develop his theory of natural selection.

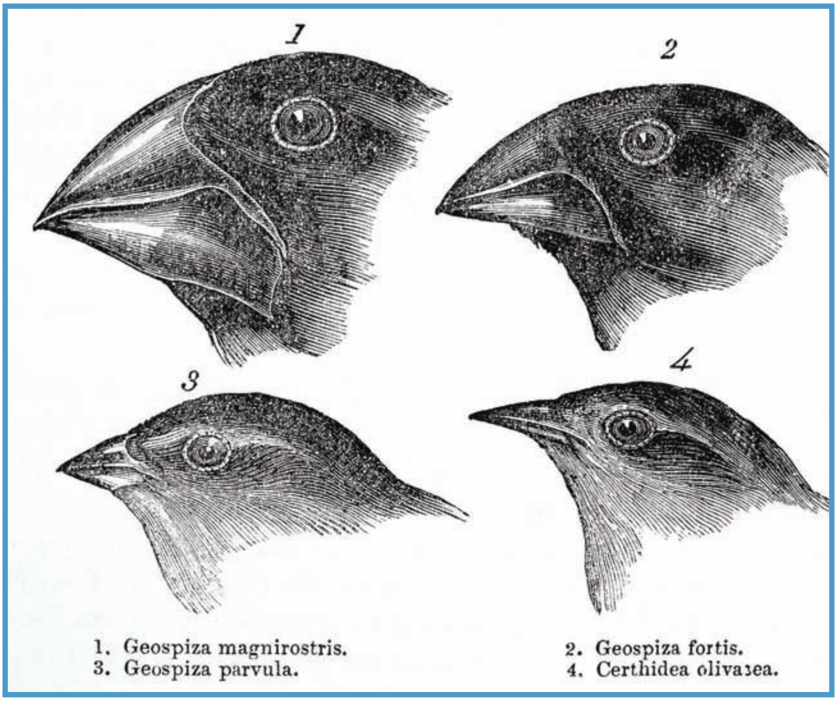

Figure 1.4 Charles Darwin's *Journal of Researches* (1839) included this image of the beaks of four species of Galápagos finches. He noted that each group of finches on the island had beaks adapted for eating specific foods.

Given the complex and changing conditions under which life exists, those individuals with the most favorable combination of inherited traits may survive and reproduce while other individuals may not. Nature is the judge and jury of which individuals make the grade. For this reason, Darwin called this process **natural selection**, meaning that the natural laws of inheritance provided or assured, by chance, some members of a species to be better equipped for survival than others.

On his return to England, Darwin meticulously documented his theory of natural selection and continued to make observations. He shared his ideas with colleagues but was slow to publish his views. Darwin drafted short articles about natural selection in 1842 and 1844, but he felt he needed to continue his research and document

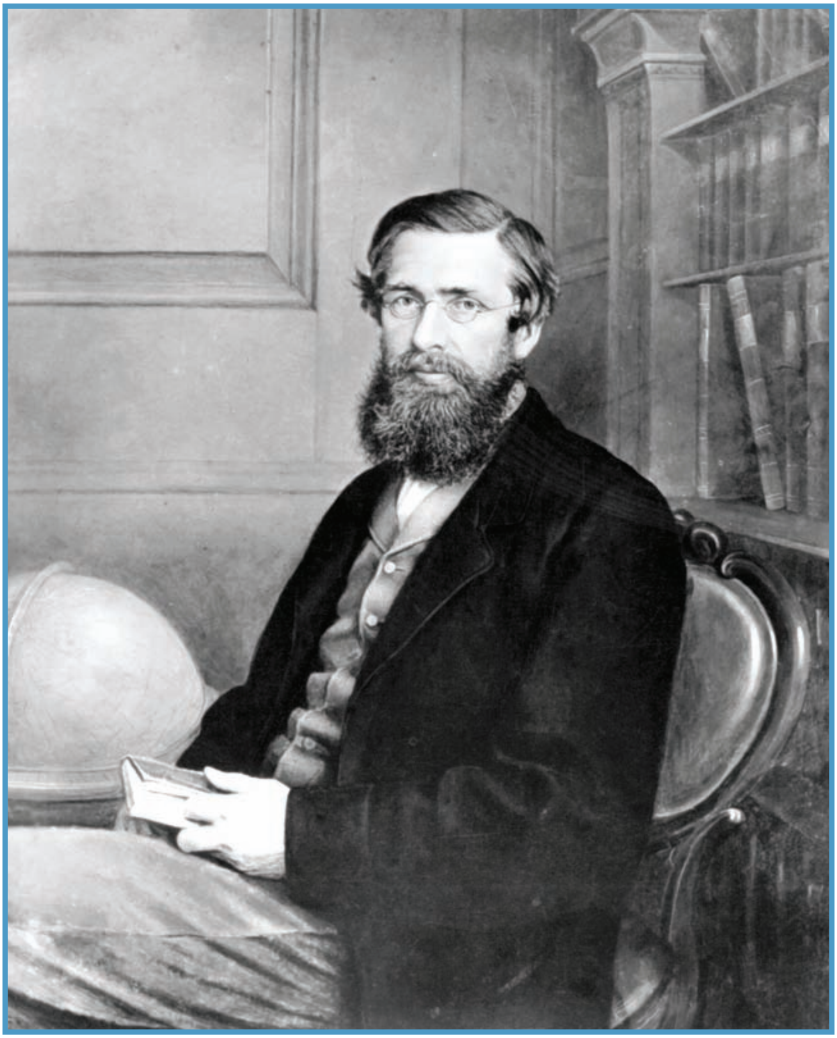

Figure 1.5 Alfred Russel Wallace, seen here circa 1860, did his fieldwork in the Amazon River basin and the Malay Archipelago (islands between the Indian and Pacific oceans).

the evidence he found before he was ready to formerly publish his views for the world.

Darwin was not alone in this quest. Alfred Russel Wallace (1823–1913) was another British naturalist, working independently of Darwin. While on his own travels, Wallace studied and collected specimens of plants, insects, and birds, much as Darwin did. Wallace also arrived at some of the same conclusions as Darwin.

Wallace published a paper in 1855 that suggested that the development of new species was driven by environmental forces. Even more startling to Darwin was a paper Wallace sent to him in 1858, in which the younger naturalist described the process of natural selection. Darwin's heart sank. Although not normally a competitive man, Darwin feared that Wallace might receive full credit for the theory of "natural selection" that he himself had been working on for nearly 30 years. In response, Darwin dashed off a paper about his own theories.

The papers by Darwin and Wallace were read at the same meeting of London's Linnaean Society in 1858. Later, Darwin's wife, Emma, Charles Lyell, and others urged Darwin to follow up his own work with a more thorough explanation of his theory. The result was Darwin's seminal book *On the Origin of Species by Means of Natural Selection*, published at the end of 1859. Although even Darwin himself gave Wallace credit for having also developed the theory of evolution by natural selection, the spotlight landed on Darwin because of his success at communicating the theory beyond the scientific community.

Darwin's views were not universally accepted in his time. Even though his observations were astute and his deductions convincing, Darwin was constrained, as were all nineteenth-century scientists, by a lack of knowledge regarding genetics, the fourth important building block of evolution. Nevertheless, Darwin deduced all of his theories regarding evolution by understanding the relationship between living organisms, their offspring, and their habitat.

DNA: AN INSTRUCTION MANUAL FOR LIVING THINGS

The fourth building block of evolution is the biochemical process that allows traits to be passed along from an organism to its offspring. This process is driven by changes to the genetic code—the **DNA**—of organisms. These genetic changes are then passed along to the next generation of a species. These changes sometimes result in dramatic changes to a species over many generations.

DNA, or **deoxyribonucleic acid**, is a molecule that is found in cells. It contains the master plan for the growth and shape of an organism. DNA contains **genes**, each of which is a section of DNA that controls one or more inherited traits. The science of genes and DNA is called **genetics**. When two organisms mate, each one of their offspring contains a unique combination of genes derived from the parent's DNA. The genetic basis of evolution is explored in Chapter 3.

Living species represent moments in the ongoing process of evolution. There is no such thing as a species that has stopped evolving. Humans and all other species on the planet continue to change with each successive generation, even if the changes occur only in ways that are nearly imperceptible. Evolution is influenced by inherited traits and changes in the environment. Knowing how these kinds of changes affected past organisms is a key to seeing the future of life. To know the past is to understand the present.

2

The Classification of Living Things

LIVING AND NON-LIVING THINGS

What is a living thing? Is it an object that moves? If that were the case, you could argue that a basketball rolling down a hill is a living thing, but it clearly is not. Living things, or organisms, all share several traits that separate them from the world of non-living, inorganic objects. Perhaps a more analytical way to deal with this question is to ask: What makes a thing alive?

All living things, no matter how big or small, have the following five traits in common:

- ***Living things are composed of one or more cells.*** Cells are the basic building blocks of organisms. There are many kinds of cells and within each are complex molecules that carry out the fundamental actions needed to sustain life.
- ***Organisms can store and spend energy.*** A living thing can get fuel from the world outside of itself and convert it into energy. Food and sunlight are examples of outside energy sources. Creating energy also produces waste. A living thing must be able to dispose of these byproducts. One result that comes from the storing and spending energy is growth, another characteristic of all living things.

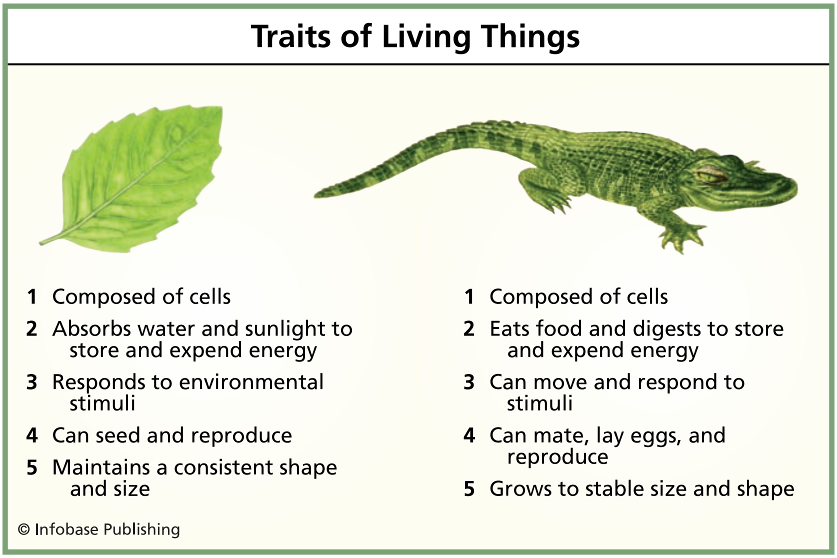

Figure 2.1 All living things—plants and animals being somewhat unique to each other—have similar traits.

The combination of these functions is called **metabolism**. Breathing, eating, and going to the bathroom are all metabolic functions.

- ***Living things respond to stimuli.*** When dust flies into your face, you instinctively close your eyes to protect them. You are responding to a stimulus in your environment, namely the dust blowing in your face. You respond to many such stimuli every day without even thinking about it. The same is true for all kinds of organisms. Yet, not all responses are so obvious. When a bear is hibernating, it looks as though it is merely sleeping. But inside, the bear's bodily functions have slowed down considerably in response to the external stimulus of the cold weather. Some stimuli cause a gradual but more obvious change to an organism, as when a dog sheds hair during the hot summer or when a plant leans toward the sun to catch more light.
- ***Organisms can reproduce.*** Creating other organisms of the same kind is a unique trait of living things. When an

organism reproduces, it creates a kind of copy of itself. Without the ability to reproduce, a species would disappear. Reproduction passes along hereditary molecules to the offspring, ensuring the continuance of the species.

- ***Living things maintain a stable biological state.*** A dog is always a dog, and a leaf is always a leaf. Living things follow the rules set forth in their DNA to become and remain whatever they are. They do not become other kinds of things, even when their environment changes.

All organisms, from a single-celled bacterium to a giant blue whale, share all five of these essential traits. Still, there are sometimes exceptions to these rules, and looking at some exceptions is a good way to understand the rules.

In some respects, for example, fire appears to be a living organism. Fire eats and breathes. It consumes fuel and converts it to heat. Fire consumes oxygen, as do living and breathing organisms. Fire responds to stimuli such as wind and water. It seems to grow. However, fire is no more alive than a rock because it lacks living cells and has no metabolism. The idea that fire is a living thing makes for a good story, but nothing more.

In another example, a mule is a sterile animal that cannot reproduce. Does this mean that it is not a living thing? Not at all. Mules are born as the offspring of a donkey and a horse. Neither male nor female mules can reproduce. A mule is a **hybrid**, an offspring of two animals of different species. Many kinds of hybrids cannot reproduce. A mule is certainly alive in all other respects, so a mule is considered an exception to the rules that define life.

More puzzling is the case of a virus, a microscopic particle that can make a person sick. A virus is thousand times smaller than a living cell. A virus has genetic material, but it can only reproduce if it is inside a living cell. In this way, a virus is a kind of parasite. A virus is inactive and seemingly dead when it is outside a host cell. By definition, then, a virus is not an independently living thing. A virus can become part of a living thing if it invades a cell, but it does not have cells of its own. Viruses can certainly make living things feel sick, and they seem to come alive when they are activated and reproducing, but they are not living things all by themselves.

CAROLUS LINNAEUS AND THE KINGDOMS OF LIVING THINGS

We live in a world of classified things. Every aisle in the grocery store is classified by a different sort of food, such as meats and vegetable, or type of household item, such as mops and mushrooms. Whenever you download music from the Internet, you choose from classifications such as rock, pop, classical, hip hop, jazz, electronic, and many other kinds of music. Sometimes these big categories are made up of even smaller categories; for example, rock music might also be broken down into alternative, heavy metal, southern rock, or rock legends. People definitely like to classify things and bring order to the choices in our lives. Classification allows us to understand the world around us by examining the traits that make up different things. The ability to categorize also provides a common vocabulary and point of reference for those who want to share their interest in a common group of things. Without classification, imagine how difficult it would be to describe the kind of music you like or compare one kind of mushroom with another.

Classification is important to the study of living things. By providing rules for categorizing different kinds of plants and animals by their characteristics, classification provides clues to the ways in which different kinds of living things are related to each other. Observing the similarities and differences in living things provided Darwin with some of the clues that he needed for his explanation of evolution.

Much classification work had been done by other natural scientists before Darwin. The Greek philosopher Aristotle (384 B.C.–322 B.C.) was perhaps the first scientific thinker to attempt to classify life. He divided organisms into the two kingdoms of plants and animals. Aristotle's two kingdoms stood the test of time for several centuries. British naturalist John Ray (1627–1705) was a botanist who used observation to classify plants and animals according to similarities in their structures. He was the first scientist to use the terms **genus** and **species** to classify different plants and animals. A genus is a major subcategory of a larger group, or family of related organisms. A genus consists of one or more species, which are the most basic biological unit of living organisms. All members of a species can interbreed and produce fertile offspring.

Ray was followed by the great Swedish botanist Carolus Linnaeus (1707–1778), who introduced an intricate new method for grouping and naming organisms. Linnaeus began by placing all living things into one of two overall categories: plants or animals. Linnaeus then suggested that living things could be further organized into a grand hierarchy of groups within groups. He recognized a species as the most basic biological unit of life, and grouped species within ever-widening categories of organisms based on the similarities of their visible structures. Dogs, for example, are part of a group, the Carnivora, or carnivorous (meat-eating) animals, which also includes such animals as cats, bears, pandas, weasels, sea lions, and walruses. The Carnivora, in turn, are part of a larger group, the Mammalia, or mammals. Mammals, in their turn, are grouped in yet a larger group with other animals with backbones: the Chordata, or vertebrates. The vertebrates include fish, amphibians, reptiles, mammals, and birds. The vertebrates are then grouped with all animals without backbones to form the kingdom of animals. The Linnaean classification method was widely accepted and refined for more than 200 years until genetic studies provided a more accurate method of determining the evolutionary relationships of organisms by looking at their DNA.

In choosing the species as his basic building block for classification, Linnaeus was the first scientist to establish a rule that affected the way that evolution works: traits are passed along from one generation to the next through genetic material. Although Linnaeus and other scientists of his time had no direct evidence of genes, DNA, or the way in which traits are passed from one generation to the next, these scientists were able to establish rules behind evolution that were observable in living organisms.

Using the Linnaeus method, all life could be classified using seven categories: kingdom, phylum, class, order, family, genus, and species. A diagram of a human being made by using the Linnaean system is shown in the accompanying table (Table 2.1).

Linnaean Classification of Humans

The following table shows where humans fit within the Linnaean classification of organisms.

Table 2.1

Linnaean Category	Name of Category in the Classification of Humans	What the Category Includes
KINGDOM	Animalia	All living and extinct animals
PHYLUM	Chordata	Animals having a backbone (vertebrates)
CLASS	Mammalia	Warm-blooded vertebrates, the females of which have mammary glands
ORDER	Primates	Living and fossil monkeys, apes, and prosimians, including humans
FAMILY	Hominoidea	Living and fossil apes and humans
GENUS	Homo	Living and extinct members of the Family Hominoidea
SPECIES	Homo sapiens	Modern humans, the only surviving humans

MODERN CLASSIFICATION: THE DOMAINS OF LIFE

Even though all organisms share the five essential traits explained above, organisms can still be extraordinarily different from one another. Linnaeus provided the first widely accepted rules for classifying life. His system for dividing living things into two kingdoms was based on what could be seen with the naked eye. The next breakthrough in the classification of life would take scientists beyond the world that can be seen with the unaided eye.

By the late nineteenth century, biologists discovered through the use of microscopes that organisms were composed of tiny cells. The first microscopes were not powerful enough to reveal the internal structure of a cell. Because they were unable to see inside the cell, most biologists assumed that each cell was a kind of grab bag of molecules. This assumption changed entirely in 1945, when Albert Claude (1899–1983) and his colleagues at the Rockefeller Institute in New York City published the first electron micrograph of an intact cell. Magnified 1,600 times, the image revealed that cells

Figure 2.2 Carolus Linnaeus is thought to be the first person to place humans in a biological classification system. He listed humans under *Homo sapiens* among primates in the first edition of his book *Systema Naturae* (1735).

contained many small functional structures. With the door now open to the world of the cell, many biologists turned their attention to deciphering these minute structures. As a result, some startling changes took place in the definitions of life-forms and our understanding of evolution.

The first great departure from the Linnaean two-kingdom system came in 1959 with the work of ecologist Robert H. Whittaker (1920–1980). Whittaker refined the definition of plant and animal kingdoms by considering their cellular structure. His system recognized two basic kinds of cells: those with nuclei, the **eukaryotes**, and those without nuclei, the **prokaryotes**. Whittaker then established five kingdoms of life based on the structure and function of cells. The Monera included prokaryotes, represented only by bacteria. All other organisms, the eukaryotes, were divided into four additional kingdoms based on their method of processing nutrition: Plants, which use **photosynthesis**; Animals, which use ingestion; and Fungi and Protists, which use absorption.

Genetic molecules, including DNA, can also be used to decipher the evolutionary links between living things and extinct organisms from the past. This is done by studying fragments of genetic molecules that are sometimes found preserved in fossils. DNA contains the best clues yet for accurately categorizing organisms within proper groups. This is because DNA can reveal inherited traits that link different organisms with common ancestors.

Another breakthrough in the classification of living things came in 1977 when molecular biologists Carl Woese (b. 1928) and George Fox (b. 1945) were studying the genetic makeup of bacteria. While studying samples of "bacteria," Woese and Fox stumbled upon a form that was different from other bacteria. This form became known as an anaerobic organism, which means that it does not require oxygen to live. Instead, it creates energy by converting carbon dioxide and hydrogen to methane. This microbe was so unlike any form of life that had been previously known that Woese and Fox considered it to be a form that was yet to be defined. The two men classified this microorganism within a new group that they called Archaebacteria ("ancient bacteria") because they felt that it represented an ancient form of life.

At the same time, Woese and Fox argued for a change in the five-kingdom system of classification. Instead of five kingdoms, they proposed a system of classification that uses three **domains**—the Archaea, Bacteria, and Eukarya—to occupy a level of classification higher than the kingdom. The domain Archaea includes the archaebacteria, the domain Bacteria includes organisms that have prokaryote cells other than Archaea, and the domain Eukarya includes all life with eukaryote cells. Within these three domains, Woese and Fox defined six kingdoms: Archaebacteria, their newly defined form of life within Archaea; Bacteria, the only member of the domain Bacteria; and the Protista, Fungi, Plantae, and Animalia kingdoms, all of which are within the domain Eukarya.

The three-domain classification system was not widely accepted by other scientists for several years. The most convincing evidence for it was discovered in 1996 when the full genetic DNA sequences of archaebacteria and bacteria were completed, showing how fundamentally different they were from each other.

Types of Organisms

The three-domain system is widely accepted today because of evidence found at the base level of all organisms: the chemistry of their cells. This system provides a common reference point for any scientist who studies the evolution of different kinds of organisms.

The three domains of life are:

- ***Bacteria***: The earliest known fossils of life-forms are those of blue-green algae, which are bacteria that date from about 3.5 billion years ago. Bacteria are single-celled organisms whose cell structure is less complex than those found in plants and animals. A bacterial cell does not have a nucleus. Instead, the cell's DNA floats freely in the cell's cytoplasm—the gelatinous fluid that fills most cells—as a tangled strand called a nucleoid. Even though bacteria consist only of a single cell, they are far from being simple organisms. They are one of the heartiest and most adaptable life-forms on the planet. Some bacteria can live in freezing temperatures. Others can live in liquid that is hotter than boiling water. Bacteria consume a wide variety of substances for food, including mere sunlight, sugar, starch, and even sulfur or iron. One species of bacteria can withstand a blast of atomic radiation 1,000 times greater than would be needed to kill a human. Bacteria usually get a bad rap because some forms can cause disease in animals and plants. But bacteria are all around us and serve many useful functions. Blue-green algae aid in the production of nitrogen, an element in the air

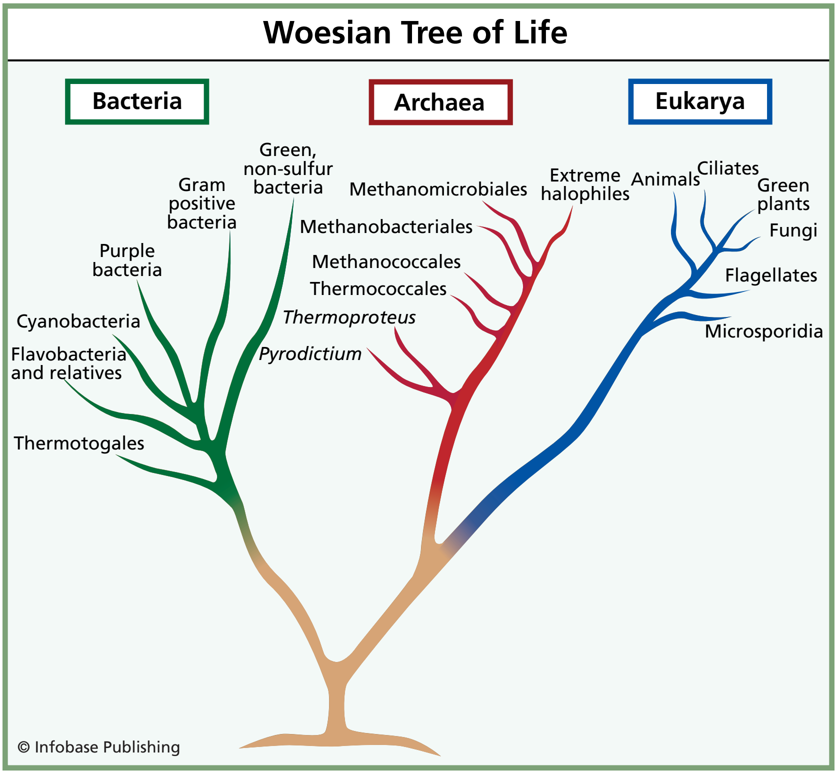

Figure 2.3 Carl Woese created the tree of life as a three-domain system based on genetic relationships.

that is essential for plant and animal growth. Bacteria live in the guts of living animals, helping to digest food and keep the animal healthy. Bacteria break down decaying leaves and other organic matter, thereby returning nutrients to the soil. They also add that little tart taste to yogurt and sourdough bread.

- ***Archaea***: This group of unusual organisms probably includes the first kinds of creatures that inhabited Earth. Archaebacteria live in environments that would be the harshest imaginable for other kinds of life. These prokaryotic microbes are composed of single cells and resemble bacteria, but their ability to survive without oxygen makes them unique among organisms. Their

Figure 2.4 Red tube worms belong to the domain Archaea. They live a mile or more below the surface of the Pacific Ocean and can tolerate extremely high temperatures and sulfur levels.

tolerance for extreme temperatures is also unusual, with some being able to live near deep ocean volcanic vents where temperatures reach 250°F (121°C). Archaebacteria thrive in some of the planet's more inhospitable places, such as hydrothermal volcanic sea vents where superheated water squirts out through cracks in the ocean floor, salt pools, and even hot springs where no other life can survive. In the absence of sunlight, archaebacteria use a process called chemosynthesis to convert inorganic compounds such as hydrogen sulfide and carbon dioxide into energy. Archaebacteria often live inside a host organism. Around hydrothermal sea vents, archaebacteria provide food for animals such as tube worms, clams, and mussels, which depend on them for the absorption of nutrients from the chemically harsh sea water in which they live. These archaebacteria convert inorganic matter from vent water into food for their animal hosts.

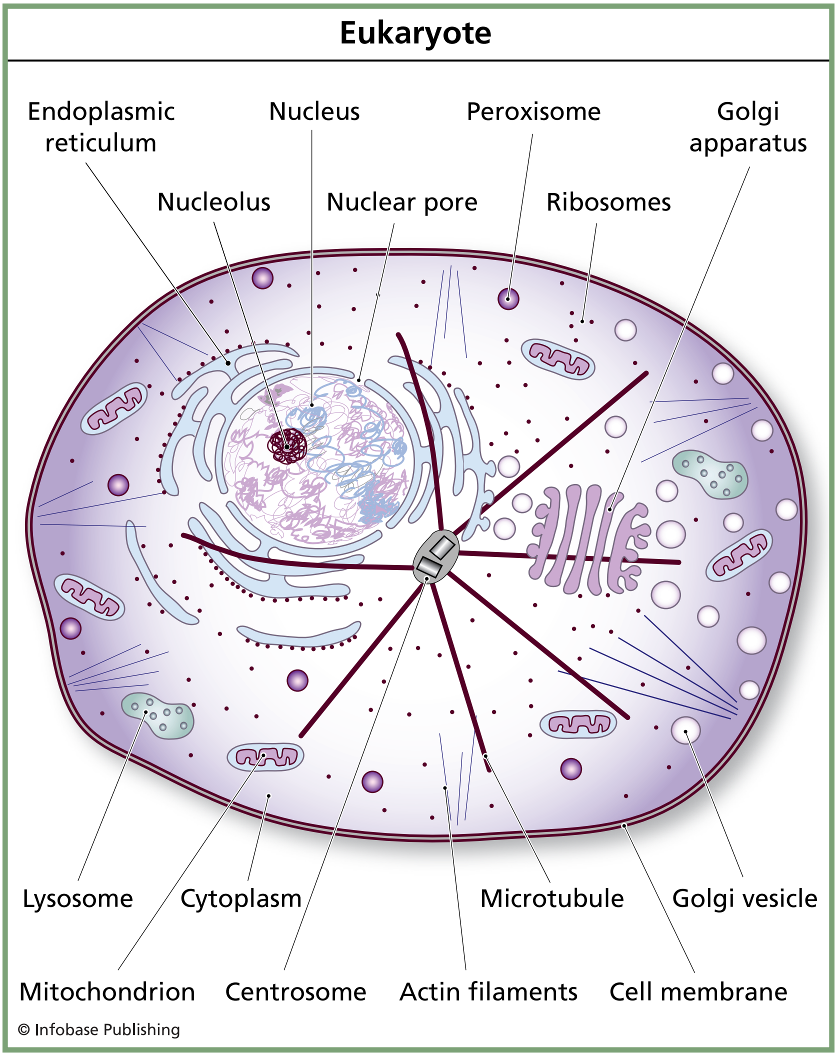

Figure 2.5 The domain Eukarya features living things that have eukaryotic cells. Each cell includes a nucleus with a DNA genome.

- ***Eukarya***: This group includes plants, animals, fungi, and protists, all of which have a eukaryote cell type. Considered to be more complex than single-celled Bacteria and Archaea, the multicellular Eukarya possess cells that can work together and take on special functions for the good

> of the organism. The eukaryote cell structure allows multicellular organisms to build larger, more complicated bodies. This is the reason why this life-form was able to rise above its microscopic origins and build creatures that are as different from each other as ants, azaleas, anteaters, and the dinosaur *Apatosaurus*.

Yet as different as they may be, all three domains of organisms are subject to the natural laws of evolution.

CLASSIFICATION LEADS TO GREATER UNDERSTANDING

In the two hundred and fifty years since Linnaeus introduced his classification system, science has broadened its knowledge of living things by leaps and bounds. By 1758, Linnaeus had succeeded in classifying about 12,100 plant and animal species, a stupendous feat for one individual. Today, with the inclusion of fossil species, there are about 1.75 million recognized species of life with many more being added each year. Current estimates as to the total number of living species range from 3 million to 30 million, with some of the most frequently discovered species being among the archaebacteria. According to the International Institute for Species Exploration, 16,969 new species of plants and animals were discovered in the year 2006 alone.

One of the first steps toward better understanding the world is to label and categorize the things that are found in it. Classifying things reveals relationships between organisms but can also create a picture of the adaptation and evolution of life as part of the bigger picture of Earth and its ecosystems.

3

How Evolution Happens

The evidence of evolution can be observed in nature, but how does evolution take place? Take the case of a wild boar, a rough and tumble ancestor of the pig whose natural enemy is the tiger. Like people, not all wild boars are born with equal athletic abilities such as the ability to run fast: Some boars are faster and stronger than others. A wild boar that inherits superior speed and strength from its parents may be able to escape a tiger attack more often than a slower, weaker boar. Any such boar that lives long enough to mature, mate, and have offspring is capable of passing along its superior speed and strength. This is an example of the process of natural selection that was first explained by Darwin. He arrived at this conclusion by studying the lives of animals in nature. What did he see that unveiled the secrets of evolution?

CHARLES DARWIN'S DISCOVERIES

Charles Darwin's ideas about evolution, first published more than 150 years ago, have remained the basis for evolutionary thought ever since. Darwin's view of evolution was built on five basic rules that he developed by closely observing the natural world around him.

- ***Species change over time; they are not constant.*** Darwin defined a species by the physiological similarities of its members, such as the shape of a bird's beak. He noted that given the right conditions, a species could undergo changes not seen in earlier generations. This was most evident to him in populations of birds that had become isolated on islands. Each island population developed a uniquely shaped beak so that they could easily eat whatever nuts and fruits were available on their island. New species formed after several generations of changes due to natural selection. Long after Darwin's death, the definition of species was further refined to mean a group of individuals that could breed only among themselves, to the exclusion of other species.
- ***All organisms arose from a common ancestral population.*** Darwin correctly argued that existing species originated from an earlier species within the same related family of organisms.
- ***Evolutionary changes occur gradually.*** It is widely accepted that evolution occurs over a long span of time and many generations of a species. There are times when evolution occurs more rapidly. (The pace of evolution will be explored more fully in Chapter 4.)
- ***A single species can diversify into more than one species.*** While the development of new species from old is widely accepted, the mechanisms that make this possible are the source of continuing study and debate. (Chapter 5 explores the process of **speciation**.)
- ***Natural selection is the primary process of evolution.*** Although accepted on principle during Darwin's lifetime, the genetic mechanism that made natural selection possible was not discovered until more than 50 years after his death.

While Darwin's theory of evolution has stood the test of time, his ideas were not widely accepted at first. Earlier, we remarked about Lamarck's theory of the inheritance of acquired characteristics—the idea that the interaction of an individual with the environment could result in biological changes that could be passed on to offspring. By providing a logical alternative to the inheritance of acquired characteristics, Darwin's theory of natural selection did much to dispel Lamarck's theory. The difference between Lamarck's theory and Darwin's can be shown by returning to the story of Lamarck and his giraffes.

According to Lamarck, giraffes gradually attained their long necks by acquiring slight increases in height, generation after generation, as the animals stretched to reach tree foliage that grew higher and higher above their reach. For this process to work, each individual giraffe in each generation would have had to encounter the same environmental problem—ever-taller trees. Furthermore, each giraffe would have to stretch equally hard to cause a slight increase in the length of its neck and legs. These slight increases would then be passed along to each individual giraffe's offspring, thereby causing each generation to grow slightly taller. Lamarck's explanation relied on environmental conditions remaining constant for each generation of giraffes and assumed that the giraffes themselves would exercise the "will" to stretch themselves to reach higher branches.

In contrast, Darwin believed that the process of natural selection could explain the evolution of height in giraffes. According to natural selection, variation has always existed in the length of giraffe necks. If height gave some giraffes an advantage in feeding, and those giraffes lived long enough to mate, the trait for height would have been passed along to their offspring. Over many generations, the trait of longer and longer necks gradually prevailed, even though variation in neck length still exists among the entire population of giraffes.

In time, a wealth of scientific evidence clearly supported Darwin's view over that of Lamarck's and established evolution by means of natural selection as the foundation of modern biological sciences.

Although Darwin could observe the results of natural selection by studying variation in plants and animals, he was unaware of the means that made this process possible. The science of genetics, which emerged after the time of Darwin, provided the biochemical basis for the inheritance of traits that leads to variation within a species. Thus, evolution is based on two factors: variation within a species and natural selection that acts on individuals within a population.

CLUES TO INHERITANCE: MENDEL'S EXPERIMENTS

Darwin was bothered by the fact that he did not understand the underlying biological means that made natural selection possible. He admitted this in 1859 while writing *On the Origin of Species*: "The laws governing inheritance are for the most part unknown. No one can say why the same peculiarity in different individuals of the same species, or in different species, is sometimes inherited and sometimes not so." Darwin was unable to explain how traits were passed on.

Gregor Mendel (1822–1884) was an Austrian monk, unknown to Darwin, whose experiments raising peas in a garden provided some answers to the puzzle of inheritance. Mendel worked in relative obscurity for many years. Like Darwin, Mendel had no knowledge about the biochemical basis of inheritance. He lived decades before the modern microscope would reveal the biochemical components of the inner cell and the discovery of DNA. Nevertheless, Mendel's groundbreaking work laid the foundation for the science of genetics.

Mendel was fascinated with the variety of traits he saw in a common variety of pea plant. These traits varied when the plants were bred. Mendel wondered if there was a predictable pattern to the appearance of such traits as plant height, the arrangement of flowers on the branch, and the color of the pea pods. Mendel's curiosity, his keen observational skills, and his zeal for record keeping drove him to experiment with thousands of plants. He carefully recorded cross-pollination combinations and results. The patterns that he discovered are now known as Mendelian genetics and provided the first basic understanding of inheritance patterns and the general laws of genetic code.

In 1856, working primarily with pea plants, Mendel began eight years of extensive breeding experiments. Pollinating the plants by hand, he crossed plants that exhibited any one of seven obvious traits and duly recorded the traits of their offspring. Mendel's experiments were the first systematic study of inheritance patterns. His carefully kept records showed which traits would result when he crossbred

Figure 3.1 Gregor Mendel's experiments showed that the inheritance of certain traits in pea plants follows a set of natural laws, or predictable patterns. Although the significance of these laws was not recognized until after his death, the patterns he described form the foundation for modern studies of genetics.

two plants with certain characteristics. Over time, and after testing thousands of combinations, certain patterns emerged. Eventually, Mendel was able to predict which traits would appear if he bred any combination of pea plants. The pattern that emerged provided him with evidence for the underlying rules of inheritance.

In one series of experiments, Mendel combined tall and short plants to produce only tall offspring. By repeatedly breeding the offspring of these tall plants, Mendel discovered that short plants began to reappear in later generations. Among the thousands of results in this sequence of breedings, a ratio of one short plant to every three tall plants emerged. Mendel had discovered that inheritance did not occur through a blending, or lessening, of traits from both parents, but through a combination of discrete units that he called "particulate factors." Today, we call these factors genes. Genes represent traits that can disappear in one generation but reappear in a later generation in their original form. By studying his meticulous record of plant breedings, Mendel correctly surmised that two genes are required for each trait.

Prior to Mendel's work, scientists had only the fuzziest understanding of inheritance. His work showed that inheritance was based on predictable patterns.

Among Mendel's discoveries were the following:

- ***Inheritance of each trait in an offspring is determined by discrete "particulate factors" (now called genes).*** These traits are passed along to the offspring unchanged.
- ***The offspring possesses two genes for each trait, one from each parent.*** These genes may come in versions that are different, which are called alleles.
- ***Gene expression is governed by three possible combinations of alleles for each trait.*** An offspring acquires one gene from each parent. These genes may come in different versions, making three possible combinations in the resulting genes of the offspring. These combinations are called genotypes.
- ***The genotype determines which trait will be expressed.*** The observable trait itself, such as the color of a person's eyes, is known as the **phenotype**.

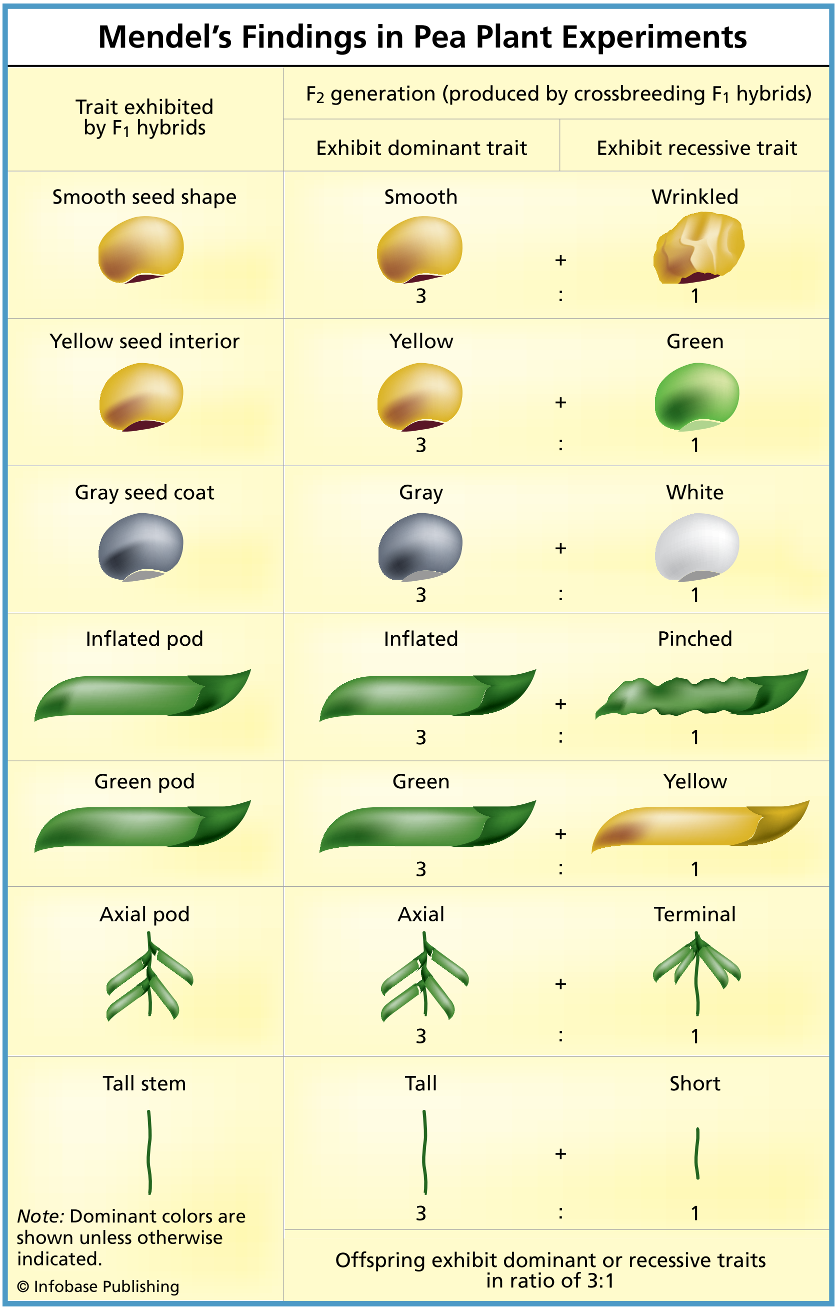

Figure 3.2 Gregor Mendel's pea plant experiments produced some predictable genetic patterns.

- ***Some alleles will be expressed over other alleles.*** In gene combinations, one of the alleles must be expressed; that allele is known as the *dominant allele*. The allele that is masked by the dominant allele is called the *recessive allele*. A recessive allele, or trait, is not destroyed and may be expressed in a later generation.
- ***Traits can be inherited independently of one another.*** The expression of one gene is not dependent on the expression of other genes. All possible combinations of traits are possible, thus providing great variety in a population. The recombination of traits is vital to the biology of evolution because it creates a variety of traits on which natural selection operates.

Mendel published the results of his plant experiments in 1866, in the scientific proceedings of the Natural History Society of Brünn, in Germany. Unfortunately for this monk, his landmark findings failed to gain wide acceptance until after his death.

THE BIOCHEMICAL BASIS FOR INHERITANCE

Mendel's experiments showed that a biochemical basis for his "particulate factors" probably existed. By about 1900, it was suggested that living organisms possessed a biochemical blueprint within living cells that was responsible for transmitting traits from parents to offspring. Continued advances in biochemistry progressively led to an understanding of chromosomes, genes, and finally DNA. All of these elements may be classed as genetic material having a bearing on the inheritance of traits.

By definition, there are several required functions of genetic material:

- Genetic material must contain all of the instructions needed to construct an entire organism. The complete instructions are called the **genome** of an organism.
- Genetic material can be passed from parent to offspring and then from cell to cell during the process of cell division.

- Genetic material can make exact copies of itself. This makes it possible to transmit genetic material from parent to offspring.
- Genetic material includes traits for the entire range of possible variation within a species.

The purpose of genetic code is to provide instructions for the construction of cells. This is done through the chemical synthesis of *proteins* from *amino acids*. Amino acids are found in the food that we eat and are contained in the cytoplasm of the cell. Of the 20 amino acids found in human cells, 11 of them are created from scratch by the cells themselves, but 9 of them, known as essential amino acids, can be obtained only from the food that we eat.

Proteins are organic compounds made from amino acids. Proteins are the actual building blocks of cells. Proteins provide structure and create an environment for other chemical processes to occur. Proteins are also used to build connective tissue, membranes, and muscle in the body. Proteins known as *enzymes* are specialized to produce chemical reactions involved with such widely different functions as digestion, muscle contraction, and the transmission of signals from cell to cell.

DNA—short for deoxyribonucleic acid—is the molecule that carries genetic code. Genes are located on strands of DNA. DNA is structured like two strands of string twisted around each other. This strand is also called a double helix. The two strands in the double helix are connected by steps like those in a ladder. The biochemical makeup of DNA specifies the order in which amino acids are arranged during protein synthesis. The biochemical structure and components of DNA also make it possible for genes to make copies of themselves—one of the primary functions of genetic materials that allows traits to be passed along to offspring.

A gene is the smallest hereditary unit. Genes are bundled onto DNA. The next largest genetic unit is the chromosome comprising both DNA, containing associated genes, and protein.

Except for those cells that are involved in reproduction, every cell in an organism has the same number of chromosomes. Humans have 23 different chromosomes, each of which can have between 300 and 2,000 genes. In addition, humans and most other organisms have two copies of each chromosome in each cell, one copy from the mother and one from the father. Humans, therefore, have 46 chromosomes in their cells.

Cells involved in sexual reproduction are called **gametes** and contain only half of the chromosomes—23 in the case of humans. For the purpose of reproducing, a gamete will combine with another sex cell, which also contains 23 chromosomes, to provide the full complement of the 46 chromosomes that are required by the human cell. When two organisms mate, the resulting offspring contains a unique combination of genes derived from the parent's DNA. These rules apply to all living organisms, from humans to hummingbirds and from haddocks to hickory trees.

Mutations

Every species possesses, by chance, genetic traits that may improve or hinder its chances of survival. Despite human scientists' success in artificially modifying genetic code, the inheritance of biological traits in nature is not under an individual organism's control. In the natural world, an organism cannot dictate which traits it will inherit, nor can its parents direct which traits to pass along. These traits also contain random errors, created by chance, called **mutations**. These slight, unpredictable variations in the genetic code occur when organisms reproduce. Mutations may have no effect on an organism's ability to survive, or they may result in traits that help or hinder its ability to get along in the world.

A mutation is any change in the genetic code. Mutations occur at random. They do not occur for a reason, nor do they occur because they are needed. Most mutations are simple errors made by cells when genes are copied, as when new cells are grown or when genetic code is "read" and reproduced by the body to produce proteins. Mutations can also be caused by such environmental factors as damage caused by chemical pollution and genetic irregularities introduced by radioactivity. These causes are less common than random changes due to the body's own normal functions, however.

Mutations can occur in any kind of cell. The only mutations that affect evolution, however, are those that occur in gametes. Mutations are perhaps the most fundamental force underlying genetically based evolutionary factors. Every species possesses, by chance, genetic traits that may improve or hinder its chances of survival. The inheritance of biological traits in nature is not under an individual organism's control. In the natural world, an organism cannot dictate which traits it will inherit, nor can its parents direct which traits to pass along. The traits are passed along by chance in the form of mutations—slight, unpredictable variations in the genetic code that happen when organisms reproduce.

When we hear the word *mutation*, we normally think that something bad has happened. But mutations are not always harmful to an organism. They might result in larger ears, longer fingers, a slightly different colored eye, or any number of other possible changes to the biology of an organism. Yet none of these traits is guaranteed to help or hurt an individual's survival. Destructive mutations are also possible, such as brain damage, badly-formed bones, and other disabling conditions that hurt the chances of an organism to make it in the world.

Nature and Nurture

It is important to note that genetic traits alone are not responsible for the survival of an organism. While inherited traits provide a starting point for an individual, the survival of an organism is also affected by its interaction with the world around it. "Nature" provides the traits associated with one's genetic makeup, such as height and hair color in humans. But the nurturing effect of the world around us also affects our development.

Personal traits such as hobbies, interests, and mental skills are largely shaped by the environment in which a person is raised. Such circumstances are difficult to define and predict, but they can make one person an avid comic book collector, another person a fan of Shakespeare, and yet another a student of both. These interests are examples of things that we learn rather then inherit.

There is evidence, however, that social behaviors of a given species can be inherited. Such species behaviors as parental care in gibbons, foraging tactics of shore crabs, territorial behavior in African sunbirds, and pack hunting in lions are adaptive and the result of natural selection. Humans also inherit certain social behaviors, like protecting the young and defending one's territory.

Evolution, then, has two causes. It is influenced by the inherited genetic traits of an individual organism *and* by the interaction of an organism with its habitat. If an organism successfully survives in its habitat long enough to mate and pass along its genetic code to its offspring, then evolution continues for that species.

Living species represent moments in the ongoing process of evolution. There is no such thing as a species that has stopped evolving. Humans and all other species on the planet continue to change with each successive generation, even if only in ways that are nearly imperceptible. Evolution is influenced by inherited traits and by changes in the environment. Knowing how these kinds of changes affected past organisms is a key to seeing the future of life.

4

Adaptation

Life forms are sometimes found in the most unlikely places. No matter where one looks on Earth, life seems to have grabbed a foothold. From the highest mountains to the depths of the deepest oceans, from the wet tropics to the hot and dry deserts, there is life. How is it that organisms are able to survive in such harsh environments?

Biological traits that make an organism better fit to survive are called **adaptations**. An organism that has successfully adapted can stay alive and reproduce.

Some adaptations result from genetic mutations that enable an organism to live in its environment. These traits can be passed on to the next generation. Adaptations may take many forms to sustain a species. Some species have adapted an outer appearance that allows them to blend in with their surroundings thereby providing camouflage that makes them nearly invisible to natural enemies. For example, the flounder has a speckled appearance that allows it to blend with the color and texture of the gravel on a sea bed. Camouflage may also be adapted by predators to prevent detection while they lay in wait for their prey. The dead leaf mantis, for instance, is an insect that takes the appearance of a dead leaf on a tree, waiting patiently until its unsuspecting prey comes within its reach. Mosquitoes adapt to become resistant to certain pesticides, such as DDT, and pass this resistance along to their offspring. Horses have adapted teeth that are highly efficient for chewing grass. Meat-eating animals may adapt specializations for each stage of the predatory process to enable them to better detect, attack, capture, and eat their prey. In each case, an adaptation helps an organism survive so that it may reproduce and give birth to offspring.

BIOLOGICAL ADAPTATION

The examples given above are forms of biological adaptation, which are changes to an organism that are inherited from its parents. Many such genetically transferred biological adaptations are influenced by the environment in which an organism lives. Birds, for example, come in many species, each with its own particular physical characteristics. A widely varying trait of birds is the size and shape of the beak. Long, pointed beaks are suited for penetrating tree bark in search of hidden insects; big beaks are suited for eating large seeds; small beaks are suited for eating small seeds; and so forth. In every known natural habitat, bird beaks have adapted for the size and shape of the food eaten by each species of bird. The structure of the beak is an adaptation, a physiological adjustment brought about through natural selection over a long period of time.

In evolution, the only adaptations that matter are those that can be passed to the next generation. This should not be confused with other forms of adaptation that affect individuals within a species population but that are not genetically based.

There are two other forms of biological adaptation in addition to genetically inherited traits. These are short-term and long-term **biological adaptations** that develop during the life of an individual but are not passed on to offspring. Short and long term adaptations are "nurturing" traits acquired during an organism's life. Until the science of genetics was able to prove which kinds of biological adaptations could be inherited, there was much scientific debate about the transference of these observable traits. It is worth contrasting the three forms of biological adaptation by means of examples that make their differences clear. Human beings provide excellent examples. In fact, the ways in which humans biologically adapt to living at high altitudes provide examples of all three forms of biological adaptation.

Living at the Top of the World: Three Kinds of Human Adaptation

The three kinds of biological adaptation can be illustrated by examining the ways that humans cope physiologically with living at mountain elevations. First, a quick lesson about the human respiratory system is in order.

Oxygen is one of the essential elements needed by organisms. Humans get their oxygen from the air. When we breathe, our lungs extract oxygen from the air and transfer it to the blood. Once in the blood, the life-giving oxygen is carried through our veins by a protein called hemoglobin. Oxygen is an essential fuel for the body's tissues. Being without oxygen for just a little while can irreparably damage sensitive tissues and organs, such as the human brain. Being totally without oxygen for three or more minutes will kill a person.

The amount of oxygen found in the air varies with elevation. At sea level, the air is most saturated with oxygen. At higher elevations, especially mountain elevations, the concentration of oxygen in the air is measurably "thinner."

Having evolved near sea level, the human body is optimally suited for breathing and functioning at low elevations where the air is richest with oxygen—from about 50 feet (15 meters) to about 2,000 to 4,000 feet (600 to 1,200 m) above sea level, for example. Most humans do not live at elevations higher than that.

The amount of oxygen in the air begins to thin out at elevations above two miles (3.2 kilometers). People inhale less oxygen with each breath at those elevations. Those who travel to such altitudes may experience physiological side effects. A body that is accustomed to breathing a certain amount of oxygen in the air will tire more quickly at altitudes where the air is thinner. The situation becomes even more risky at altitudes over 8,125 feet (2,440 m), such as those that are found on a mountain or highland plain. At these elevations, a person will get altitude sickness, also known as *hypoxia*. This condition is caused by a low concentration of oxygen in the air. Hypoxia can result in headaches, fatigue, dizziness, shortness of breath, loss of appetite, and nausea. At elevations over 25,000 feet (7,575 m), oxygen is so sparse that hypoxia will kill a person.

While hypoxia seems unavoidable at high altitudes, humans can adapt their bodies to cope with dangerously thin air when given

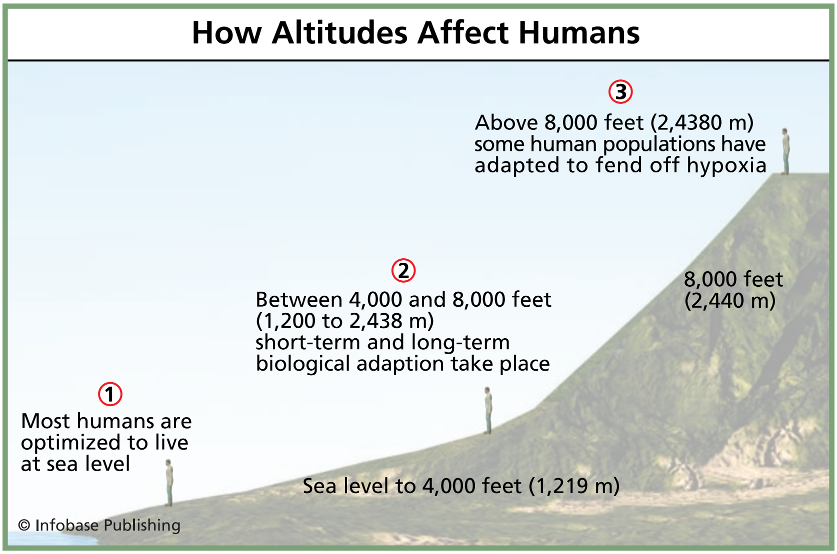

Figure 4.1 Altitude affects the way a person lives and breathes. While most people can comfortably live at sea level, other people's bodies are able to adapt to living with less oxygen in much higher altitudes.

enough time to adjust. In fact, people have three different kinds of biological adaptations to higher altitudes and thinner air.

Individuals who are new arrivals to mountainous areas will experience a short-term physiological adaptation. This short-term change might include shortness of breath and a rapid heart beat as the body adjusts to the thinner air. More rapid breathing causes a person to inhale an amount of air comparable to that taken in by longer, slower breaths during the same amount of time. When the person's heart beats faster, it compensates for the reduced amount of oxygen in the air by pumping the oxygen that *is* available more rapidly, thus fueling tissues and organs at acceptable rates. Rapid breathing and an accelerated heart rate are examples of how the body automatically adjusts to a lower amount of breathable oxygen.

An individual who was born in a lowland area but who later grows up in a higher altitude region, or even someone who moves to a higher altitude as an adult, may experience the second kind of biological adaptation, a long-term physiological change that occurs as the person adjusts to the environment. This person's lungs and circulatory system can become more efficient at taking oxygen from thin air. The person may develop more red blood cells and vessels to carry oxygen, the lungs may grow larger to improve oxygen exchange, and the muscles of the respiratory and vascular systems may become stronger in order to accommodate the processing of oxygen under these more stressful conditions. These physiological changes are neither permanent nor genetic and cannot be passed along to one's offspring. If a person leaves the environment that created this change for a long period of time, they will lose the long-term physiological change. One might liken this to a dedicated bodybuilder who suddenly stops pumping iron for a long time. Their body will eventually lose its exceptional muscle tone and revert to its normal state.

The third kind of biological adaptation is a genetic one that is transferred from one generation to the next through DNA. A group of native people that has lived in a mountainous region for many generations might inherit genetic advantages that enable them at high altitudes. Three excellent examples of this have been documented in mountain-dwelling populations in different parts of the world.

Tourists who visit the highland plains of Tibet in Central Asia, the Andes Mountains in South America, or the highlands of Ethiopia in Africa soon find themselves gasping for air. They are also astounded at how the rugged residents of these regions, who live at elevations greater than 11,000 feet (3,300 m), can go about their daily chores without losing their breath. The natives go about their daily business unhindered by the fact that they live at an altitude where the air has only two-thirds as much oxygen as there is at sea level. Each of these populations has developed its own unique physiological immunity to hypoxia.

The Andeans survive in the thin air because they have developed higher concentrations of oxygen-carrying hemoglobin in their blood. The Andeans' lungs can grab more oxygen from the air with each breath, effectively counteracting the potential effects of hypoxia.

The Tibetans cope with thin air in a much different way. First, they breathe faster than people who live at sea level. By taking in more breaths per minute, they can inhale more oxygen. Unlike the Andeans, however, the blood of the Tibetans does not have more hemoglobin than is normal. To compensate for the low oxygen content of their blood, the Tibetans have wider blood vessels to carry

Figure 4.2 A Tibetan woman and child pose with their yak in front of Karuola Mountain, south of Tibet's capital of Lhasa in August 2003. Native Tibetans' bodies have adapted to living in the highest region on Earth, where the average elevation is 16,000 feet (4,900 meters).

blood to their bodies' tissues. Wider blood vessels increase the amount of blood and oxygen that reaches the tissues with each beat of the heart.

The Andeans and Tibetans are examples of organisms with genetically based biological adaptations. These adaptations can be passed along to offspring and probably become slightly more efficient with each successive generation. Biological adaptations clearly take a long time, and many generations, to develop. Of these two peoples, the Tibetans are the hisotorically older, having first populated their mountains about 23,000 years ago. The Andeans have lived in their mountains for about 10,000 years.

There is yet a third example. In Ethiopia, there lives a highland population that has adapted amazingly well to mountainous living. Despite the fact that they live at an elevation of 11,580 feet (3,530 m), a zone where they should be suffering from hypoxia, these people also show no signs of altitude sickness. Most puzzling, though, is that the highland people of Ethiopia do not have either of the biological adaptations of the Tibetans or the Andeans. In fact, the proportion of hemoglobin in the Ethiopians' blood is about the same as that of people who live at sea level. The mystery of their biological adaptation remains unsolved, although recent studies suggest that Ethiopians may have adapted a way of processing oxygen in the brain that differs from other peoples who live at high altitudes. It is also worth noting that the Ethiopians have been native to their mountains for about 50,000 years—twice as long as the Tibetans and five times longer than the Andeans. The Ethiopians evidently represent a third form of evolutionary adaptation to highland living that is genetically passed along to each generation.

The following table shows three ways that humans adapt biologically to their environment.

In addition to the three forms of biological adaptation, humans have the unique ability to make additional adaptations by using technology. Clothing is one simple but effective technology that humans use to adapt to different climates. Other technological adaptations are dazzling, such as spacecraft, submarines, and other portable environments humans have created to protect human life in places where it cannot survive without help.

THE RATE OF EVOLUTION

Darwin viewed evolution and the emergence of new species as a slow and gradual process. In his view, it took thousands and even millions of years to create a new species. This view is called **gradualism**. Gradualism assumes that slow and gradual changes over a long period of time lead to major biological changes to a species. The fossil record does indeed provide many clues to such gradual changes.

Table 4.1 Forms of Biological Adaptation

Type of Adaptation	Cause	Example
Short-term physiological change	Occurs naturally when an organism encounters a change to its environment	Body adapts by faster heart rate, taking gulps of air (hyperventilation).
Long-term physiological change	Occurs during the growth stage of an individual organism or during long-term exposure to a new or changing environment	More red blood cells and vessels develop to carry oxygen; lungs may grow larger to improve oxygen exchange; the muscles of the respiratory and vascular systems may become stronger to improve the processing of oxygen.
Genetic change	Occurs over many generations	Higher concentrations of oxygen-carrying hemoglobin in the blood (Andeans); wider blood vessels increase the amount of blood and oxygen that reaches the tissues with each beat of the heart (Tibetans); possible brain adaptation for processing oxygen (Ethiopians)

The concept of gradualism was challenged in 1972 by a bold new idea proposed by paleontologists Stephen Jay Gould (1941–2002) and Niles Eldredge (b. 1943). Gould and Eldredge still assumed that natural selection was the underlying machinery of evolution, but they noticed that evolution sometimes occurs more quickly than Darwin thought. The fossil record shows that many species can go for millions of years without any significant change. It is as if evolution were standing still for some species. Living examples, such as the cockroach and bowfin fish, seem to follow this pattern, remaining relatively unchanged for many millions of years. Dramatic evolutionary changes can sometime kick into high gear, however, if a population of a given species suddenly encounters a significant change to its habitat. Such a change might be caused by a geological event, a change in climate, or even interaction with other species. Following such an occurrence, a short period of rapid evolution may take place that affects a subgroup of a species population. Those individuals with certain traits favoring their survival may change dramatically over a period of tens of thousands or several million years—mere seconds and minutes on the scale of geologic time. The changes may result in new species. This rapid twist to the evolutionary story is called **punctuated equilibria.**

The phenomenon of punctuated equilibria first affects a small portion of an overall species population. For example, when insects are exposed to pesticides, certain members of the population can rapidly develop resistance. Many others die off but those that do survive breed offspring that are equally resistant. The same can be said of bacteria that grow resistant to antibiotic medicines. These adaptations are the result of natural selection. Such changes can mark the beginning of the development of a new species.

The fossil record of the flowering plants provides a dramatic example of evolutionary opportunism and the influence of one species of life on another. Prior to the appearance of flowering plants about 140 million years ago, the world landscape was dominated by seed-bearing plants such as conifers, ginkgos, ferns, and palms. These plants reproduce by simply dropping their seeds. Flowering plants cannot reproduce without pollination, which is the physical transmittal of a plant's pollen so that it comes into contact with a plant's seed. Although this reproductive complication might seem too daunting for a new plant species to overcome, flowering plants actually rose and diversified rapidly. This rapid rise and diversification are revealed by an abundant fossil record of leaves and pollen.

The fossil record shows that the first leaves of flowering plants were shaped simply and had poorly organized veins. The earliest examples of pollen also were primitive, with an unadorned surface structure. As time went on, both leaves and pollen evolved more complex structures that aided their survival. Leaf structures became broader and varied in shape, with geometrically laid-out veins—features that added to the robustness of the plants. Pollen began to exhibit a more sculpted surface texture that was more easily grabbed by the other organisms, such as insects, that were transporting the pollen to facilitate pollination. The rise of flowering plants to the position of the most dominant form of vegetation took only about 10 million years. This rapid spread was most likely due to the role played by birds and insects in the process of pollination.

What can be concluded from this evidence is that the rate of evolution for any given species will vary depending on the biologic, geographic, and environmental circumstances affecting a population of organisms. The rate is often slow and gradual, as Darwin thought, but it can also be rapid, as Gould and Eldredge suggested. The facts favor a wide range of evolutionary rates on a spectrum represented by gradualism at one end and punctuated equilibria at the other.

5

The Evolution of New Species

The small differences distinguishing varieties of the same species steadily tend to increase, till they equal the greater differences between species of the same genus, or even of distinct genera.
—Charles Darwin, The Origin of Species

Natural selection enables species to improve the chances that successive generations will survive in a changing world. This is evident when weeds become resistant to weed killers and bacteria grow to become impervious to antibiotics. Because of natural selection, organisms that are fitter to survive have more of a chance to pass along their traits to offspring. This is not to say that natural selection leads to a more perfect species. Natural selection merely allows a species to keep up with its changing habitat by taking advantage of genetic mutations that make it fitter for survival.

What becomes more difficult to understand is the rise of new species as a result of evolution by natural selection. Darwin did not have knowledge of genetics, but he could see that new species could evolve from existing species. He knew that animals alive today had their origins in much different species of animals that lived millions of years ago. This is a difficult leap of faith for most people to accept.

It not only requires that we accept that humans evolved from something akin to an ape, but that apes, in turn, evolved from yet another kind of mammal further back in time. Taking this line of evidence to its ultimate conclusion, all life today is related to the first living microbe that brewed in the primordial seas of the planet.

Earlier, we defined a species as the most basic biological unit of living organisms. All members of a species can interbreed and produce fertile offspring. For example, all kinds of dogs can interbreed because they are all part of the species *Canis lupus*. Even though dogs are also related to bears, weasels, foxes, and sea lions as part of the group called Carnivora, dogs cannot breed with those other animals because they are different species. But how can it be that these different species are related to each other? What events lead to the development of new species? These are the same questions that puzzled Charles Darwin.

MICROEVOLUTION AND POPULATIONS

Evolution begins with a population of individuals in which breeding is possible. The term *speciation* refers to the formation of a new species from an existing one. What this simply means is that a group within a given population can no longer exchange genes with other members of the species. Given that genetic changes occur with every generation of a given species, it might seem that the development of new species should be more common than it is. But speciation is a rare event and requires many generations and possibly millions of years to occur in populations of the most complex animals, such as vertebrates. Speciation, by means of natural selection, is the most dramatic outcome of evolution. More common is the **genetic evolution** of inherited traits within a given species, a process that may never result in a new species but will, indeed, lead to some interesting variations within a breeding population. Dogs are an excellent example of what this means because any dog of any kind, big or small, is capable of breeding with another dog. The forces of genetic evolution—which are controlled by the selective breeding of dogs by people—has resulted in a wide variety of inherited traits and differences in dogs. But this practice will not result in new species.

In terms of genetics, a **population** includes all members of a species in a given geographic location. Individuals in a population have access to all other members of their population, which makes breeding possible. **Population genetics** is the study of the frequency of alleles, genotypes, and phenotypes in a given group, or population. The combined genetic makeup of a population is called the **gene pool.** The gene pool contains the potential for variation of inherited traits.

Evolution at the genetic level takes place all the time within a breeding population. The genetic changes that can occur within a population are the result of **microevolution**. In microevolution, a population can develop genetically unique traits but retain membership in the same species of which it is a part. As noted earlier, a population of native peoples that has lived in the mountains for many generations might inherit genetic advantages for living at high altitudes. Tourists visiting the Andes Mountains in South America soon find themselves gasping for air. This is not true for the locals, however, who have adapted to living above 11,000 feet (3,300 m) by having developed higher concentrations of oxygen-carrying hemoglobin in their blood. However, this genetic variation does not make these two populations—the tourists and the highland people—different species. They are capable of breeding with each other. Even so, this special genetic trait of the highland people, restricted to this population, is an example of microevolution.

Several natural forces are at play in microevolution. Natural selection, as originally described by Darwin, is at work at the population level. Through natural selection, such genetic adaptations as being able to breathe comfortably at high altitudes are passed along from generation to generation to protect a species from the stressful characteristics of its habitat. An adaptation such as the one that the Andes people made probably began as a genetic mutation that grew stronger and spread throughout the population over many hundreds of years.

Genetic mutations do not always result in a fitter organism. Some mutations can make an organism less healthy, lessening the chances that an individual will reproduce successfully and pass along its traits to an offspring.

Two additional phenomena affect the genetic makeup of a population: **genetic drift** and **gene flow**.

Genetic drift is a chance fluctuation in allele frequency in a gene pool that is not caused by natural selection. Genetic drift is random and figures most importantly in the genetic makeup of small populations. It can occur, for example, if some members of a gene pool die before they are able to reproduce, thus depriving the gene pool of additional variance in the traits that can be passed on to future generations.

Gene flow is the introduction of new alleles—meaning additional variety in inheritable traits—from an outside population of the same species. This can happen when a member of the species from another place breeds within a different population. The outsider introduces genes that might not have been a part of the native population. Using our earlier example of highland Andes peoples, gene flow would occur if a tourist from the outside had a child with one of the local people.

MACROEVOLUTION AND SPECIATION

Microevolution refers to changes in the gene pool at a population level. The larger forces of evolution can, however, also lead to the development of entirely new species and a new breeding population. The process of speciation is also called **macroevolution.**

Speciation occurs when subgroups within a breeding population become separated. Subgroups that are separated can no longer interbreed. When this occurs, what was once a common gene pool is now divided between two populations of the same species. This prevents the genes of one group from being introduced into the other group. The natural introduction of random mutations causes alleles to appear in one group that do not appear in the other. Over many generations, the forces of natural selection and genetic drift may affect the two populations differently. In this way, two separate populations of the same creature begin to evolve slight differences in their genes. Over a long time, the differences may become increasingly numerous. Eventually, the genetic makeup of one group may differ significantly from the other, making it no longer possible for them to interbreed. When this occurs, the new group has become a new species. It will retain characteristics of its ancestors but will have formed its own branch on the family tree of related species.

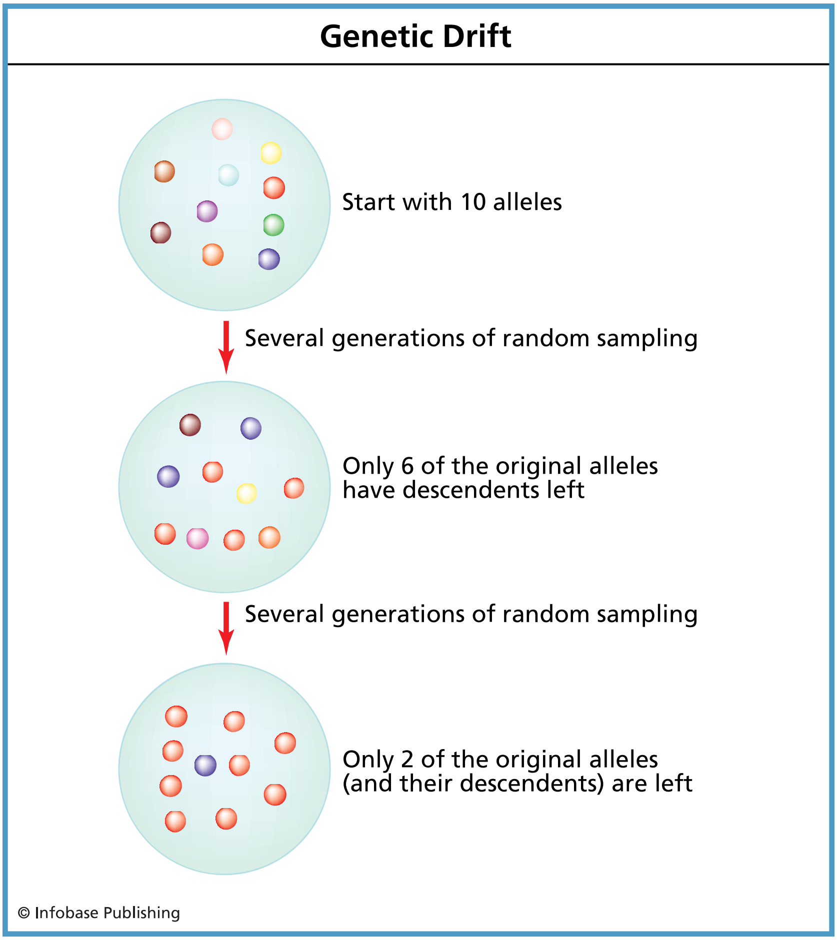

Figure 5.1 Genetic drift is the change in the genetic composition of individuals in a random sampling of a finite population over time. In other words, the alleles (gene variants) in offspring are a random sample of those in parents. Genetic drift also notes that chance has a role in developing an individual's traits.

If speciation is such a rare occurrence, how does evolution account for the diversity of life on Earth? How can mammals include such widely different creatures as the blue whale, the vole, and humans? One reason is that speciation requires a vast, nearly unimaginable span of time. Another is that new species do not appear all that dramatically different at first. The vast differences in species occur only after several stages of speciation. Initially, one species splits into two species that are very similar. Over time, and possibly over many additional instances of speciation, a species may no longer bear a close resemblance to its distant ancestors. Take the case of birds.

The first birds having a modern body plan—a pair of wings, a toothless beak, and tail feathers—emerged during the end of the age of dinosaurs by about 68 million years ago. One of these birds is known as *Vegavis*, whose fossils were found in Antarctica in 1992. The first indisputable bird of any kind known from the fossil record is *Archaeopteryx*, whose fossil was first found in Germany and dates from about 150 million years ago. While *Archaeopteryx* had wings and feathers, it also had a tail like a dinosaur and a toothed beak, which suggest that it was but one step in the evolution of small dinosaurs into birds. Nearly 90 million years separate the appearance of *Archaeopteryx*, the first known primitive bird, and *Vegavis*, an early bird with modern bird features. What was happening in bird evolution during the intervening years?

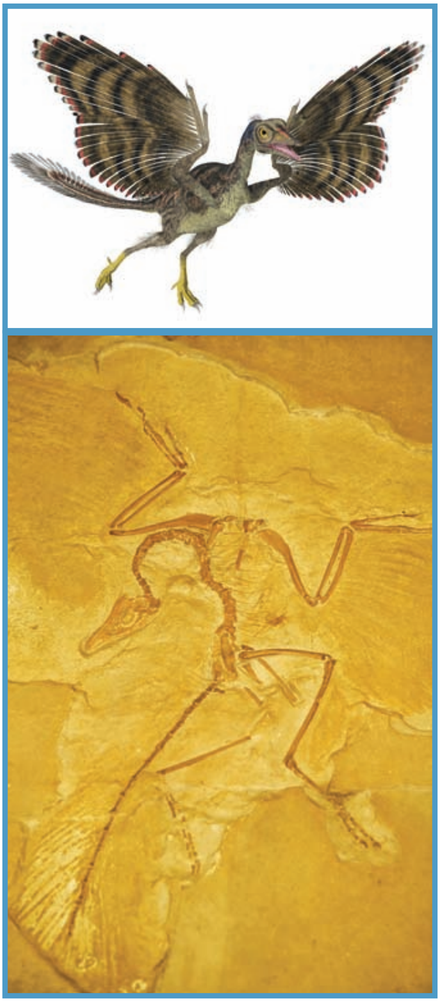

Figure 5.2 *Archaeopteryx* (*seen here as an illustration and a fossil*) is believed to be the earliest bird ever to exist. It lived around 150 to 145 million years ago, and measures about 1.6 feet (0.5 m) in length.

There is a temptation when studying similar fossil creatures to connect the dots as if they were directly related. Yet the fossil record is full of gaps and it is a mistake to assume that any fossils show a direct connection to any later species. *Archaeopteryx* was not the great-great-great grandfather, millions of times removed, from *Vegavis*. The process of speciation is more complicated than that. If one species splits into two, there is then the chance that those two will split yet again, and so on for millions of years. What began as similar species at the beginning will eventually undergo dramatic changes over time. Many of these species will also become extinct.

Extinction, in fact, is what happened to *Archaeopteryx*. It was one experiment in the evolution of feathers and wings on small, meat-eating dinosaurs, but it ended long before the time of modern birds. There were many such experiments in the evolution of birds from dinosaurs. Between the time of *Archaeopteryx* and *Vegavis* lived any number of examples of small, feathered dinosaurs, some with wings, and some without. Some had teeth, some did not. Some had two wings, others had four. Some evolved as water birds, while others evolved to sit in trees. Among these was a sequence of successive speciations that resulted in several kinds of modern birds, but it is impossible to trace them all back to one ancestor, other than to say that the ancestor was a small, meat-eating dinosaur.

Theodosius Dobzhansky (1900–1975) was a Ukrainian evolutionary biologist noted for developing modern evolutionary theory. He explained evolution by applying knowledge from several scientific disciplines, including genetics, biology, and Darwinian evolutionary theory. Dobzhansky was instrumental in defining several **reproductive isolating mechanisms**, which are factors that prevent two species from interbreeding and therefore helps to maintain the uniqueness of each species. These possible mechanisms that help maintain separate species include:

- ***Geographic isolation***: Species may not occupy the same habitat. Geographic isolation makes reproductive contact impossible.
- ***Seasonal isolation***: Species may have different mating seasons.
- ***Physiological incompatibility:*** Two different species may have morphologically mismatched sexual organs, making

The Complete Set of Genetic Instructions for Building an Organism

Genomes are made of DNA and associated protein molecules that are organized into bundles called chromosomes. The human genome is estimated to contain 20,000 to 25,000 genes and 3 billion DNA base pairs. These genes are all stored in 23 pairs of chromosomes, which are contained in every cell in the human body. The human body is made up of about 100 trillion cells.

Different kinds of organisms have different numbers of chromosomes. Some note-worthy examples:

Number of Chromosomes in the Individual Cells of Some Common Plants:

- durum wheat, 28
- corn (maize), 20
- rye, 14
- onion, 16

Number of Chromosomes in the Individual Cells of Some Common Animals:

- human, 46
- chimpanzee/gorilla, 48
- cow, 60
- cat, 38
- dog, 78
- goldfish, 104
- fruit fly, 8

The number of genes and chromosomes does not explain every difference between organisms. Humans and apes may share as much as 98% of their DNA. The obvious physical and behavioral differences between the two species result from the way that their genetic traits are regulated and expressed.

it impossible for two members of different species to interbreed.

- ***Hybrid differences*:** Two species might be able to mate, but the resulting hybrid fertilized egg does not survive, or the hybrid survives but cannot produce functional gametes. The mule is an infertile hybrid, the cross between a male donkey and a female horse.

Darwin's theory of natural selection has stood the test of time, and scientific observation, to explain how species evolve. All species participate in a process called evolution, a process that never ends. What is happening today in the cells and genetic architecture of every living organism may influence, in a small part, the continued development of that organism's species. It is only through the theory of evolution that the many branches of Earth's family tree can be linked, starting from the first single-celled organisms that arose 3.5 billion years ago.

6

Evolution at Work

Connecting the dots in the evolution of life is not easy to do. When life began 3.5 billion years ago, it consisted only of single cells that floated in the sea. Inside those cells was early DNA, the blueprint for life that is still found in the cells of organisms today. The great variety of life on Earth all goes back to those single-celled organisms that once populated the oceans. Over many millions of years, those tiny organisms reproduced, adapted, mutated, and became increasingly capable of surviving on land and in the sea. From those single-celled organisms evolved multi-celled organisms and the first plants and animals. This is the process that brought about all life on the planet.

Can evolution be observed? To observe evolutionary change in living organisms, scientists must study microorganisms and other creatures whose lifespan is very short, such as insects. Scientists who study evolution from a genetic standpoint often use the common fruit fly as a laboratory subject. This is because the lifespan of a fruit fly is only about 30 days, and they are able to reproduce after 10 days. This means that several generations of fruit flies—and their DNA—can be studied in only a few weeks.

Observing evolution at work in higher organisms, such as vertebrates, is not as easy. When Darwin first explained his theory, the evidence for evolution consisted of observations made in nature that were visible to the naked eye such as the way that island birds adapted their beaks to their local food resources. Otherwise, animals generally live too long to reveal visible evidence of evolutionary change. Evidence for evolution in humans and other animals comes from three lines of investigation: examining the fossil record, studying biological molecules and genes, and reviewing the findings in the field of comparative anatomy.

EVIDENCE FROM THE FOSSIL RECORD

Soon after Darwin published his theories in 1859, other scientists began to look for evidence of evolution in the fossil record. Only two years later, in 1861, a most amazing fossil was uncovered in the Bavarian region of Germany. Preserved as a squashed specimen in fine-grained limestone deposits, the small creature resembled both a small reptilian dinosaur and a feathered bird. Dating from 150 million years ago, it was, in fact, the oldest known bird, *Archaeopteryx* ("ancient wing"). Unlike birds of today, it had teeth and a tail, much like a small, meat-eating dinosaur. Finely etched markings around the skeleton were also revealed to be impressions of wing feathers. *Archaeopteryx* was a remarkable transition between dinosaurs, which came first, and birds. It is now widely believed that birds are the living descendents of small, bipedal dinosaurs. *Archaeopteryx* represented a transition stage in evolution from a ground-dwelling creature to a flying creature.

Archaeopteryx is an example of a **transitional fossil**. A transitional fossil shows just one step in the many stages that exist as species evolve. Sometimes transitional fossils are found for closely related species; at other times, transitional fossils are found for families of organisms that are less directly related. In the case of *Archaeopteryx*, no other fossils of its relatives dating from just before or after its appearance have yet been found, so other stages in the development of *Archaeopteryx* are currently unknown. Recent findings in northeast China, however, in younger fossil beds that date from 125 million years ago, have provided many examples of transitional forms between dinosaurs and birds. These Chinese fossils are not directly related to *Archaeopteryx*, but they suggest the kinds of evolutionary changes that also may have been taking place in Germany, where the official "first bird" was discovered.

Transitional fossils can provide powerful evidence for evolution. A dramatic example is that of the evolution of early whales. *Pakicetus* was an early ancestor to the modern whale. This creature lived 50 million years ago. A fossil of its skull shows that its nostrils were at the front of its long skull. A modern beluga whale has a skull with many similarities to *Pakicetus,* but its nostrils are on top of its skull. This suggests that, over time, as species of whales evolved, the nostrils gradually moved to the top of the skull. A paleontologist looking for a transitional form in the evolution of the whale would expect to find a fossil with the nostrils located somewhere in between those of *Pakicetus* and those of the beluga whale. That transitional form can be found in the skull of *Aetiocetus*, a whale ancestor from 25 million years ago that has its nostrils midway between the end of its nose and the top of its skull.

The fossil record for the evolution of the modern horse from its most distant ancestors is full of gaps. Paleontologists do not know all of the steps that led from the pig-sized horse ancestors, which lived 55 million years ago, to the modern stallion. Yet, enough fossils have been found of horse relatives from long ago to reveal a remarkable record of transition. The front foot of the horse did not always have just one toe, or hoof, as it does today. The horse's earliest ancestors had four toes. Over millions of years, the environment of horse ancestors changed, from a tropical woodland to a vast open plain with grasses. The ability to run fast to escape predators became more and more vital to the survival of ancient horses. The feet of ancient horses gradually favored fewer and fewer toes. The fossil record includes horses that had three, two, and, finally, one toe on each foot. With each transition, the third toe of the foot became increasingly bigger than the other, providing superior footing. This led to the sure-footed single hoof of the modern horse, one of the fastest animals alive.

Many more dramatic examples of transitional fossils exist that document the evolution of invertebrates, plants, sharks, and other fish, plus amphibians, reptiles, mammals, and birds. Fossils are like photographs that capture a moment in evolution, thereby allowing us to see what was happening in the lineage of a species.

EVIDENCE FROM DNA AND GENES

Since the discovery in the 1950s that the DNA molecule carried genetic traits, molecular biologists have made great strides in decoding the DNA of many kinds of organisms. Although the mysteries of DNA are far from solved, what has been learned from DNA reinforces the fact that evolution happens.

One startling fact is that the DNA of all organisms is composed of the same set of 20 amino acids. This fact alone strongly suggests that all organisms—conifers and clams, dachshunds and daffodils—are descended from one common ancestor. This common ancestor was a family of single-celled organisms that first appeared 3.5 billion years ago. As they evolved into new species, and those species in turn continued to evolve into the whole array of life that is before us, each organism continued to carry the same basic stuff of life in its DNA molecules.

Tens of thousands of genes make up the DNA sequences of individual species. Genetic mutations occur randomly to a species over time. These mutations may be passed along to offspring and continued in future generations of a species. In this way, the original DNA sequence found in a species gradually changes over time. But the DNA sequence does not change so dramatically that it is no longer recognizable. Organisms that are closely related, even over enormous periods of geologic time, will still have similar DNA sequences.

To an observer who is relying on physical appearances only, most creatures appear to be quite different. A starfish is not a spider monkey, and a finch is not a ferret. Still, sometimes DNA can reveal a kinship that was not otherwise obvious. Until the availability of DNA analysis, the only evidence for this theory came from the fossil record. *Pakicetus* was one of the first whales, and the structure of its inner ear was not yet fully compatible with water life. It can be assumed that *Pakicetus* probably spent most of its time on land. This whale was descended from a line of land-bound mammals, but which ones? DNA analysis of whales now reveals that they are most closely related to a branch of mammals that also led to the hippopotamus.

Molecular biology adds further hard evidence for the phenomenon of evolution. As scientists continue to examine and compare the DNA of different living things, it is possible to construct a tree of life that accurately shows who is genetically-related most closely to whom. This new data may upset some long-held assumptions about the evolution of some organisms. For example, until molecular studies provided concrete evidence of genetically-based evolutionary links, most naturalists relied primarily on the comparison of anatomical features, such as skulls, teeth, and hooves, to link one family of creatures to another. While these skeletal traits remain important in understanding evolution, genetic studies sometimes reveal evolutionary links that were not previously known. One such case is that of the hippopotamus. It was long held that hippos were closely related to pigs based on the structure of their molar teeth. Genetic studies have now shown that hippos are more closely related to whales and that the two share a semi-aquatic ancestor.

This naturally leads the curious mind to ask, what about the DNA of extinct creatures? Is it possible to extract DNA from a fossil bone? The answer is a qualified yes. The older the fossil, however, the less likely it is that DNA can be extracted from it.

Still, how old is old? In 1997, DNA was successfully obtained from a 40,000-year-old fossil bone of a Neanderthal human. Claims have also been made of DNA being recovered from 17-million-year-old fossil leaves and 25-million-year-old fossil insects, but these results have been disputed by scientists who have been unable to reproduce the same results. Indisputable pieces of fossil DNA have not yet been found in fossils as old as the dinosaurs (c. 65 million years or older), but some remnants of organic molecules sometimes become fossilized. The oldest fossils from which DNA has been recovered date from about 800,000 years ago and consist of genetic material from pine trees, butterflies, and other organisms that lived in Greenland. Claims for the recovery of DNA from ancient bacteria extend the oldest known DNA back to more than 400 million years. Yet, when it comes to extracting DNA molecules from the bones of extinct vertebrates, the record goes back no further than tens of thousands of years. Some of the oldest DNA from an extinct vertebrate is that of ancient human Neanderthals dated to about 40,000 years ago.

EVIDENCE FROM COMPARATIVE ANATOMY

Further clues that evolution happens can be seen by comparing the structures of different organisms. The theory of evolution predicts that descendants will share similarities with common ancestors. Every organism has anatomical and biochemical structures that can be compared to others. **Homologies** are traits, both structural and behavioral, that different species of organisms have inherited from a common ancestor. Homologies are the basis for knowledge of how organisms are related. Homologies show which organisms evolved from which ancestors. The often sketchy similarities observed in anatomical structures can be reinforced by DNA analysis of related organisms. In the case of humans, gorillas, and chimpanzees, all of which share skeletal similarities, the true closeness of these species is revealed by comparing their DNA. Humans, gorillas, and chimpanzees, for example, share 98% of their DNA. This homology illustrates that all three of these species descended from a common ancestor prior to their appearance as individual species. This common descent occurred sometime about 10 million years ago. After that period, the species of early humans, gorillas, and chimpanzees began to evolve separately.

Some homologies reach back even further in time. The history of land vertebrates begins around 370 million years ago in the Late Devonian period. Some primitive fishes developed specialized front fins to support their body weight in shallow water. From this lineage came true limbed animals, including the first walking fishes whose front fins evolved into forelimbs. Beginning with this remarkable adaptation, the forelimb of vertebrates with legs (which are known as *tetrapods*) has evolved in many different ways to serve different species. No matter what their size, lifestyle, habitat, or geologic time, all tetrapods have the same set of bones in their forelimbs: the humerus, radius, and ulna. These bones are seen in both tetrapods that are living today and in prehistoric animals that are extinct. The exact shape and size of the bones may vary depending on the structure of the tetrapod body, but the similarity of their forelimbs suggests that all tetrapods have a common ancestor. The history of the forelimb is another good example of a homology.

Homologies relate not only to the hard parts of an organism—the bones, teeth, shells, and other parts that become fossilized—but also to the soft tissues or organs that are not found in the fossil record, such as the heart, lungs, brain, and gut. A scientist who is given only the fossil skeleton of an extinct vertebrate can assume that that organism shared most of the internal organs of today's vertebrates. Knowing that homologies exist allows paleontologists to piece together the lifestyle of an extinct animal with some confidence.

There is an old saying, "If it looks like a duck, walks like a duck, and quacks like a duck, it must be a duck." This may be true of ducks, but it is not always true when it comes to the evidence found in the fossil record.

Similar inherited traits can arise in organisms that are not related to one another. These traits are called **analogies** and are the result of **convergent evolution**. When is a duck not a duck? The answer is when it is the result of convergent evolution. Different species can sometimes respond to forces of nature in similar ways. Convergent evolution occurs when unrelated species each develop similar adaptations to similar environmental conditions.

Consider the case of powered flight. This ability is not unique to birds. Among vertebrates, powered flight has evolved three separate times. These instances were separated by long stretches of time and happened independently of one another. Flight in the vertebrates first happened in winged reptiles called pterosaurs, then in birds, and finally in bats, which are mammals. In each case, the forelimbs of the species changed over time to form wings. This is an example of convergent evolution.

Another striking case of convergent evolution involves animals of the sea. Most fishes have streamlined bodies with fins, and oceangoing mammals such as the porpoise have developed similar bodies with fins. Even more striking is the comparison of porpoises with ichthyosaurs, a group of extinct oceangoing reptiles. The two species are not related, even though they both exhibit nearly identical body plans with hairless, scaleless bodies and flippers structured to improve locomotion through the water.

These examples of homology and analogy, convergent evolution, and inherited traits are all forms of comparative anatomy. This shows that clues to evolution can be found by studying the structures of living organisms and how they compare to extinct life-forms.

CONSTANTLY CHANGING LIFE

Erwin Schrödinger (1887–1961), a German physicist who was interested in the underlying causes of evolution, described the life of an individual organism as "but a minute blow of the chisel at the ever unfinished statue." For evolution is a work in progress, and the

Figure 6.1 The pterosaur is a flying reptile that lived 65 to 220 million years ago, evolving independently from birds.

organisms that exist today are only the leading indicators of what is yet to come and what has gone before.

There are no more profound questions than those about the nature and development of life. Darwin's mechanism of natural selection has proved to be a durable explanation for the ways species change over time. Ample support for evolution comes from several disciplines as distinct as genetics, paleontology, and anatomy. The evidence converges on a stark realization about the nature of life. All species participate in a process called evolution that never ends. What is happening today in the cells and genetic architecture of every living organism may influence, in a small part, the continued development of that organism's species.

7

The Evolution of Humans

Even though humans and apes may share 98% of their DNA, you would never confuse a person with a chimpanzee or gorilla. But we are all **primates** ("of the first"), a biologically related group of mammals made up of all lemurs, monkeys, and apes, including humans.

What, then, is a human being? Today, we would say that a human being is a primate that walks upright, talks, has a relatively hairless body (compared to other primates), and the largest brain of all apes. Yet, the earliest humans that arose about 200,000 years ago were not quite so distinct from their ape-like ancestors. The earliest humans did not resemble us much at all and retained many ape-like features. The modern human body form took shape only about 100,000 years ago.

The body alone is not the only clue to our humanity, however. Perhaps even more important are the behaviors that humans developed by using their enlarged brains and superior intelligence. Humans were expressing themselves through the use of arts and crafts long before the appearance of written history. The development of language led to the formation of large human communities. Advanced intelligence also made humans one of the most adaptable species on the planet. People have a knack for survival and problem solving, for planning ahead, and for toolmaking that enables them to build houses, hunt for food, make clothing, and adapt to climates of all kinds.

The rise of humans is one of the most interesting stories in evolution. There is an abundance of evidence regarding the connections between humans and our nonhuman primate ancestors. This chapter traces the story of human evolution and the ongoing development of our own species.

FROM NONHUMAN PRIMATES TO HUMAN ANCESTORS

Before there were humans, there were primates that showed physical and behavioral traits that would become part of the makeup of the human species. Scientists refer to primates other than humans as **nonhuman primates**. Humans are one of more than 200 kinds of living primates in the world today. One of the most familiar features of the primate body is the grasping hand. Interestingly, most primates other than humans are quadrupedal (walking on all fours) when on the ground. The jaws and teeth of primates are shaped so that they can eat a wide range of food, from seeds and plants to fish, fowl, and meat. Primates have large brains and **binocular** vision. Binocular vision occurs when both eyes are aimed forward on a relatively flat face. The field of vision of the two eyes overlaps, which allows the brain to combine images that are ever so slightly different, providing a sense of depth and dimension that is not possible with the use of only one eye. Judging distance is especially important to tree-dwelling animals that are capable of jumping from branch to branch, but it is also essential for running and maneuvering with speed and accuracy on the ground. Evolutionary changes in the primate skull and brain generally have favored the sense of vision over the sense of smell, particularly in nocturnal (nighttime) species.

Primates tend to live longer than most other mammals. Living in social groups began with nonhuman primates and probably furthered their collective survival. People have taken this behavior to great lengths in the formation of towns, cities, countries, and global communities that support one another.

Primates engage in a large collection of verbal and nonverbal expressions, from vocalizations to gestures, facial expressions, and touching. Higher primates, including gorillas, orangutans, chimpanzees, and humans are good learners and skilled at using tools.

The human species is marked by several distinctive skeletal features. These include upright posture, a brain capacity that is much larger than other primates, changes to the teeth and jaws, and a reduced number of teeth overall. Paleontologists tracing the early evolution of humans look for clues such as these to distinguish fossil humans from other fossil primates. Sometimes the fossils are not complete enough to make this distinction clear, and work continues in the search for the earliest humans.

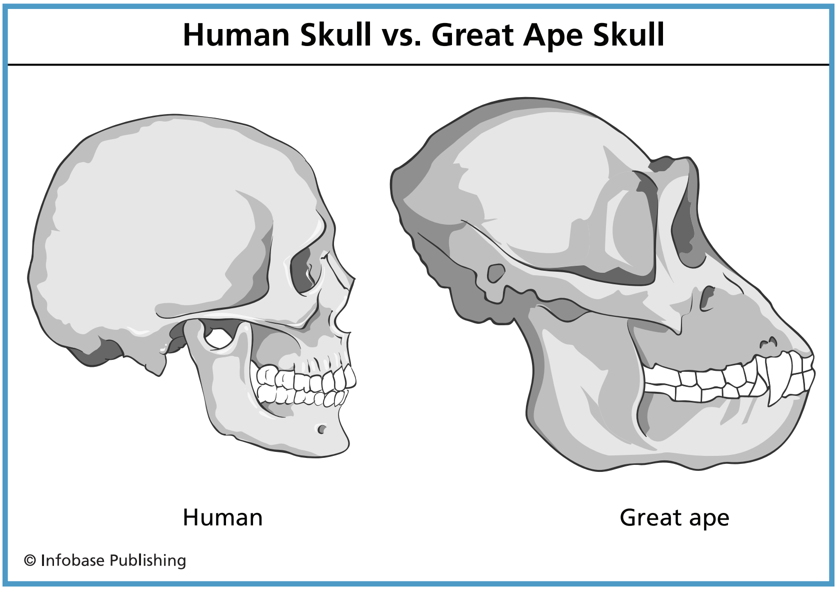

Figure 7.1 The human skull has some elements in common with that of the great ape, although the differences are also notable. The ape's skull includes forward-pointing sockets for the eyes, and the foramen magnum—the opening in the base of the cranium where the spinal cord goes into the vertebral column—is located underneath the skull. This placement allows the eyes to always face forward and protects them even more than is possible in the human skull.

The accompanying figure summarizes the kinds of anatomical traits that enable paleontologists to distinguish fossil humans from fossil apes.

Out of Africa: Early Humans

Fossils representing the earliest examples of human species have been found in east Africa and date from about 7 million years ago. Identifying early humans from fragmentary fossils is difficult because of how closely the bones resemble the bones of apes. The fossil record of humans is poorest during a time span representing 5 to 7 million years ago when humans first evolved as a species that was distinct from the great apes. The fossil record is much clearer a little later, between 2 and 4 million years ago. During this period, a fairly complete picture of early humans can be traced.

The first significant early human specimen was found in South Africa in 1925 and described by Raymond Dart (1893–1988), an

Table 7.1: Anatomical Traits of Early Humans

Features of the Skull

- reduced teeth overall, especially the canines
- reduced shearing mechanism between the upper canine and lower premolar when the jaw was closed
- molars with thick enamel
- rounded, bowl-shaped dental battery
- foramen magnum, the point of connection where the skull meets the vertebral column, positioned below the skull

Other Skeletal Features

- modifications to enable bipedalism, including:
  - broad, bowl-like pelvis
  - angled connection of the femur to the hip
  - arched feet
  - big toe aligned with other toes for balance
  - flexible knee
  - long lower leg bones
- shortening arms
- less curved fingers

Early Human Skeletons

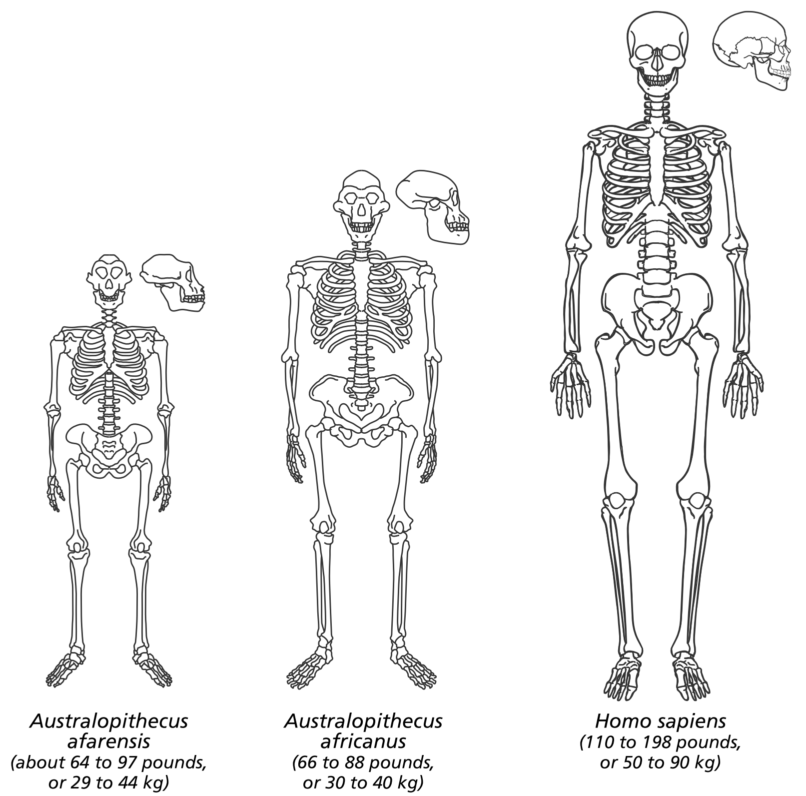

Figure 7.2 The skeletons of early humans show a fair amount of variety in size, cranial shape, and the weight the average human could hold.

Australian anatomist. Discovered in a limestone quarry in the small town of Taung, the fossil consisted of a small skull that Dart painstakingly extracted from the tough rocky matrix in which it was sealed. The result was a lovely specimen of a juvenile skull. Dart had reason to believe that he was holding something more than the skull of an ape child. The specimen lacked the large canine teeth of apes, and the connection between the skull and the neck suggested that the individual walked with an upright posture. Dart gave the fossil the scientific name of *Australopithecus africanus* ("southern ape of

Africa"). The genus *Australopithecus* is now considered to be an ancestral human—a species that came before modern humans.

Following the initial discoveries in South Africa, the search for early humans broadened to east Africa. East Africa has produced many extraordinary human specimens from a rugged area known as the Great Rift Valley. Located in the eastern Serengeti Plain of northern Tanzania, the Olduvai Gorge is one of the most important fossil-bearing regions of the Great Rift Valley. The gorge is about 30 miles long and consists of a deeply cut ravine that is located in a mile-high, grassy plateau. The climate is similar to the way it was when early humans first lived there. This part of east Africa is hot, dry, and devoid of thick vegetation. These conditions help make it possible to see fossils on the rocky surfaces.

Many significant finds of early human fossils were made in the Olduvai Gorge by Kenyan Louis Leakey (1903–1972) and his British wife, Mary Leakey (1913–1996). Born of missionary parents in British East Africa, which is now known as the nation of Kenya, Louis met Mary while they were both doing field work in England. They married and moved to Kenya in 1937, had three children, and began to explore the Olduvai Gorge for fossils of human ancestors. The Leakeys' son Richard (b. 1944) and Richard's wife Meave (b. 1942) also became noted fossil hunters. Together, for more than 40 years, this "first family" of anthropology has been at the center of discovery of early humans. The family's work naturally attracted other researchers to the area, and although some of the work now has shifted to other areas of east Africa, the Leakeys and their pioneering work remain influential on the science of early humans.

The hub of ape evolution was eastern Africa, along the area where the Great Rift Valley was formed. The earliest fossils of true apes are known to come from Kenya, Namibia, Uganda, and Ethiopia. Evolution caused a split in the family tree of ancient apes, and they proceeded on two different evolutionary paths. One path split off between 13 million and 15 million years ago and led to orangutans. The other path led to modern African apes, including chimpanzees. It was from the line of chimpanzees that another split took place, eventually leading to early humans. Humans split from the lineage of the genus *Pan* (the chimpanzee) between 5 million and 7 million years ago.

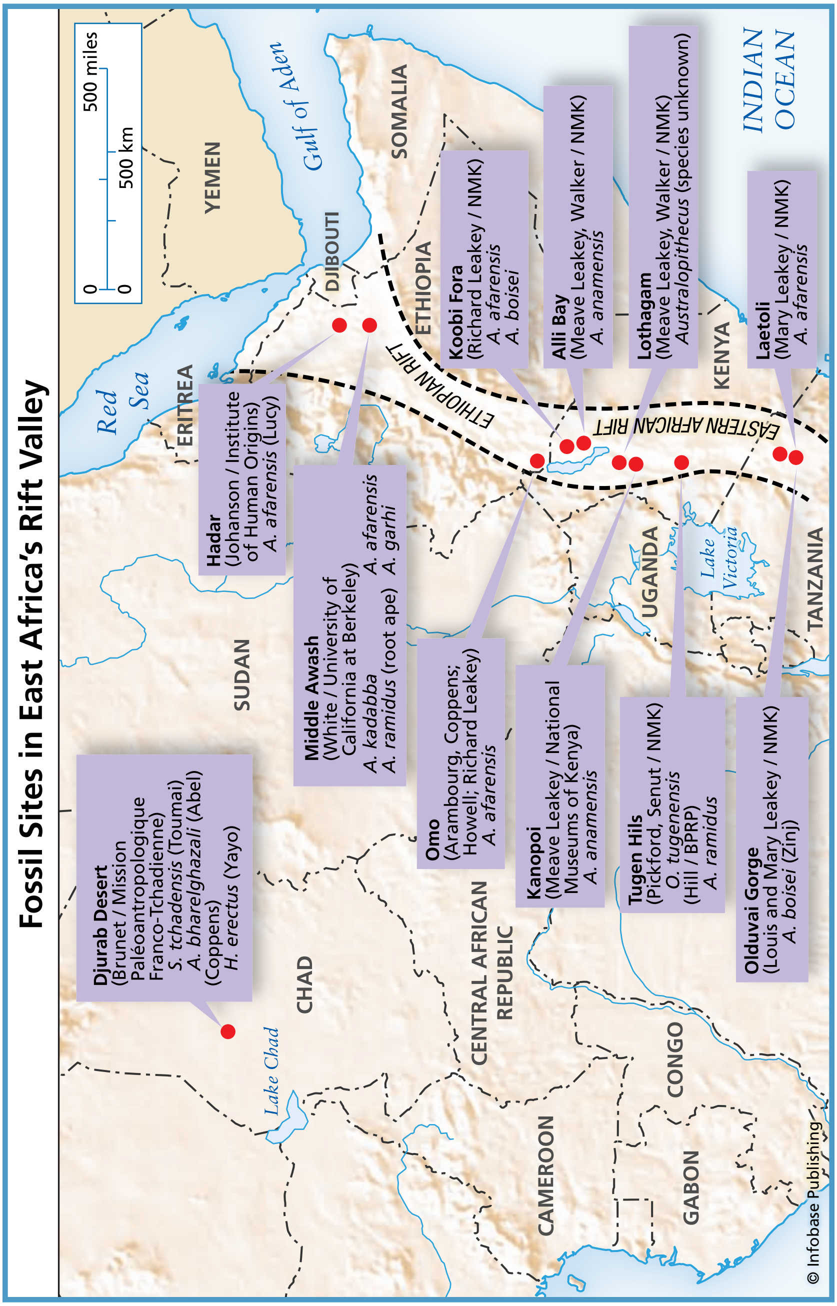

Figure 7.3 East Africa's Great Rift Valley is the site of numerous important fossil finds.

EARLY HUMAN SPECIES

Modern human species belong to the genus *Homo*. Evidence for Homo in the fossil record reaches back a mere two million years. Of several species of *Homo* that once existed, *Homo sapiens* is the last. In one sense, we are the last of our kind. But in another sense, humans represent one of the most remarkably oddball outcomes in the entire 500 million-year evolutionary history of the vertebrates. Humans are unique. What other creature is capable of contemplating, writing, and reading about its own existence?

Paleoanthropologist John Fleagle of the State University of New York at Stony Brook reminds us that humans did not possess, from their very start, the familiar attributes that clearly distinguish us from our ape relatives: bipedal locomotion, enlarged brains, grasping hands, and the use of tools and language. The earliest humans did not suddenly appear with all of these distinguishing traits intact. Instead, the many features found in living humans appear to have evolved one by one.

The anatomical and behavioral traits that distinguish humans from the great apes did not appear suddenly but developed gradually, over the course of more than four million years. Human achievements such as the appearance of language, religious beliefs, and art are relatively recent phenomena in human history: None of them appeared earlier than 200,000 years ago, and most of them occurred much more recently than that. These traits were preceded by important changes to the human body, traces of which are found in the fossil record of ancestral humans.

Fossils of early humans show a variety of evolutionary paths regarding the appearance and timing of these human traits. This evidence strongly suggests that the evolution of humans did not occur as a straight line of connected families but arose from several independently developing species in which the occurrence of these traits coevolved at different times.

The earliest possible human specimens include a trio of species that date from 4 to 7 million years ago. They are known from fragmentary evidence, and their position as humans is a matter of much debate among paleoanthropologists. Yet these specimens include some humanlike features that represent either evidence of ancestral human species or a transitional phase in the development of great apes that had some humanlike features.

Sahelanthropus tchadensis was discovered in Chad, a nation in north-central Africa, in 2001. Reconstruction of the skull suggests that the neck was positioned far enough beneath the skull to make possible for it to have upright posture. The small brain and ape-like face of *Sahelanthropus* suggest that it was probably more ape than human, but it is a curious case indeed.

Orrorin tugenensis, from Kenya and discovered in 2000, is known from its teeth and a few skeletal remains. The front teeth of *Orrorin* were more ape-like, but the molars had a square shape like those of humans. The long, ape-like canine teeth argue against *Orrorin* being a human, however.

Ardipithecus kadabba and *Ardipithecus ramidus*, from Ethiopia, were discovered in 1992 in an area where exploration has yielded fragmentary remains of more than two dozen humanlike individuals. These originally were thought to be fossils of *Australopithecus*, but differences in the tooth enamel, the limb structure, and the position of the neck suggest that these species were more primitive. *Ardipithecus* had several traits that link it more closely to apes; these include thin tooth enamel and large canine teeth. The most humanlike characteristic of *Ardipithecus* was represented by the more forward position of the neck at the base of the skull. One interpretation of *Ardipithecus* is that it was at the beginning of the human divergence from the great apes and displayed a more upright, though possibly not fully erect, bipedal posture.

The genus *Australopithecus* is the most likely direct ancestor of *Homo*. *Australopithecus* existed during a period of about 2 to 4 million years ago. Their extinction coincides closely with the appearance of the first *Homo* species. *Australopithecus* individuals were clearly bipedal, their molars had thick enamel like that of modern humans, and there were measurable increases in the size of their brains during the 2 million years of their existence. *Australopithecus* was also short compared to modern humans. They are found in the eastern and southern regions of Africa where the remains of different species appear to have arisen roughly about the same time.

One of the most significant specimens of *Australopithecus* is that of the species *Australopithecus afarensis* from Ethiopia. More than 70 specimens of this species have been discovered, making it the best understood example of early humans. The first known specimen was that of a small female individual that measured only

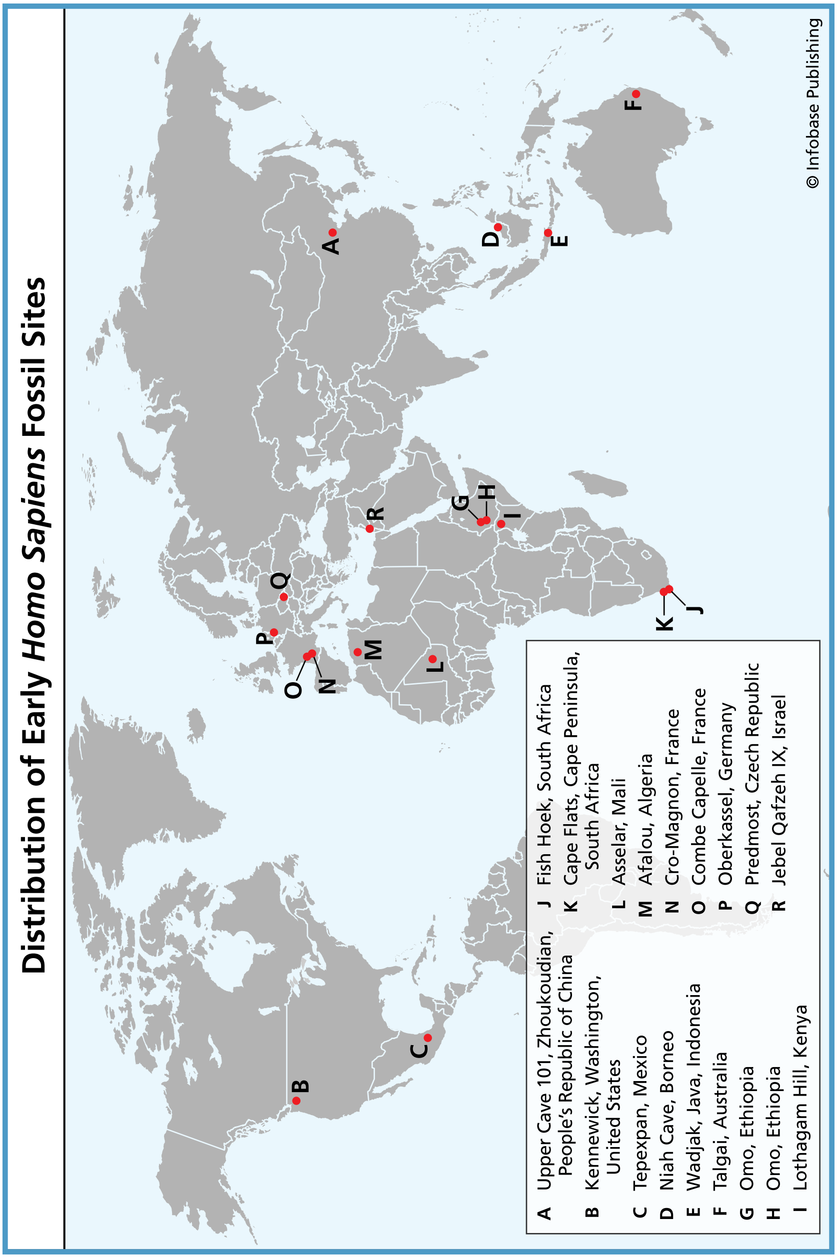

Figure 7.4 Fossils of Early *Homo sapiens* have been found around the world, including parts of the North America, Europe, Africa, Asia, and Australia.

3.5 feet (1 meter) tall. Nicknamed "Lucy," *Australopithecus afarensis* was remarkably well preserved. About 20% of the skeleton was found, including bits of skull, jaws, teeth, ribs, pelvis, spine, arms, and legs. *Australopithecus afarensis* was unquestionably bipedal, yet it was primitive in many other aspects of its anatomy. Its brain was about as big as that of a modern chimpanzee. Its arms were longer than those of later humans, and they may have had curved fingers, a trait that reveals their tree-climbing ancestry.

THE GENUS *HOMO*

By about 4.2 million years ago, fossils show that ancestral humans were well established on the savannahs of Africa. The human adaptations of bipedalism and a set of teeth that were well suited for a varied diet gave early humans an adaptive advantage. Before very long, humans had left the forests of their ape ancestors to explore the open grasslands that stretched throughout Africa. Humans then migrated northward out of Africa to occupy Europe, Asia, and other parts of the globe, marking the emergence of the modern genus of humans known as *Homo*.

Modern humans of the species *Homo sapiens* arose very quickly from their ancestral roots in the family of early human primates. In the 200,000 years following the demise of *Australopithecus,* modern humans rapidly eclipsed their ancestors in several astonishing ways. *Homo* species developed into the tallest humans, adapted jaws and teeth capable of eating a diversity of food types, and evolved brains that today are roughly three times larger than those of the most advanced species of *Australopithecus*.

Because evolution is such a gradual process, there are several stages of development leading from *Australopithecus* to modern *Homo*. The accompanying table shows some of the traits found in specimens of *Australopithecus* and *Homo*. Note that in addition to skeletal remains, the presence of tools at early human sites is considered to be a calling card left by a *Homo* species—clear evidence of the increased intelligence and problem-solving and planning skills that marked an advance over *Australopithecus*.

Figure 7.5 The bone fragments belong to Lucy, the 3.2 million year-old member of the *Australopithecus afarensis* species.

The earliest known *Homo* species is that of *Homo habilis*, the "handy man," named by Louis Leakey and his colleagues in 1964. The original *H. habilis* specimen was found in the Olduvai Gorge of Tanzania by Leakey and his wife, Mary. Because species of *Australopithecus* had been found in the same general location as this specimen, the discovery of *H. habilis* revealed for the first time that the two species lived and thrived together at the same time. Primitive stone tools had been found previously at Olduvai, but none of the humans found previously in the area were likely candidates for having made such tools; the humans found earlier had less dexterous hand anatomy and

Table 7.2 Trends in Human Evolution

Features	*Australopithecus* Traits	*Homo* Traits
Skull and Crania	Smaller brain Larger face in proportion to overall skull Face often flat or concave Large to moderate brow Sagittal crest (some) Protruding jaw Receding chin Thinner braincase wall	Larger brain Smaller face in proportion to overall skull Face never concave Large to slight brow Vertical forehead Domed cranium, no sagittal crest Chin may protrude Thicker braincase wall
Teeth	U-shaped dental battery Massive jaw Larger incisors and canines Very large premolars and molars, heavily enameled	Parabolic-shaped dental battery Less massive jaw Small incisors and canines Smaller premolars and molars, not heavily enameled
Limbs	Longer arms Shorter legs Curved fingers (climbing) Limited grasping capability in hands Heavier (thicker) postcranial bones	Shorter arms Longer legs, greater height Grasping fingers, thumb, precision grip Lighter (thinner) postcranial bones
Torso	Funnel shaped Mostly upright	Cylindrically shaped Fully upright
Tools	Possible early stone tools	Early stone toolmaking

smaller brains. With the discovery of *H. habilis*, the Leakeys had also discovered the most likely makers of such tools.

There were more than one species of early *Homo*. Although *Homo* sapiens are the only remaining Homo species, other early species included *Homo erectus*, *Homo ergaster*, and *Homo neanderthalensis*, also known as the Neanderthals. By about 1.8 million years ago, species of *Homo* had begun to migrate beyond eastern and southern Africa. This dispersal was fairly rapid by evolutionary standards and was made possible by land bridges that connected Africa, Europe, Asia, and Indonesia. The earliest *Homo erectus* species found in southeast Asia, on Java, dates from soon after the species left Africa, between 1.6 and 1.8 million years ago. It may have taken about 20,000 years for this population to make its way to Asia from Africa, traveling on foot, walking the 10,000 to 15,000 miles (16,000 to 24,000 km) from Africa and expanding its numbers eastward, generation after generation. Other fossils document the appearance of *Homo* in Europe (0.9 millions of years ago, Italy); central Asia (1.75 mya, Georgia); and China (1.8 mya).

Homo Neanderthalensis

Homo neanderthalensis, the Neanderthals, were a species of *Homo* that arose in Europe around 300,000 years ago, became widespread throughout Europe and western Asia by about 120,000 years ago and became extinct only 30,000 years ago. Fossil evidence and a comparison of the *Homo neanderthalensis* and *Homo sapiens* genomes confirm that the Neanderthals were a species of *Homo*, separate from all others. Neanderthals were hunters and lived in caves, rock shelters, and outside shelters that they made themselves; they also buried their dead. Although anatomically and genetically capable of using verbal language, it is unknown whether Neanderthals had a spoken language.

The name Neanderthal comes from the Neander Valley near Düsseldorf, Germany, where some of the first specimens were found in 1856. Apart from modern humans, we understand more about *Homo neanderthalensis* than any other extinct human species. Their remains are often found in caves that include tool artifacts, animal bones, and other clues to their lifestyle.

Neanderthals are not a "missing link" in any sense of the word. Not only do they come later than the split of early humans from

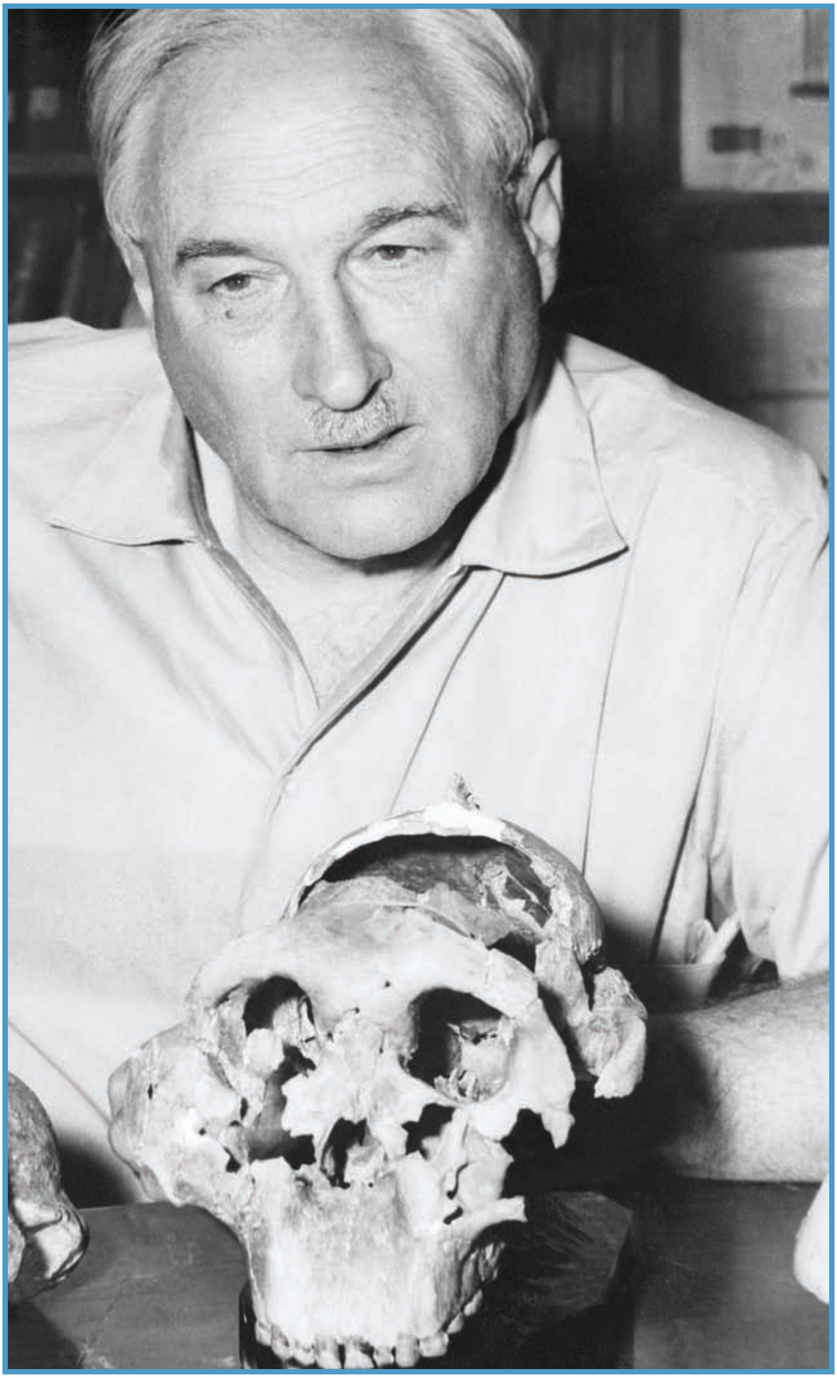

Figure 7.6 Louis Leakey poses with the skull of a fossil human at least 1,700,000 years old.

the great apes by a couple of million years, Neanderthals were an entirely separate *Homo* species. Even though they lived in the same geographic range as early modern humans for the last 40,000 years of their existence, Neanderthals could not have mated or bred with the species *Homo sapiens*.

Modern humans are not descendants of Neanderthals. Whatever Neanderthals were, they were not exactly like modern humans. Yet, they successfully adapted to climate changes and other challenges for several hundred thousand years.

The origins of Neanderthals are not well understood, but their presence in Europe is well documented, especially within the past 100,000 years. Some of the earliest Neanderthal remains date from about 300,000 years and, again, were found in Spain. While not much is known about their origins, it is known is that Neanderthals were widespread but isolated in Europe and western Asia. Their evolutionary path split off from the lineage of humans that led to the speciation of *Homo sapiens*.

Neanderthals were superficially similar to modern humans. If they were alive today, one might have difficulty telling them from *Homo sapiens*. A closer look at their skeletal features reveals, however, many features of their skulls and postcranial anatomy that clearly distinguish Neanderthals from *Homo sapiens*.

The Neanderthal skull had a large cranial vault but low, sloped forehead. In comparison to modern humans, Neanderthals had large, rounded eye sockets, a prominent bony brow, a wide and high nose, large front teeth, backward sloping cheekbones, and a small rounded bulge on the back of the skull. Their teeth projected forward more than modern humans.

From the standpoint of their bodies, Neanderthals were undoubtedly more sturdily built and muscular than modern humans. Neanderthal ribs were wide, giving their abdomen a more barrel-like shape. The forearm was surprisingly short, the knees and ankles were thick jointed and the feet equipped with wide and strong toes. The shoulders of *Homo neanderthalensis* were broader than modern humans and the limb bones generally thicker and heavier. The hands and fingers were robust and capable of a mighty grip. In comparison, the early modern humans that encountered *Homo neanderthalensis* were no doubt lighter on their feet, but would surely have lost most arm wrestling contests to their early human neighbor. Just

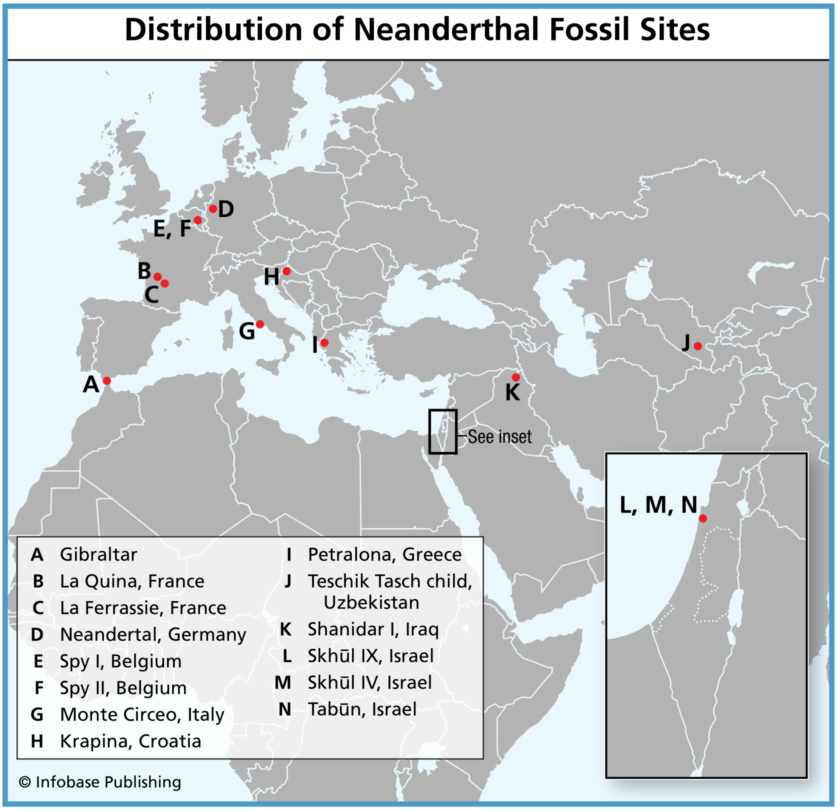

Figure 7.7 Neanderthal fossils and stone tools have been found in a number of countries, including those noted in this map. Neanderthal cranial capacity is thought to have been as large as or larger than that of *Homo sapiens*, which makes scientists theorize that their brains may have been comparable as well.

why Neanderthals became extinct and modern humans did not is a puzzling question because, in many ways, Neanderthals were better adapted for the harsh Ice Age climates of Europe than *Homo sapiens*. It may be that Neanderthals were not able to adapt well enough to the warming climates and changing fauna at the end of the Ice Age, making it difficult to compete with modern humans who had devised techniques for hunting on the open grassy plains of Europe.

The story of human evolution is one of gradual adaptation and natural selection of traits that led to the survival and spread of the human species. The most important evolutionary developments that led up to modern humans were the ability to walk upright and make tools. Walking on two legs changed our anatomy from that of forest dwellers to occupiers of open spaces. Walking also made humans mobile, allowing them to migrate beyond their homelands and spread their kind from Africa to Europe, western Asia and beyond in a matter of tens of thousands of years. Toolmaking allowed early humans to devise strategies for survival through hunting and food preparation. These developments in anatomy and behavior evolved step by step over many thousands of years. The only remaining human species—*Homo sapiens*—continues to thrive because of these same innovations.

8

Is There a Reason for Evolution?

Every species possesses, by chance, genetic traits that may improve or hinder its chances of survival. The inheritance of biological traits in nature cannot be willed by the individual organism. In the natural world, an organism cannot dictate which traits it will inherit, nor can its parents direct which traits to pass along. The traits are passed along by chance in the form of *mutations*—slight, unpredictable variations in the genetic code that happen when organisms reproduce.

WHAT EVOLUTION IS—AND IS NOT

Evolution is the result of natural selection and happens by chance. Evolution has no purpose or plan but effectively weeds out unfit organisms and selects for those that are better fit—better structured—to survive in their habitat.

Evolution has no particular direction. Evolution does not necessarily progress from simple to more complex forms, as was thought before Darwin. Life simply evolves to adapt to its environment and there is no intrinsic value placed on one kind of adaptation over another. There are many examples in which organisms adapt to a new environment and then return to a previous environment at a later stage in their evolution. Land animals originally evolved from fish, but there also are cases, such as that of the whale, in which land animals have returned to an aquatic lifestyle. In the southeastern United States, the non-venomous scarlet king snake has adapted coloration that resembles that of the poisonous eastern coral snake. By taking on the appearance of a deadly snake, the harmless scarlet king snake

Understanding Evolution

Here are eight key ideas for understanding evolution:

- Evolution is the natural process that causes life gradually to change biologically over time.
- Evolutionary changes to a species are caused by changes to the genetic code—the DNA—of organisms that are passed along to the next generation of a species through the process of natural selection.
- Genetic traits are passed along by chance in the form of mutations—slight, unpredictable variations in the genetic code that happen when organisms reproduce. Physical traits and social behavior of a species can be passed along to the next generation by genes.
- Evolution has two causes. It is influenced by the inherited genetic traits of an individual organism and by the interaction of an organism with its habitat.
- Adaptations are biological traits that make an organism better fit to survive.
- Evolution may occur gradually or rapidly.
- Evidence for evolution can be found in the fossil record, the study of biological molecules and genes, and comparative anatomy.
- Convergent evolution occurs when unrelated species each develop similar adaptations to similar environmental conditions.

fools predators into leaving it alone. If the scarlet king snake is removed from an environment that it shares with coral snakes, however, natural selection can override such mimicry and promote the evolution of a scarlet king snake that looks less like the coral snake.

Evolution does not always lead to longevity in species. Evolution does not always lead to success or longevity in species when compared to others. There are many examples of organisms, simple and complex, that encountered changes in their environment or other factors to which they could not adequately adapt. The result is extinction.

There are no more profound questions than those about the nature and development of life. Darwin's mechanism of natural selection has proved to be a durable explanation for the ways species change over time. Ample support for evolution comes from several disciplines as distinct as molecular biology, paleontology, mathematics, and quantum physics. The evidence converges on a stark realization about the nature of life. All species participate in a process called evolution that never ends. What is happening today in the cells and genetic architecture of every living organism may influence, in a small part, the continued development of that organism's species.

While the study of evolution provides some answers to those profound questions about where life comes from, it has also greatly influenced the way that humans view, understand, and classify other organisms in the world. It is only through evolution that the many branches of Earth's family tree can be traced and linked from the first single-celled organisms that sprouted 3.5 billion years ago.

Glossary

adaptations Anatomical, physiological, and behavioral features that enable an organism to survive in a given environment and that are selected for by evolution

analogies Similar traits that arise in unrelated kinds of organisms

binocular Overlapping vision of the two eyes

biological adaptations Genetic changes to an organism that are inherited from its parents

convergent evolution When unrelated species each develop similar adaptations to similar environmental conditions

DNA (deoxyribonucleic acid) The molecule of life, which carries genetic instructions from parent to offspring; DNA is found in the cells of all organisms.

domains of life Three classifications of life forms that occupy a level of classification higher than the kingdom; the archaea, bacteria, and eukarya

eukaryotes Living organisms in the domain eukarya; multicelled organisms with a distinct cell structure whose nucleus contains strands of DNA

evolution The natural process by which species gradually change over time, controlled by changes to the genetic code—the DNA—of organisms and whether or not those changes enable an organism to survive in a given environment

extinction The irreversible elimination of an entire species of organism because it cannot adapt effectively to changes in its environment

fossil Any physical trace of prehistoric life, such as skeletal remains

gamete Cells involved in sexual reproduction, found in male and females of the same species, and that contain only half of the chromosomes needed to form a complete set of genes for the development of an offspring

gene A portion of a DNA strand that controls a specific inherited trait

gene flow The introduction of new alleles from an outside population of the same species

gene pool The combined genetic makeup of a species population

genetic drift A chance fluctuation in allele frequency in a gene pool that is not caused by natural selection

genetic evolution Inherited traits within a given species population

genetics The scientific study of DNA, genes, and inherited traits

genome The complete genetic instructions embodied in the DNA of a species

genus (plural genera) A scientific name for one or more closely related organisms that is further divided into one or more species; names of organisms, such as *Tyrannosaurus rex*, are composed of two parts, the genus name (first) and the species name (second).

geologic time scale A scale for measuring time based on observations about the layers of the earth and how long these layers took to accumulate

gradualism The evolution of new species as a slow and gradual process

homologies Structural and behavioral traits that different species of organisms have inherited from a common ancestor

hybrid An offspring of two animals of different varieties, breeds, or species, such as a mule

hypothesis A guess or prediction in need of scientific proof; an hypothesis is the basis for scientific research

macroevolution The evolutionary process that results in new species

metabolism The combination of all biochemical processes that take place in an organism to keep it alive

microevolution Genetic changes that can take place within a species population without resulting in a new species

mutations Slight, unpredictable variations in the genetic code that happen when organisms reproduce

natural selection One of Darwin's observations regarding the way in which evolution works; given the complex and changing conditions under which life exists, those individuals with the combination of inherited traits best suited to a particular environment will survive and reproduce while others will not.

nonhuman primates Primates other than humans, such as the gorilla, chimpanzee, and orangutan

phenotype An observable trait in an individual, such as eye color

photosynthesis A metabolic process in which an organism's cells convert energy from the sun, carbon dioxide, and water to reproduce their cells; the waste product of photosynthesis is free oxygen released into the atmosphere; plants use this metabolic process.

population Members of the same species that live in a particular area

population genetics The study of the frequency of alleles, genotypes, and phenotypes in a given group of individuals

primate Living and fossil monkeys, apes, and prosimians, including humans

prokaryotes Single-celled organisms whose cells do not have a nucleus; the prokaryotes include members of the domains archaea and bacteria.

punctuated equilibria Rapid evolutionary changes caused when a population of a given species suddenly encounters a dramatic change to its habitat

reproductive isolating mechanisms Factors that prevent two species from interbreeding, thus helping to maintain the uniqueness of each species

sedimentary Rock that forms in layers from the debris of other rocks or the remains of organisms

speciation The evolution of new species

species The most basic biological unit of living organisms; members of a species can interbreed and produce fertile offspring.

theory A comprehensive, testable explanation about some aspect of the natural world that is backed by an extensive body of facts over time

transitional fossil A fossil that represents one step in the many stages that exist in the evolution of a species

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Web sites

BBC: Human Beginnings
http://www.bbc.co.uk/sn/prehistoric_life/human/

This site provides a collection of text and video content related to the evolution of humans.

Complete Works of Charles Darwin Online
http://darwin-online.org.uk/

This Web site includes the complete, searchable works of Charles Darwin including published books and private papers.

National Museums of Kenya
http://www.museums.or.ke/

Here is a guide to museums in Kenya, many of which house important fossils of ancestral humans from east Africa.

National Primate Research Center, University of Wisconsin
http://pin.primate.wisc.edu/index.html

This is an excellent resource for scientific information about living primates; it includes fact sheets about different species and an audio-visual library of primate vocalizations and research videos.

Public Broadcasting Service: Evolution Library: Evidence for Evolution
http://www.pbs.org/wgbh/evolution/library/04/

This resource outlines the extensive evidence in support of both the fact and theory of evolution, basing its approach on studies of the fossil record, molecular sequences, and comparative anatomy.

Investigating Common Descent: Formulating Explanations and Models
http://www.nap.edu/html/evolution98/evol6-d.html

This educational resource designed for high school science teachers provides background, research ideas, and facts regarding human evolution as defined by the National Research Council.

The Tree of Life Web Project
http://tolweb.org/tree/phylogeny.html

The site provides a detailed view of life forms based on their evolutionary connections.

University of California Museum of Paleontology: The History of Evolutionary Thought
http://www.ucmp.berkeley.edu/history/evothought.html

The site offers a tutorial about the thinkers who founded the modern science of evolutionary biology.

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About the Author

Thom Holmes is a writer who specializes in natural history subjects and dinosaurs. He is noted for his expertise on the early history of dinosaur science in America. Holmes was the publications director of The Dinosaur Society for five years and the editor of its newsletter, *Dino Times*, the world's only monthly publication devoted to news about dinosaur discoveries. It was through the society and his work with the Academy of Natural Sciences in Philadelphia that he developed widespread contacts and working relationships with paleontologists and paleo-artists throughout the world.

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