

# 1

## *The Science of Biology*

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### Concept Outline

#### 1.1 Biology is the science of life.

**Properties of Life.** Biology is the science that studies living organisms and how they interact with one another and their environment.

#### 1.2 Scientists form generalizations from observations.

**The Nature of Science.** Science employs both deductive reasoning and inductive reasoning.

**How Science Is Done.** Scientists construct hypotheses from systematically collected objective data. They then perform experiments designed to disprove the hypotheses.

#### 1.3 Darwin's theory of evolution illustrates how science works.

**Darwin's Theory of Evolution.** On a round-the-world voyage Darwin made observations that eventually led him to formulate the hypothesis of evolution by natural selection.

**Darwin's Evidence.** The fossil and geographic patterns of life he observed convinced Darwin that a process of evolution had occurred.

**Inventing the Theory of Natural Selection.** The Malthus idea that populations cannot grow unchecked led Darwin, and another naturalist named Wallace, to propose the hypothesis of natural selection.

**Evolution After Darwin: More Evidence.** In the century since Darwin, a mass of experimental evidence has supported his theory of evolution, now accepted by practically all practicing biologists.

#### 1.4 This book is organized to help you learn biology.

**Core Principles of Biology.** The first half of this text is devoted to general principles that apply to all organisms, the second half to an examination of particular organisms.



**FIGURE 1.1**  
A replica of the *Beagle*, off the southern coast of South America. The famous English naturalist, Charles Darwin, set forth on H.M.S. *Beagle* in 1831, at the age of 22.

**Y**ou are about to embark on a journey—a journey of discovery about the nature of life. Nearly 180 years ago, a young English naturalist named Charles Darwin set sail on a similar journey on board H.M.S. *Beagle* (figure 1.1 shows a replica of the *Beagle*). What Darwin learned on his five-year voyage led directly to his development of the theory of evolution by natural selection, a theory that has become the core of the science of biology. Darwin's voyage seems a fitting place to begin our exploration of biology, the scientific study of living organisms and how they have evolved. Before we begin, however, let's take a moment to think about what biology is and why it's important.

## 1.1 Biology is the science of life.

### Properties of Life

In its broadest sense, *biology is the study of living things—the science of life*. Living things come in an astounding variety of shapes and forms, and biologists study life in many different ways. They live with gorillas, collect fossils, and listen to whales. They isolate viruses, grow mushrooms, and examine the structure of fruit flies. They read the messages encoded in the long molecules of heredity and count how many times a hummingbird’s wings beat each second.

What makes something “alive”? Anyone could deduce that a galloping horse is alive and a car is not, but *why*? We cannot say, “If it moves, it’s alive,” because a car can move, and gelatin can wiggle in a bowl. They certainly are not alive. What characteristics *do* define life? All living organisms share five basic characteristics:

- 1. Order.** All organisms consist of one or more cells with highly ordered structures: atoms make up molecules, which construct cellular organelles, which are contained within cells. This hierarchical organization continues at higher levels in multicellular organisms and among organisms (figure 1.2).
- 2. Sensitivity.** All organisms respond to stimuli. Plants grow toward a source of light, and your pupils dilate when you walk into a dark room.
- 3. Growth, development, and reproduction.** All organisms are capable of growing and reproducing, and they all possess hereditary molecules that are passed to their offspring, ensuring that the offspring are of the same species. Although crystals also “grow,” their growth does not involve hereditary molecules.
- 4. Regulation.** All organisms have regulatory mechanisms that coordinate the organism’s internal functions. These functions include supplying cells with nutrients, transporting substances through the organism, and many others.
- 5. Homeostasis.** All organisms maintain relatively constant internal conditions, different from their environment, a process called homeostasis.

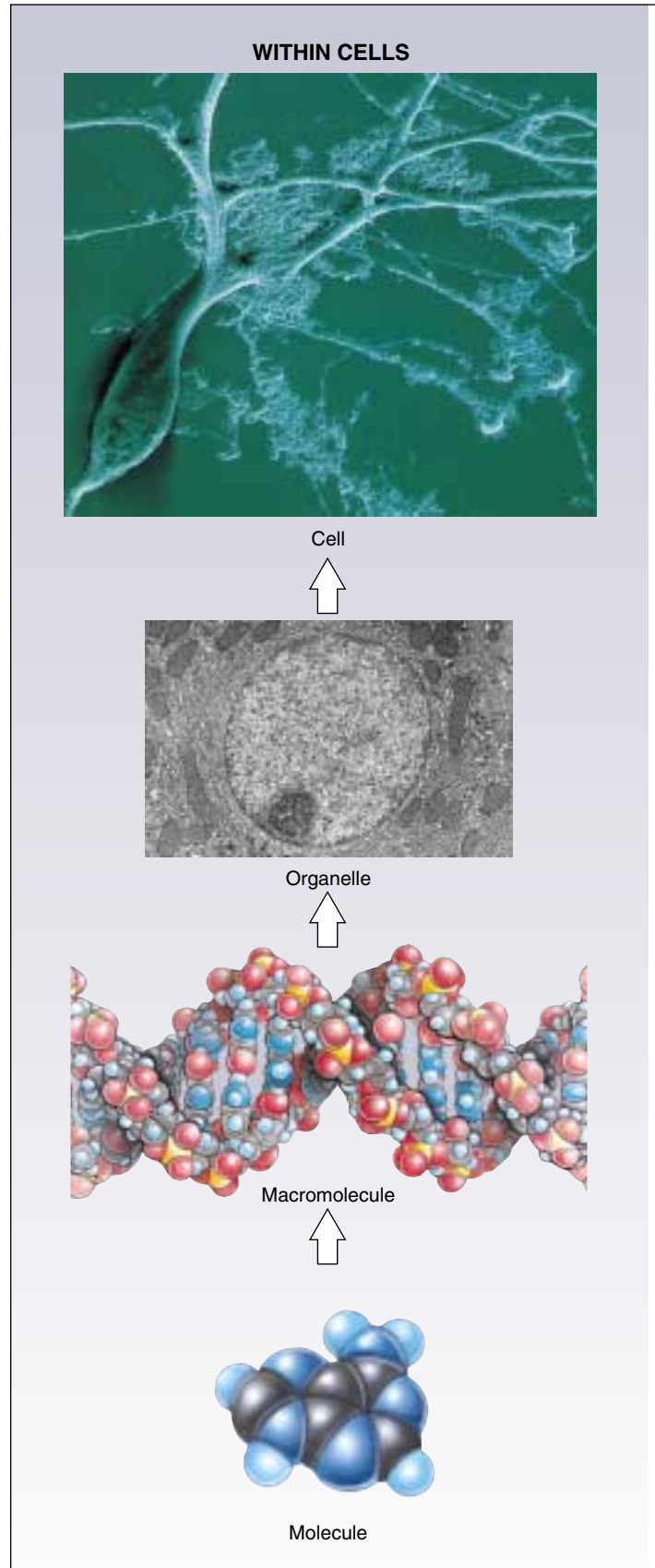
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All living things share certain key characteristics: order, sensitivity, growth, development and reproduction, regulation, and homeostasis.

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FIGURE 1.2

**Hierarchical organization of living things.** Life is highly organized—from small and simple to large and complex, within cells, within multicellular organisms, and among organisms.



**WITHIN MULTICELLULAR ORGANISMS**



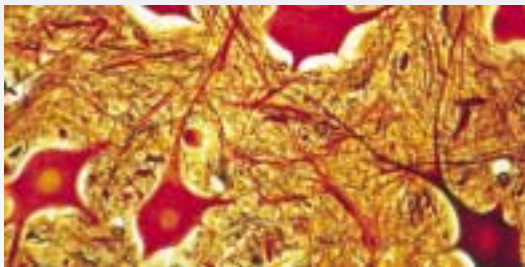
Organism



Organ system



Organ



Tissue

**AMONG ORGANISMS**



Ecosystem



Community



Species



Population

## 1.2 Scientists form generalizations from observations.

### The Nature of Science

Biology is a fascinating and important subject, because it dramatically affects our daily lives and our futures. Many biologists are working on problems that critically affect our lives, such as the world's rapidly expanding population and diseases like cancer and AIDS. The knowledge these biologists gain will be fundamental to our ability to manage the world's resources in a suitable manner, to prevent or cure diseases, and to improve the quality of our lives and those of our children and grandchildren.

Biology is one of the most successful of the “natural sciences,” explaining what our world is like. To understand biology, you must first understand the nature of science. The basic tool a scientist uses is thought. To understand the nature of science, it is useful to focus for a moment on how scientists think. They reason in two ways: deductively and inductively.

#### Deductive Reasoning

**Deductive reasoning** applies general principles to predict specific results. Over 2200 years ago, the Greek Eratosthenes used deductive reasoning to accurately estimate the circumference of the earth. At high noon on the longest day of the year, when the sun's rays hit the bottom of a deep well in the city of Syene, Egypt, Eratosthenes measured the length of the shadow cast by a tall obelisk in Alexandria, about 800 kilometers to the north. Because he knew the distance between the two cities and the height of the obelisk, he was able to employ the principles of Euclidean geometry to correctly deduce the circumference of the earth (figure 1.3). This sort of analysis of specific cases using general principles is an example of deductive reasoning. It is the reasoning of mathematics and philosophy and is used to test the validity of general ideas in all branches of knowledge. General principles are constructed and then used as the basis for examining specific cases.

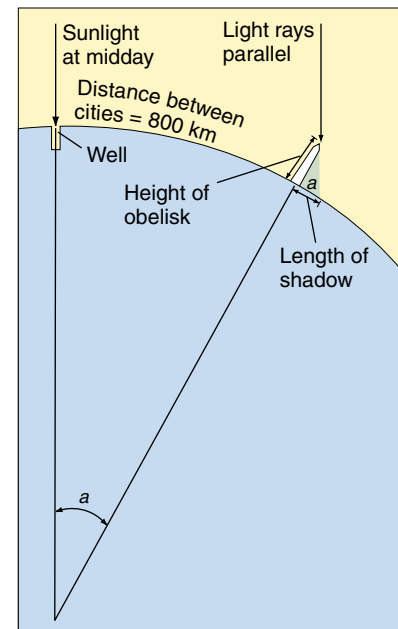
#### Inductive Reasoning

Inductive reasoning uses specific observations to construct general scientific principles. *Webster's Dictionary* defines science as systematized knowledge derived from observation and experiment carried on to determine the principles underlying what is being studied. In other words, a scientist determines principles from observations, discovering general principles by careful examination of specific cases. Inductive reasoning first became important to science in the 1600s in Europe, when Francis Bacon, Isaac Newton, and others began to use the results of particular experiments to infer general principles about how the world operates. If

FIGURE 1.3

**Deductive reasoning: How Eratosthenes estimated the circumference of the earth using deductive reasoning.** 1. On a day when sunlight shone straight down a deep well at Syene in Egypt, Eratosthenes measured the length of the shadow cast by a tall obelisk in the city of Alexandria, about 800 kilometers away. 2. The shadow's length and the obelisk's height formed two sides of a triangle. Using the recently developed principles of Euclidean geometry, he calculated the angle,  $a$ , to be  $7^\circ$  and  $12'$ , exactly  $\frac{1}{50}$  of a circle ( $360^\circ$ ). 3. If angle  $a = \frac{1}{50}$  of a circle, then the distance between the obelisk (in Alexandria) and the well (in Syene) must equal  $\frac{1}{50}$  of the circumference of the earth. 4. Eratosthenes had heard that it was a 50-day camel trip from Alexandria to Syene. Assuming that a camel travels about 18.5 kilometers per day, he estimated the distance between obelisk and well as 925 kilometers (using different units of measure, of course).

5. Eratosthenes thus deduced the circumference of the earth to be  $50 \times 925 = 46,250$  kilometers. Modern measurements put the distance from the well to the obelisk at just over 800 kilometers. Employing a distance of 800 kilometers, Eratosthenes's value would have been  $50 \times 800 = 40,000$  kilometers. The actual circumference is 40,075 kilometers.



you release an apple from your hand, what happens? The apple falls to the ground. From a host of simple, specific observations like this, Newton inferred a general principle: all objects fall toward the center of the earth. What Newton did was construct a mental model of how the world works, a family of general principles consistent with what he could see and learn. Scientists do the same today. They use specific observations to build general models, and then test the models to see how well they work.

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**Science is a way of viewing the world that focuses on objective information, putting that information to work to build understanding.**

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## How Science Is Done

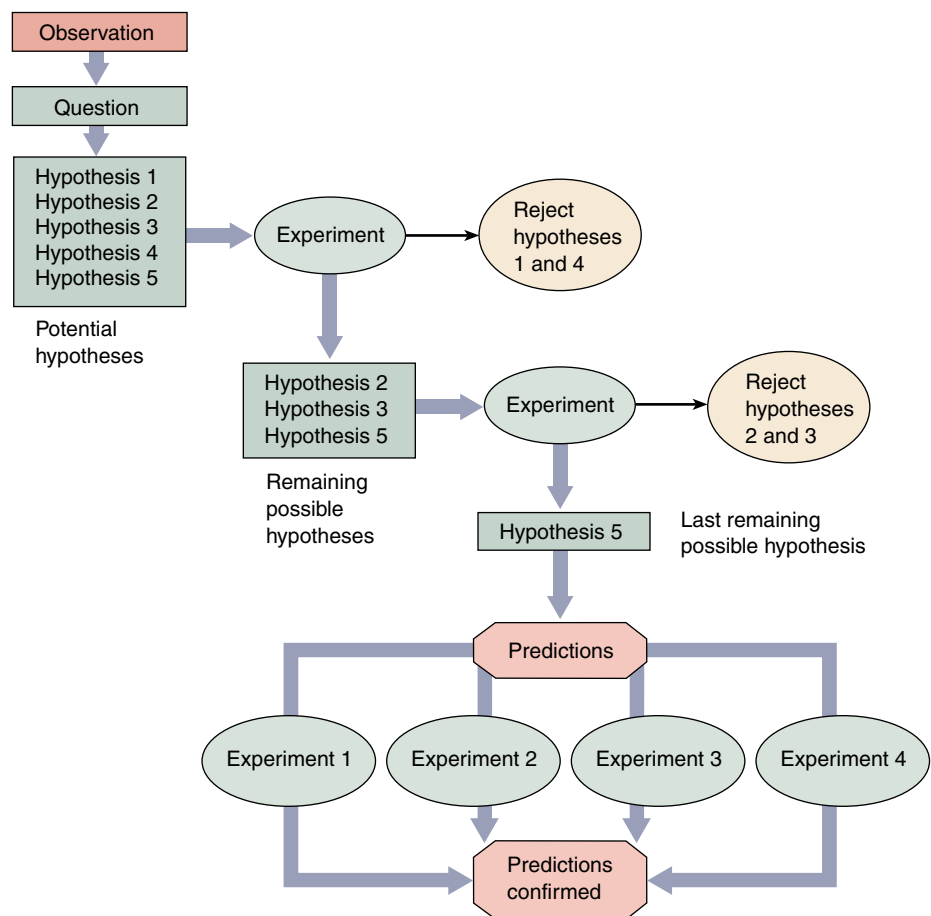
How do scientists establish which general principles are true from among the many that might be true? They do this by systematically testing alternative proposals. If these proposals prove inconsistent with experimental observations, they are rejected as untrue. After making careful observations concerning a particular area of science, scientists construct a **hypothesis**, which is a suggested explanation that accounts for those observations. A hypothesis is a proposition that might be true. Those hypotheses that have not yet been disproved are retained. They are useful because they fit the known facts, but they are always subject to future rejection if, in the light of new information, they are found to be incorrect.

### Testing Hypotheses

We call the test of a hypothesis an **experiment** (figure 1.4). Suppose that a room appears dark to you. To understand why it appears dark, you propose several hypotheses. The first might be, “There is no light in the room because

the light switch is turned off.” An alternative hypothesis might be, “There is no light in the room because the light-bulb is burned out.” And yet another alternative hypothesis might be, “I am going blind.” To evaluate these hypotheses, you would conduct an experiment designed to eliminate one or more of the hypotheses. For example, you might test your hypotheses by reversing the position of the light switch. If you do so and the light does not come on, you have disproved the first hypothesis. Something other than the setting of the light switch must be the reason for the darkness. Note that a test such as this does not prove that any of the other hypotheses are true; it merely demonstrates that one of them is not. A successful experiment is one in which one or more of the alternative hypotheses is demonstrated to be inconsistent with the results and is thus rejected.

As you proceed through this text, you will encounter many hypotheses that have withstood the test of experiment. Many will continue to do so; others will be revised as new observations are made by biologists. Biology, like all science, is in a constant state of change, with new ideas appearing and replacing old ones.



**FIGURE 1.4**  
**How science is done.** This diagram illustrates the way in which scientific investigations proceed. First, scientists make observations that raise a particular question. They develop a number of potential explanations (hypotheses) to answer the question. Next, they carry out experiments in an attempt to eliminate one or more of these hypotheses. Then, predictions are made based on the remaining hypotheses, and further experiments are carried out to test these predictions. As a result of this process, the least unlikely hypothesis is selected.

## Establishing Controls

Often we are interested in learning about processes that are influenced by many factors, or **variables**. To evaluate alternative hypotheses about one variable, all other variables must be kept constant. This is done by carrying out two experiments in parallel: in the first experiment, one variable is altered in a specific way to test a particular hypothesis; in the second experiment, called the **control experiment**, that variable is left unaltered. In all other respects the two experiments are identical, so any difference in the outcomes of the two experiments must result from the influence of the variable that was changed. Much of the challenge of experimental science lies in designing control experiments that isolate a particular variable from other factors that might influence a process.

## Using Predictions

A successful scientific hypothesis needs to be not only valid but useful—it needs to tell you something you want to know. A hypothesis is most useful when it makes predictions, because those predictions provide a way to test the validity of the hypothesis. If an experiment produces results inconsistent with the predictions, the hypothesis must be rejected. On the other hand, if the predictions are supported by experimental testing, the hypothesis is supported. The more experimentally supported predictions a hypothesis makes, the more valid the hypothesis is. For example, Einstein’s hypothesis of relativity was at first provisionally accepted because no one could devise an experiment that invalidated it. The hypothesis made a clear prediction: that the sun would bend the path of light passing by it. When this prediction was tested in a total eclipse, the light from background stars was indeed bent. Because this result was unknown when the hypothesis was being formulated, it provided strong support for the hypothesis, which was then accepted with more confidence.

## Developing Theories

Scientists use the word **theory** in two main ways. A “theory” is a proposed explanation for some natural phenomenon, often based on some general principle. Thus one speaks of the principle first proposed by Newton as the “theory of gravity.” Such theories often bring together concepts that were previously thought to be unrelated, and offer unified explanations of different phenomena. Newton’s theory of gravity provided a single explanation for objects falling to the ground and the orbits of planets around the sun. “Theory” is also used to mean the body of interconnected concepts, supported by scientific reasoning and experimental evidence, that explains the facts in some area of study. Such a theory provides an indispensable framework for organizing a body of knowledge. For example, quantum theory in physics brings together a

set of ideas about the nature of the universe, explains experimental facts, and serves as a guide to further questions and experiments.

To a scientist, such theories are the solid ground of science, that of which we are most certain. In contrast, to the general public, *theory* implies just the opposite—a *lack* of knowledge, or a guess. Not surprisingly, this difference often results in confusion. In this text, theory will always be used in its scientific sense, in reference to an accepted general principle or body of knowledge.

To suggest, as many critics outside of science do, that evolution is “just a theory” is misleading. The hypothesis that evolution has occurred is an accepted scientific fact; it is supported by overwhelming evidence. Modern evolutionary theory is a complex body of ideas whose importance spreads far beyond explaining evolution; its ramifications permeate all areas of biology, and it provides the conceptual framework that unifies biology as a science.

## Research and the Scientific Method

It used to be fashionable to speak of the “scientific method” as consisting of an orderly sequence of logical “either/or” steps. Each step would reject one of two mutually incompatible alternatives, as if trial-and-error testing would inevitably lead one through the maze of uncertainty that always impedes scientific progress. If this were indeed so, a computer would make a good scientist. But science is not done this way. As British philosopher Karl Popper has pointed out, successful scientists without exception design their experiments with a pretty fair idea of how the results are going to come out. They have what Popper calls an “imaginative preconception” of what the truth might be. A hypothesis that a successful scientist tests is not just any hypothesis; rather, it is an educated guess or a hunch, in which the scientist integrates all that he or she knows and allows his or her imagination full play, in an attempt to get a sense of what *might* be true (see Box: How Biologists Do Their Work). It is because insight and imagination play such a large role in scientific progress that some scientists are so much better at science than others, just as Beethoven and Mozart stand out among most other composers.

Some scientists perform what is called basic research, which is intended to extend the boundaries of what we know. These individuals typically work at universities, and their research is usually financially supported by their institutions and by external sources, such as the government, industry, and private foundations. Basic research is as diverse as its name implies. Some basic scientists attempt to find out how certain cells take up specific chemicals, while others count the number of dents in tiger teeth. The information generated by basic research contributes to the growing body of scientific knowledge, and it provides the scientific foundation utilized by applied research. Scientists who conduct applied research are often employed in

# How Biologists Do Their Work

## The Consent

Late in November, on a single night  
Not even near to freezing, the ginkgo trees  
That stand along the walk drop all their leaves  
In one consent, and neither to rain nor to wind  
But as though to time alone: the golden and  
green

Leaves litter the lawn today, that yesterday  
Had spread aloft their fluttering fans of light.  
What signal from the stars? What senses took it  
in?

What in those wooden motives so decided  
To strike their leaves, to down their leaves,  
Rebellion or surrender? And if this  
Can happen thus, what race shall be exempt?  
What use to learn the lessons taught by time,  
If a star at any time may tell us: Now.

Howard Nemerov

What is bothering the poet Howard Nemerov is that life is influenced by forces he cannot control or even identify. It is the job of biologists to solve puzzles such as the one he poses, to identify and try to understand those things that influence life.

Nemerov asks why ginkgo trees (figure 1.A) drop all their leaves at once. To find an answer to questions such as this, biologists and other scientists pose *possible* answers and then try to determine which answers are false. Tests of alternative possibilities are called experiments. To



**FIGURE 1.A**  
A ginkgo tree.

learn why the ginkgo trees drop all their leaves simultaneously, a scientist would first formulate several possible answers, called hypotheses:

*Hypothesis 1:* Ginkgo trees possess an internal clock that times the release of leaves to match the season. On the day Nemerov describes, this clock sends a “drop” signal (perhaps a chemical) to all the leaves at the same time.

*Hypothesis 2:* The individual leaves of ginkgo trees are each able to sense day length, and

when the days get short enough in the fall, each leaf responds independently by falling.

*Hypothesis 3:* A strong wind arose the night before Nemerov made his observation, blowing all the leaves off the ginkgo trees.

Next, the scientist attempts to eliminate one or more of the hypotheses by conducting an experiment. In this case, one might cover some of the leaves so that they cannot use light to sense day length. If hypothesis 2 is true, then the covered leaves should not fall when the others do, because they are not receiving the same information. Suppose, however, that despite the covering of some of the leaves, all the leaves still fall together. This result would eliminate hypothesis 2 as a possibility. Either of the other hypotheses, and many others, remain possibilities.

This simple experiment with ginkgoes points out the essence of scientific progress: science does not prove that certain explanations are true; rather, it proves that others are not. Hypotheses that are inconsistent with experimental results are rejected, while hypotheses that are not proven false by an experiment are provisionally accepted. However, hypotheses may be rejected in the future when more information becomes available, if they are inconsistent with the new information. Just as finding the correct path through a maze by trying and eliminating false paths, scientists work to find the correct explanations of natural phenomena by eliminating false possibilities.

some kind of industry. Their work may involve the manufacturing of food additives, creating of new drugs, or testing the quality of the environment.

After developing a hypothesis and performing a series of experiments, a scientist writes a paper carefully describing the experiment and its results. He or she then submits the paper for publication in a scientific journal, but before it is published, it must be reviewed and accepted by other scientists who are familiar with that particular field of research. This process of careful evaluation, called peer review, lies at the heart of modern science, fostering careful work, precise description, and thoughtful analysis. When an important discovery is announced in a paper, other scientists attempt to reproduce the result, providing a check on accuracy and honesty. Nonreproducible results are not taken seriously for long.

The explosive growth in scientific research during the second half of the twentieth century is reflected in the enormous number of scientific journals now in existence. Although some, such as *Science* and *Nature*, are devoted to a wide range of scientific disciplines, most are extremely specialized: *Cell Motility and the Cytoskeleton*, *Glycoconjugate Journal*, *Mutation Research*, and *Synapse* are just a few examples.

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**The scientific process involves the rejection of hypotheses that are inconsistent with experimental results or observations. Hypotheses that are consistent with available data are conditionally accepted. The formulation of the hypothesis often involves creative insight.**

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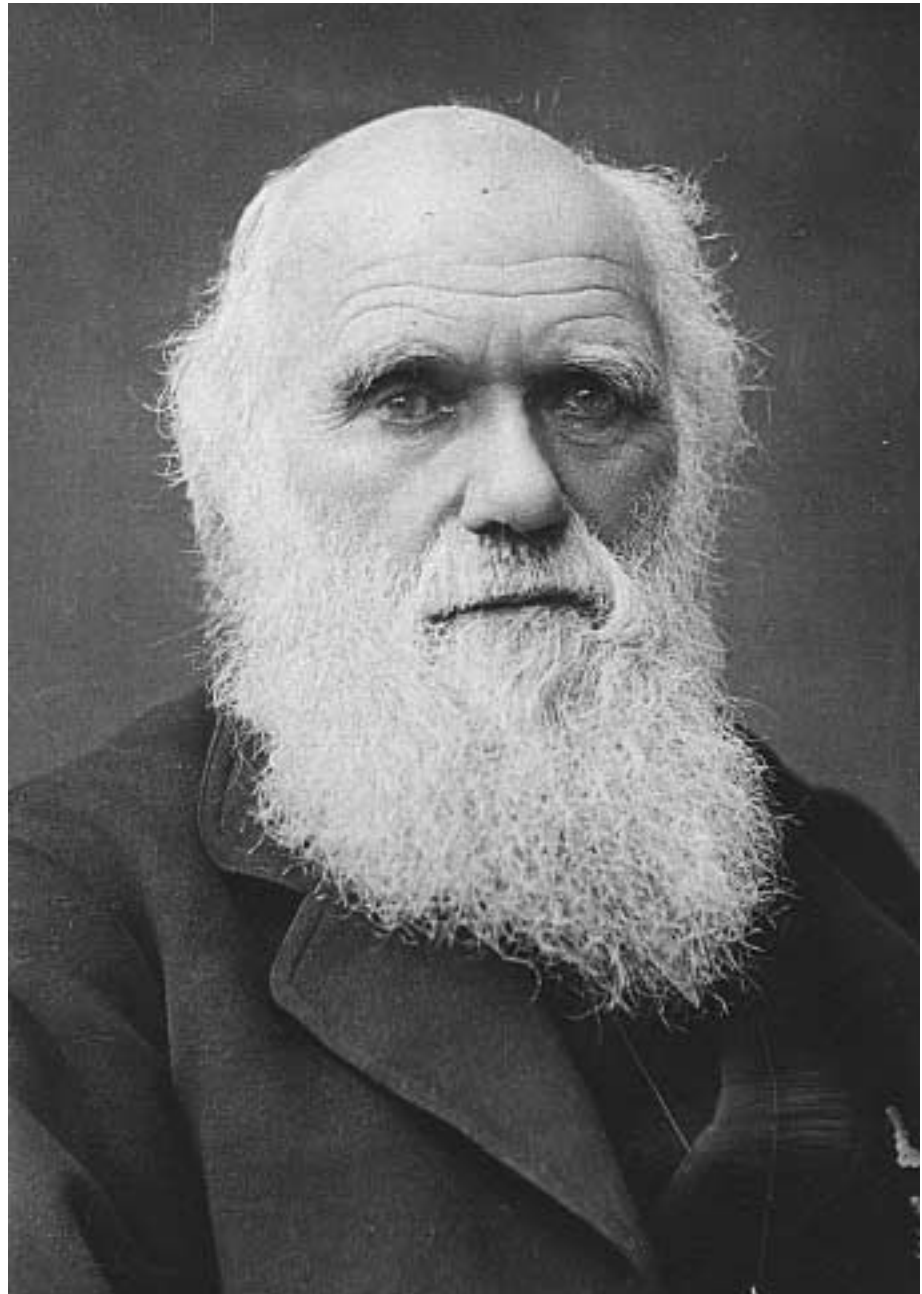
## 1.3 Darwin's theory of evolution illustrates how science works.

### Darwin's Theory of Evolution

Darwin's theory of evolution explains and describes how organisms on earth have changed over time and acquired a diversity of new forms. This famous theory provides a good example of how a scientist develops a hypothesis and how a scientific theory grows and wins acceptance.

Charles Robert Darwin (1809–1882; figure 1.5) was an English naturalist who, after 30 years of study and observation, wrote one of the most famous and influential books of all time. This book, *On the Origin of Species by Means of Natural Selection, or The Preservation of Favoured Races in the Struggle for Life*, created a sensation when it was published, and the ideas Darwin expressed in it have played a central role in the development of human thought ever since.

In Darwin's time, most people believed that the various kinds of organisms and their individual structures resulted from direct actions of the Creator (and to this day many people still believe this to be true). Species were thought to be specially created and unchangeable, or immutable, over the course of time. In contrast to these views, a number of earlier philosophers had presented the view that living things must have changed during the history of life on earth. Darwin proposed a concept he called natural selection as a coherent, logical explanation for this process, and he brought his ideas to wide public attention. His book, as its title indicates, presented a conclusion that differed sharply from conventional wisdom. Although his theory did not challenge the existence of a Divine Creator, Darwin argued that this Creator did not simply create things and then leave them forever unchanged. Instead, Darwin's God expressed Himself through the operation of natural laws that produced change over time, or **evolution**. These views put Darwin at odds with most people of his time, who believed in a literal interpretation of the Bible and accepted the idea of a fixed and constant world. His revolu-

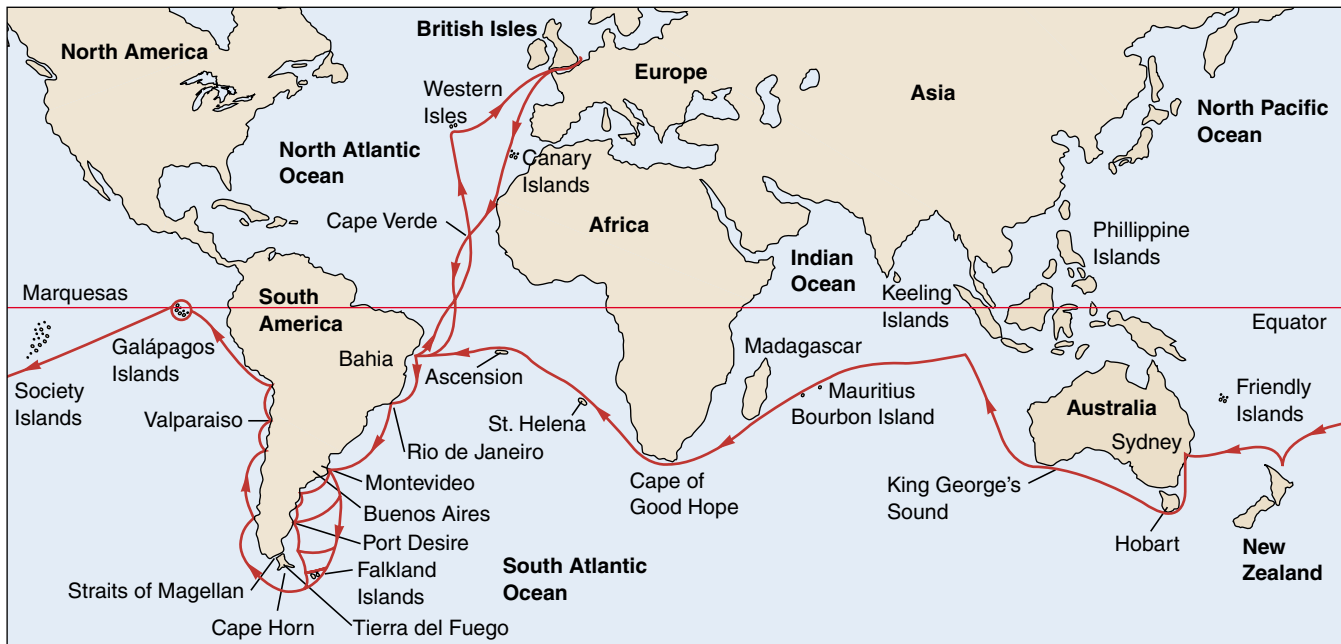


**FIGURE 1.5**  
**Charles Darwin.** This newly rediscovered photograph taken in 1881, the year before Darwin died, appears to be the last ever taken of the great biologist.

tionary theory deeply troubled not only many of his contemporaries but Darwin himself.

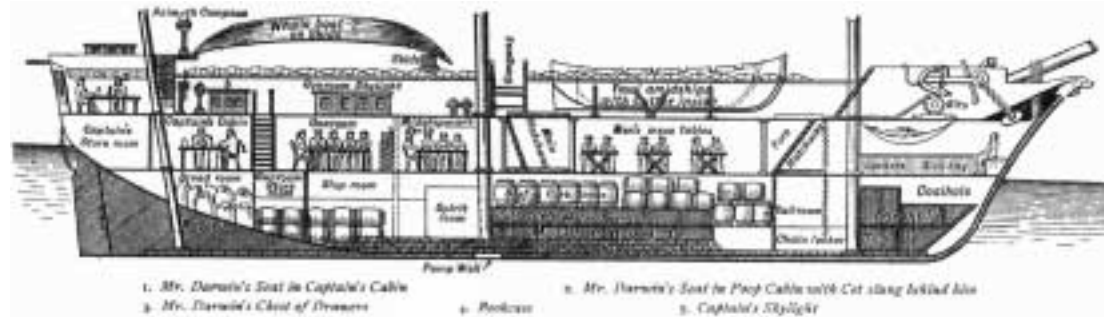
The story of Darwin and his theory begins in 1831, when he was 22 years old. On the recommendation of one of his professors at Cambridge University, he was selected to serve





**FIGURE 1.6**  
**The five-year voyage of H.M.S. *Beagle*.** Most of the time was spent exploring the coasts and coastal islands of South America, such as the Galápagos Islands. Darwin's studies of the animals of the Galápagos Islands played a key role in his eventual development of the theory of evolution by means of natural selection.

**FIGURE 1.7**  
**Cross section of the *Beagle*.** A 10-gun brig of 242 tons, only 90 feet in length, the *Beagle* had a crew of 74 people! After he first saw the ship, Darwin wrote to his college professor Henslow: "The absolute want of room is an evil that nothing can surmount."



as naturalist on a five-year navigational mapping expedition around the coasts of South America (figure 1.6), aboard H.M.S. *Beagle* (figure 1.7). During this long voyage, Darwin had the chance to study a wide variety of plants and animals on continents and islands and in distant seas. He was able to explore the biological richness of the tropical forests, examine the extraordinary fossils of huge extinct mammals in Patagonia at the southern tip of South America, and observe the remarkable series of related but distinct forms of life on the Galápagos Islands, off the west coast of South America. Such an opportunity clearly played an important role in the development of his thoughts about the nature of life on earth.

When Darwin returned from the voyage at the age of 27, he began a long period of study and contemplation. During the next 10 years, he published important books on several

different subjects, including the formation of oceanic islands from coral reefs and the geology of South America. He also devoted eight years of study to barnacles, a group of small marine animals with shells that inhabit rocks and pilings, eventually writing a four-volume work on their classification and natural history. In 1842, Darwin and his family moved out of London to a country home at Down, in the county of Kent. In these pleasant surroundings, Darwin lived, studied, and wrote for the next 40 years.

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**Darwin was the first to propose natural selection as an explanation for the mechanism of evolution that produced the diversity of life on earth. His hypothesis grew from his observations on a five-year voyage around the world.**

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## Darwin's Evidence

One of the obstacles that had blocked the acceptance of any theory of evolution in Darwin's day was the incorrect notion, widely believed at that time, that the earth was only a few thousand years old. Evidence discovered during Darwin's time made this assertion seem less and less likely. The great geologist Charles Lyell (1797–1875), whose *Principles of Geology* (1830) Darwin read eagerly as he sailed on the *Beagle*, outlined for the first time the story of an ancient world of plants and animals in flux. In this world, species were constantly becoming extinct while others were emerging. It was this world that Darwin sought to explain.

### What Darwin Saw

When the *Beagle* set sail, Darwin was fully convinced that species were immutable. Indeed, it was not until two or three years after his return that he began to consider seriously the possibility that they could change. Nevertheless, during his five years on the ship, Darwin observed a number of phenomena that were of central importance to him in reaching his ultimate conclusion (table 1.1). For example, in the rich fossil beds of southern South America, he observed fossils of extinct armadillos similar to the armadillos that still lived in the same area (figure 1.8). Why would similar living and fossil organisms be in the same area unless the earlier form had given rise to the other?

Repeatedly, Darwin saw that the characteristics of similar species varied somewhat from place to place. These geographical patterns suggested to him that organismal lineages change gradually as species migrate from one area to another. On the Galápagos Islands, off the coast of Ecuador, Darwin encountered giant land tortoises. Surprisingly, these tortoises were not all identical. In fact, local residents and the sailors who captured the tortoises for food could tell which island a particular tortoise had come from just by looking at its shell. This distribution of physical variation suggested that all of the tortoises were related, but that they had changed slightly in appearance after becoming isolated on different islands.

In a more general sense, Darwin was struck by the fact that the plants and animals on these relatively young volcanic islands resembled those on the nearby coast of South America. If each one of these plants and animals had been created independently and simply placed on the Galápagos Islands, why didn't they resemble the plants and animals of islands with similar climates, such as those off the coast of Africa, for example? Why did they resemble those of the adjacent South American coast instead?

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**The fossils and patterns of life that Darwin observed on the voyage of the *Beagle* eventually convinced him that evolution had taken place.**

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**Table 1.1** Darwin's Evidence that Evolution Occurs

#### FOSSILS

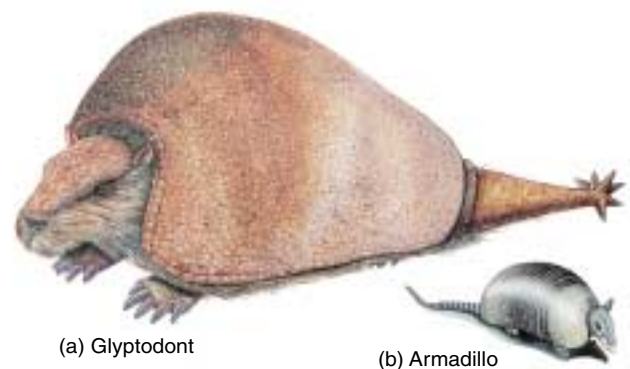
1. Extinct species, such as the fossil armadillo in figure 1.8, most closely resemble living ones in the same area, suggesting that one had given rise to the other.
2. In rock strata (layers), progressive changes in characteristics can be seen in fossils from earlier and earlier layers.

#### GEOGRAPHICAL DISTRIBUTION

3. Lands with similar climates, such as Australia, South Africa, California, and Chile, have unrelated plants and animals, indicating that diversity is not entirely influenced by climate and environment.
4. The plants and animals of each continent are distinctive; all South American rodents belong to a single group, structurally similar to the guinea pigs, for example, while most of the rodents found elsewhere belong to other groups.

#### OCEANIC ISLANDS

5. Although oceanic islands have few species, those they do have are often unique (endemic) and show relatedness to one another, such as the Galápagos tortoises. This suggests that the tortoises and other groups of endemic species developed after their mainland ancestors reached the islands and are, therefore, more closely related to one another.
6. Species on oceanic islands show strong affinities to those on the nearest mainland. Thus, the finches of the Galápagos Islands closely resemble a finch seen on the western coast of South America. The Galápagos finches do *not* resemble the birds on the Cape Verde Islands, islands in the Atlantic Ocean off the coast of Africa that are similar to the Galápagos. Darwin visited the Cape Verde Islands and many other island groups personally and was able to make such comparisons on the basis of his own observations.



**FIGURE 1.8**  
**Fossil evidence of evolution.** The now-extinct glyptodont (a) was a 2000-kilogram South American armadillo, much larger than the modern armadillo (b), which weighs an average of about 4.5 kilograms. (Drawings are not to scale.)

## Inventing the Theory of Natural Selection

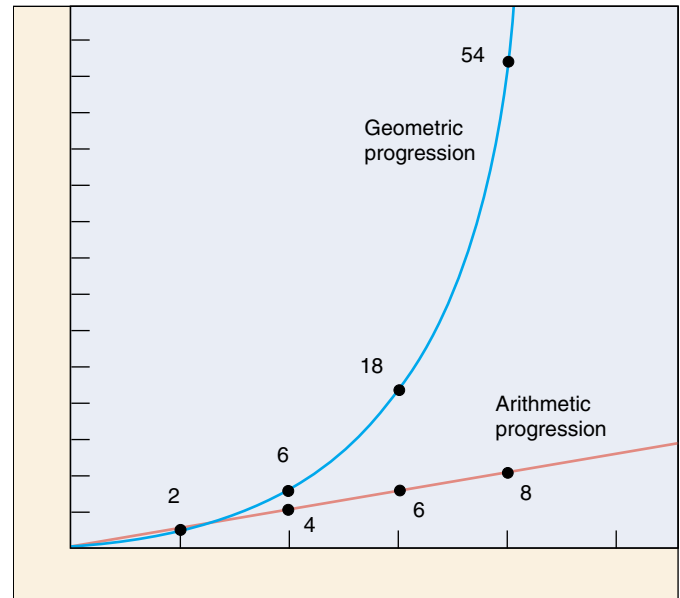
It is one thing to observe the results of evolution, but quite another to understand how it happens. Darwin's great achievement lies in his formulation of the hypothesis that evolution occurs because of natural selection.

### Darwin and Malthus

Of key importance to the development of Darwin's insight was his study of Thomas Malthus's *Essay on the Principle of Population* (1798). In his book, Malthus pointed out that populations of plants and animals (including human beings) tend to increase geometrically, while the ability of humans to increase their food supply increases only arithmetically. A *geometric progression* is one in which the elements increase by a constant *factor*; for example, in the progression 2, 6, 18, 54, . . . , each number is three times the preceding one. An *arithmetic progression*, in contrast, is one in which the elements increase by a constant *difference*; in the progression 2, 6, 10, 14, . . . , each number is four greater than the preceding one (figure 1.9).

Because populations increase geometrically, virtually any kind of animal or plant, if it could reproduce unchecked, would cover the entire surface of the world within a surprisingly short time. Instead, populations of species remain fairly constant year after year, because death limits population numbers. Malthus's conclusion provided the key ingredient that was necessary for Darwin to develop the hypothesis that evolution occurs by natural selection.

Sparked by Malthus's ideas, Darwin saw that although every organism has the potential to produce more offspring than can survive, only a limited number actually do survive and produce further offspring. Combining this observation with what he had seen on the voyage of the *Beagle*, as well as with his own experiences in breeding domestic animals, Darwin made an important association (figure 1.10): Those individuals that possess superior physical, behavioral, or other attributes are more likely to survive than those that are not so well endowed. By surviving, they gain the opportunity to pass on their favorable characteristics to their offspring. As the frequency of these characteristics increases in the population, the nature of the population as a whole will gradually change. Darwin called this process selection. The driving force he identified has often been referred to as survival of the fittest.



**FIGURE 1.9**

**Geometric and arithmetic progressions.** A geometric progression increases by a constant factor (e.g.,  $\times 2$  or  $\times 3$  or  $\times 4$ ), while an arithmetic progression increases by a constant difference (e.g., units of 1 or 2 or 3). Malthus contended that the human growth curve was geometric, but the human food production curve was only arithmetic. Can you see the problems this difference would cause?

*"Can we doubt . . . that individuals having any advantage, however slight, over others, would have the best chance of surviving and procreating their kind? On the other hand, we may feel sure that any variation in the least degree injurious would be rigidly destroyed. This preservation of favorable variations, I call Natural Selection."*

**FIGURE 1.10**

An excerpt from Charles Darwin's *On the Origin of Species*.

## Natural Selection

Darwin was thoroughly familiar with variation in domesticated animals and began *On the Origin of Species* with a detailed discussion of pigeon breeding. He knew that breeders selected certain varieties of pigeons and other animals, such as dogs, to produce certain characteristics, a process Darwin called **artificial selection**. Once this had been done, the animals would breed true for the characteristics that had been selected. Darwin had also observed that the differences purposely developed between domesticated races or breeds were often greater than those that separated wild species. Domestic pigeon breeds, for example, show much greater variety than all of the hundreds of wild species of pigeons found throughout the world. Such relationships suggested to Darwin that evolutionary change could occur in nature too. Surely if pigeon breeders could foster such variation by “artificial selection,” nature could do the same, playing the breeder’s role in selecting the next generation—a process Darwin called **natural selection**.

Darwin’s theory thus incorporates the hypothesis of evolution, the process of natural selection, and the mass of new evidence for both evolution and natural selection that Darwin compiled. Thus, Darwin’s theory provides a simple and direct explanation of biological diversity, or why animals are different in different places: because habitats differ in their requirements and opportunities, the organisms with characteristics favored locally by natural selection will tend to vary in different places.

## Darwin Drafts His Argument

Darwin drafted the overall argument for evolution by natural selection in a preliminary manuscript in 1842. After showing the manuscript to a few of his closest scientific friends, however, Darwin put it in a drawer, and for 16 years turned to other research. No one knows for sure why Darwin did not publish his initial manuscript—it is very thorough and outlines his ideas in detail. Some historians have suggested that Darwin was shy of igniting public criticism of his evolutionary ideas—there could have been little doubt in his mind that his theory of evolution by natural selection would spark controversy. Others have pro-



**FIGURE 1.11**  
**Darwin greets his monkey ancestor.** In his time, Darwin was often portrayed unsympathetically, as in this drawing from an 1874 publication.

posed that Darwin was simply refining his theory all those years, although there is little evidence he altered his initial manuscript in all that time.

## Wallace Has the Same Idea

The stimulus that finally brought Darwin’s theory into print was an essay he received in 1858. A young English naturalist named Alfred Russel Wallace (1823–1913) sent the essay to Darwin from Malaysia; it concisely set forth the theory of evolution by means of natural selection, a theory Wallace had developed independently of Darwin. Like Darwin, Wallace had been greatly influenced by Malthus’s 1798 essay. Colleagues of Wallace, knowing of Darwin’s work, encouraged him to communicate with Darwin. After receiving Wallace’s essay, Darwin arranged for a joint presentation of their ideas at a seminar in London. Darwin then completed his own book, expanding the 1842 manuscript which he had written so long ago, and submitted it for publication.

## Publication of Darwin’s Theory

Darwin’s book appeared in November 1859 and caused an immediate sensation. Many people were deeply disturbed by the suggestion that human beings were descended from the same ancestor as apes (figure 1.11). Darwin did not actually discuss this idea in his book, but it followed directly from the principles he outlined. In a subsequent book, *The Descent of Man*, Darwin presented the argument directly, building a powerful case that humans and living apes have common ancestors. Although people had long accepted that humans closely resembled apes in many characteristics, the possibility that there might be a direct evolutionary relationship was unacceptable to many. Darwin’s arguments for the theory of evolution by natural selection were so compelling, however, that his views were almost completely accepted within the intellectual community of Great Britain after the 1860s.

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**The fact that populations do not really expand geometrically implies that nature acts to limit population numbers. The traits of organisms that survive to produce more offspring will be more common in future generations—a process Darwin called natural selection.**

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## Evolution After Darwin: More Evidence

More than a century has elapsed since Darwin's death in 1882. During this period, the evidence supporting his theory has grown progressively stronger. There have also been many significant advances in our understanding of how evolution works. Although these advances have not altered the basic structure of Darwin's theory, they have taught us a great deal more about the mechanisms by which evolution occurs. We will briefly explore some of this evidence here; in chapter 21 we will return to the theory of evolution and examine the evidence in more detail.

### The Fossil Record

Darwin predicted that the fossil record would yield intermediate links between the great groups of organisms, for example, between fishes and the amphibians thought to have arisen from them, and between reptiles and birds. We now know the fossil record to a degree that was unthinkable in the nineteenth century. Recent discoveries of microscopic fossils have extended the known history of life on earth back to about 3.5 billion years ago. The discovery of other fossils has supported Darwin's predictions and has shed light on how organisms have, over this enormous time span, evolved from the simple to the complex. For vertebrate animals especially, the fossil record is rich and exhibits a graded series of changes in form, with the evolutionary parade visible for all to see (see Box: Why Study Fossils?).

### The Age of the Earth

In Darwin's day, some physicists argued that the earth was only a few thousand years old. This bothered Darwin, because the evolution of all living things from some single

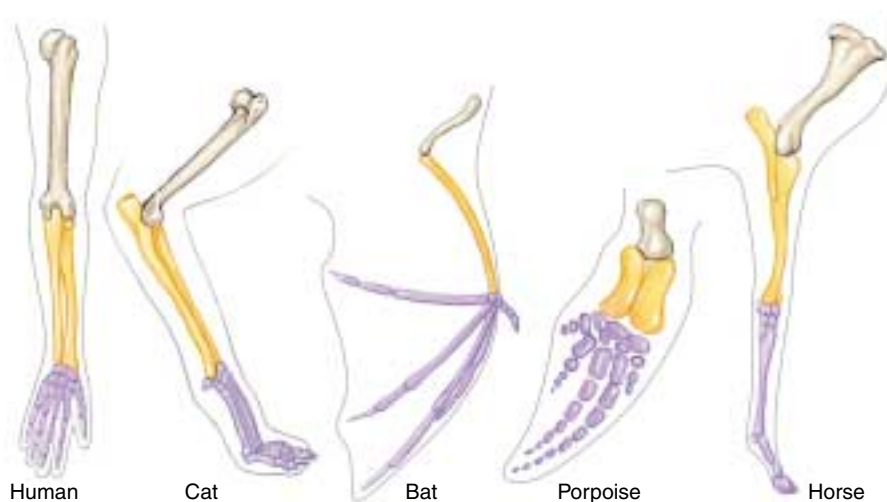
original ancestor would have required a great deal more time. Using evidence obtained by studying the rates of radioactive decay, we now know that the physicists of Darwin's time were wrong, very wrong: the earth was formed about 4.5 billion years ago.

### The Mechanism of Heredity

Darwin received some of his sharpest criticism in the area of heredity. At that time, no one had any concept of genes or of how heredity works, so it was not possible for Darwin to explain completely how evolution occurs. Theories of heredity in Darwin's day seemed to rule out the possibility of genetic variation in nature, a critical requirement of Darwin's theory. Genetics was established as a science only at the start of the twentieth century, 40 years after the publication of Darwin's *On the Origin of Species*. When scientists began to understand the laws of inheritance (discussed in chapter 13), the heredity problem with Darwin's theory vanished. Genetics accounts in a neat and orderly way for the production of new variations in organisms.

### Comparative Anatomy

Comparative studies of animals have provided strong evidence for Darwin's theory. In many different types of vertebrates, for example, the same bones are present, indicating their evolutionary past. Thus, the forelimbs shown in figure 1.12 are all constructed from the same basic array of bones, modified in one way in the wing of a bat, in another way in the fin of a porpoise, and in yet another way in the leg of a horse. The bones are said to be **homologous** in the different vertebrates; that is, they have the same evolutionary origin, but they now differ in structure and function. This contrasts with **analogous** structures, such as the wings of birds and butterflies, which have similar structure and function but different evolutionary origins.



**FIGURE 1.12**  
**Homology among vertebrate limbs.** The forelimbs of these five vertebrates show the ways in which the relative proportions of the forelimb bones have changed in relation to the particular way of life of each organism.

## Why Study Fossils?

I grew up on the streets of New York City, in a family of modest means and little formal education, but with a deep love of learning. Like many urban kids who become naturalists, my inspiration came from a great museum—in particular, from the magnificent dinosaurs on display at the American Museum of Natural History. As we all know from *Jurassic Park* and other sources, dinomania in young children (I was five when I saw my first dinosaur) is not rare—but nearly all children lose the passion, and the desire to become a paleontologist becomes a transient moment between policeman and fireman in a chronology of intended professions. But I persisted and became a professional paleontologist, a student of life's history as revealed by the evidence of fossils (though I ended up working on snails rather than dinosaurs!). Why?

I remained committed to paleontology because I discovered, still as a child, the wonder of one of the greatest transforming ideas ever discovered by science: evolution. I learned that those dinosaurs, and all creatures that have ever lived, are bound together in a grand family tree of physical relationships, and that the rich and fascinating changes of life, through billions of years in

Flight has evolved three separate times among vertebrates. Birds and bats are still with us, but pterosaurs, such as the one pictured, became extinct with the dinosaurs about 65 million years ago.



Stephen Jay Gould  
Harvard University

geological time, occur by a natural process of evolutionary transformation—"descent with modification," in Darwin's words. I was thrilled to learn that humans had arisen from apelike ancestors, who had themselves evolved from the tiny mouselike mammals that had lived in the time of dinosaurs and seemed then so inconspicuous, so unsuccessful, and so unpromising.

Now, at mid-career (I was born in 1941) I remain convinced that I made the right choice, and committed to learn and convey, as much as I can as long as I can, about evolution and the history of life. We can learn a great deal about the *process* of evolution

by studying modern organisms. But history is complex and unpredictable—and principles of evolution (like natural selection) cannot specify the *pathway* that life's history has actually followed. Paleontology holds the archives of the pathway—the fossil record of past life, with its fascinating history of mass extinctions, periods of rapid change, long episodes of stability, and constantly changing patterns of dominance and diversity. Humans represent just one tiny, largely fortuitous, and late-arising twig on the enormously arborescent bush of life. Paleontology is the study of this grandest of all bushes.

## Molecular Biology

Biochemical tools are now of major importance in efforts to reach a better understanding of how evolution occurs. Within the last few years, for example, evolutionary biologists have begun to "read" genes, much as you are reading this page. They have learned to recognize the order of the "letters" of the long DNA molecules, which are present in every living cell and which provide the genetic information for that organism. By comparing the sequences of "letters" in the DNA of different groups of animals or plants, we can specify the degree of relationship among the groups more precisely than by any other means. In many cases, detailed family trees can then be constructed. The consistent pattern emerging from a growing mountain of data is one of progressive change over time, with more distantly related species showing more differences in their DNA than closely related ones, just as Darwin's theory predicts. By measuring the degree of difference in the genetic coding, and by interpreting the information available from the fossil record, we

can even estimate the *rates* at which evolution is occurring in different groups of organisms.

## Development

Twentieth-century knowledge about growth and development further supports Darwin's theory of evolution. Striking similarities are seen in the developmental stages of many organisms of different species. Human embryos, for example, go through a stage in which they possess the same structures that give rise to the gills in fish, a tail, and even a stage when the embryo has fur! Thus, the development of an organism (its ontogeny) often yields information about the evolutionary history of the species as a whole (its phylogeny).

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Since Darwin's time, new discoveries of the fossil record, genetics, anatomy, and development all support Darwin's theory.

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## 1.4 This book is organized to help you learn biology.

### Core Principles of Biology

From centuries of biological observation and inquiry, one organizing principle has emerged: biological diversity reflects history, a record of success, failure, and change extending back to a period soon after the formation of the earth. The explanation for this diversity, the theory of evolution by natural selection, will form the backbone of your study of biological science, just as the theory of the covalent bond is the backbone of chemistry, or the theory of quantum mechanics is that of physics. Evolution by natural selection is a thread that runs through everything you will learn in this book.

### Basic Principles

The first half of this book is devoted to a description of the basic principles of biology, introduced through a levels-of-organization framework (see figure 1.2). At the molecular, organellar, and cellular levels of organization, you will be introduced to *cell biology*. You will learn how cells are constructed and how they grow, divide, and communicate. At the organismal level, you will learn the principles of *genetics*, which deal with the way that individual traits are transmitted from one generation to the next. At the population level,

you will examine *evolution*, the gradual change in populations from one generation to the next, which has led through natural selection to the biological diversity we see around us. Finally, at the community and ecosystem levels, you will study *ecology*, which deals with how organisms interact with their environments and with one another to produce the complex communities characteristic of life on earth.

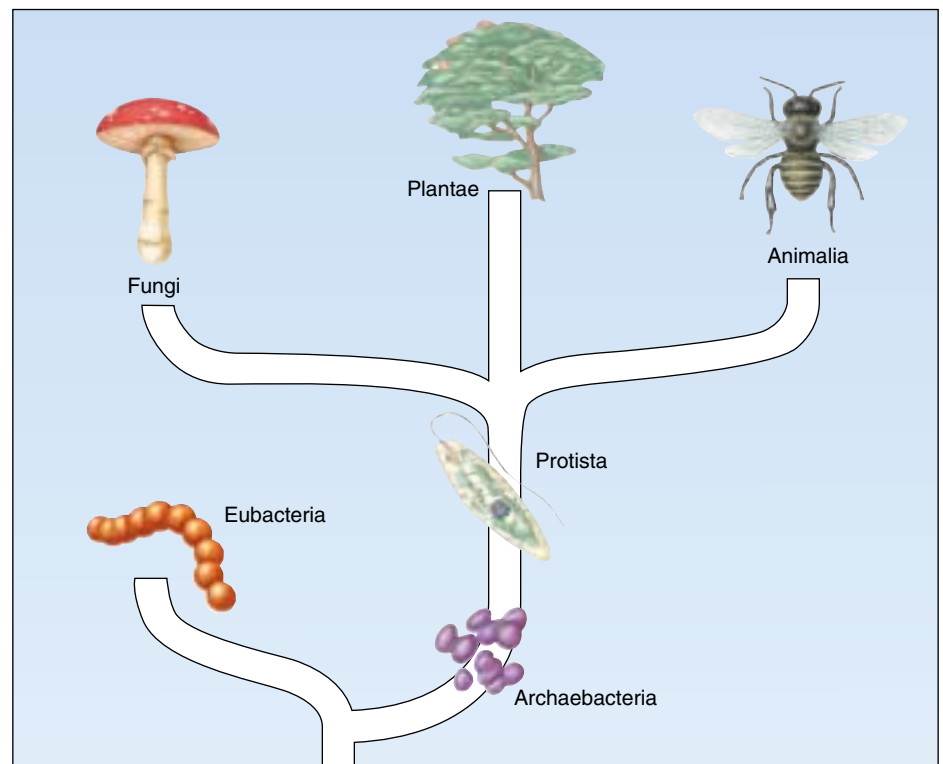
### Organisms

The second half of the book is devoted to an examination of organisms, the products of evolution. It is estimated that at least 5 million different kinds of plants, animals, and microorganisms exist, and their diversity is *incredible* (figure 1.13). Later in the book, we will take a particularly detailed look at the vertebrates, the group of animals of which we are members. We will consider the vertebrate body and how it functions, as this information is of greatest interest and importance to most students.

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As you proceed through this book, what you learn at one stage will give you the tools to understand the next. The core principle of biology is that biological diversity is the result of a long evolutionary journey.

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**FIGURE 1.13**  
**The diversity of life.** Biologists categorize all living things into six major groups called kingdoms: archaeobacteria, eubacteria, protists, fungi, plants, and animals.

**Summary****Questions****Media Resources****1.1 Biology is the science of life.**

- Living things are highly organized, whether as single cells or as multicellular organisms, with several hierarchical levels.

1. What are the characteristics of living things?



- Art Activity: Biological organization

**1.2 Scientists form generalizations from observations.**

- Science is the determination of general principles from observation and experimentation.
- Scientists select the best hypotheses by using controlled experiments to eliminate alternative hypotheses that are inconsistent with observations.
- A group of related hypotheses supported by a large body of evidence is called a theory. In science, a theory represents what we are most sure about. However, there are no absolute truths in science, and even theories are accepted only conditionally.
- Scientists conduct basic research, designed to gain information about natural phenomena in order to contribute to our overall body of knowledge, and applied research, devoted to solving specific problems with practical applications.

2. What is the difference between deductive and inductive reasoning? What is a hypothesis?
3. What are variables? How are control experiments used in testing hypotheses?
4. How does a hypothesis become a theory? At what point does a theory become accepted as an absolute truth, no longer subject to any uncertainty?
5. What is the difference between basic and applied research?



- Scientists on Science: Why Paleontology?
- Experiments: Probability and Hypothesis Testing in Biology

**1.3 Darwin's theory of evolution illustrates how science works.**

- One of the central theories of biology is Darwin's theory that evolution occurs by natural selection. It states that certain individuals have heritable traits that allow them to produce more offspring in a given kind of environment than other individuals lacking those traits. Consequently, those traits will increase in frequency through time.
- Because environments differ in their requirements and opportunities, the traits favored by natural selection will vary in different environments.
- This theory is supported by a wealth of evidence acquired over more than a century of testing and questioning.

6. Describe the evidence that led Darwin to propose that evolution occurs by means of natural selection. What evidence gathered since the publication of Darwin's theory has lent further support to the theory?
7. What is the difference between homologous and analogous structures? Give an example of each.



- Introduction to Evolution
- Before Darwin
- Voyage of the Beagle
- Natural Selection
- The Process of Natural Selection
- Evidence for Evolution



- Student Research: The Search for Medicinal Plants on Science Articles
- 140 Years Without Darwin Are Enough
- Bird-Killing Cats: Nature's Way of Making Better Bids

**1.4 This book is organized to help you learn biology.**

- Biological diversity is the result of a long history of evolutionary change. For this reason evolution is the core of the science of biology.
- Considered in terms of levels-of-organization, the science of biology can be said to consist of subdisciplines focusing on particular levels. Thus one speaks of molecular biology, cell biology, organismal biology, population biology, and community biology.

8. Can you think of any alternatives to levels-of-organization as ways of organizing the mass of information in biology?