CONCEPTUAL Integrated Science

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CHAPTER 17

The Evolution of Life

17.1 The Origin of Life
INTEGRATED SCIENCE 17A ASTRONOMY
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MARINE IGUANAS swim through seawater with their long, flattened tails. Flies taste food with the hairs on their feet. Bats catch insects in midair. Cactuses grow sharp spines that protect them from animals. These adaptations, and the countless other ways in which organisms are structured to survive and reproduce, make up the incredible story of evolution. How do living things change over time in response to their environments? After all, a giraffe can't grow a long neck just because it *wants* to. So, how do adaptations (such as a giraffe's long neck) actually come about? Does the same process explain how new types of living things—new species—originate? Also, if all organisms today evolved from earlier organisms, then how did life get started in the first place? Read on to discover these secrets of life.

17.3 Charles Darwin and *The Origin of Species*

LEARNING OBJECTIVE
Describe some of the influences and events that brought Darwin to his theory of evolution through natural selection.

EXPLAIN THIS How did the Galápagos finches contribute to Darwin's ideas about evolution?

How has life on Earth changed over time? For example, how did we get from tiny, primitive cells to humans, hippos, redwoods, and all the amazing diversity of life on Earth today?

For thousands of years, people believed that life on Earth did not change. They believed that Earth had always had the same species, and always would. Then fossils were discovered in Earth's rocks, and people began to wonder. Fossils suggested that the kinds of species living on Earth changed over time—old species disappeared, and new species appeared. Also interesting was that fossil organisms sometimes showed a distinct resemblance to modern species (Figure 17.8). Could some fossils actually be the ancestors of modern species?

French naturalist Jean-Baptiste Lamarck (1744–1829) was one of the first to argue that this was the case. Lamarck believed that modern species were descended from ancestors that had evolved—changed over time—to become better adapted to the environments they lived in. According to Lamarck, organisms acquired new characteristics during their lifetimes and then passed these characteristics to their offspring. For example, ancestral giraffes stretched their necks to grab the high leaves on a tree, and their necks became longer. They then passed these longer necks to their offspring. The offspring reached for even higher leaves, stretching their necks even further, and so on (Figure 17.9a). Lamarck's theory for how change occurs, called the ***inheritance of acquired characteristics***, proved to be incorrect: Organisms cannot pass characteristics acquired during their lifetimes to their offspring because these acquired characteristics are not genetic. However, Lamarck's fierce support for the idea that organisms evolve set the stage for Charles Darwin.

FIGURE 17.8
Could fossils be the ancestors of modern species? This fossil, found in Germany, is about 50 million years old. It has a clear resemblance to a horse, yet is only the size of a fox.

UNIFYING CONCEPT
• ***The Scientific Method***
Section 1.3

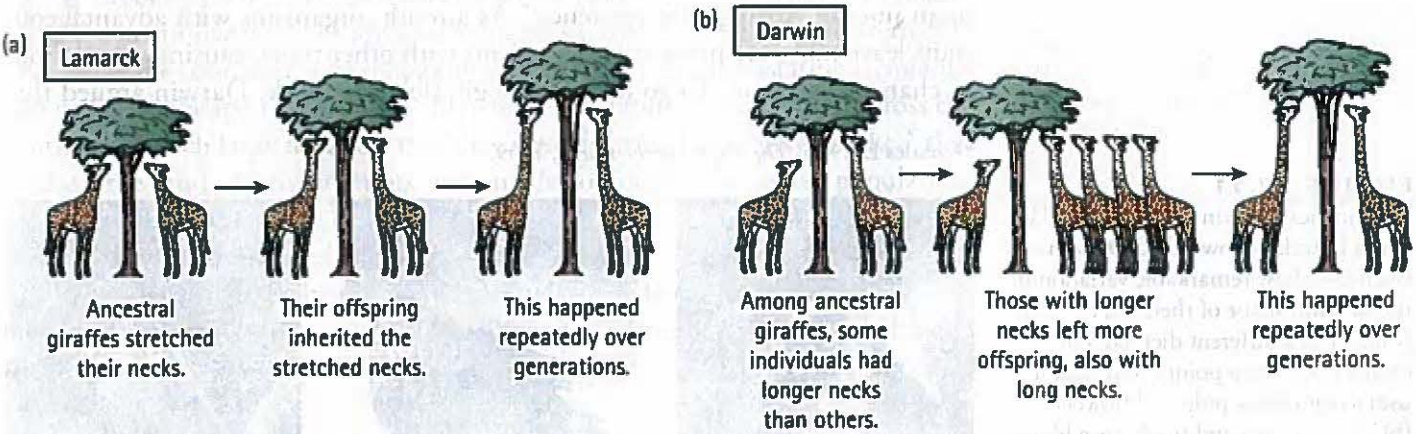

FIGURE 17.9
(a) Lamarck believed that organisms acquired new characteristics during their lifetimes and passed these characteristics to their offspring. (b) In his theory of evolution by natural selection, Darwin argued that organisms with advantageous traits left more offspring than organisms with other traits. As a result, advantageous traits became more common in a population.

FIGURE 17.10
Charles Darwin developed the theory of evolution by natural selection.

English naturalist Charles Darwin (1809–1882), shown in Figure 17.10, set forth the theory of evolution in his book *The Origin of Species by Means of Natural Selection*, published in 1859. Darwin proposed that **evolution**—inherited changes in populations of organisms over time—had produced all the living forms on Earth.

Darwin's theory of evolution grew out of the observations he made as the official naturalist aboard the H.M.S. *Beagle*, which sailed around South America from 1831 to 1836. During these years, Darwin studied South American species, collecting large numbers of plants, animals, and fossils. Darwin became increasingly intrigued by the question of how species got to be the way they were. He was particularly struck by the living things he encountered on the Galápagos Islands, 950 kilometers from the South American continent. Darwin took particular note of the 13 species of Galápagos finches—now known as Darwin's finches. Darwin's finches showed remarkable variation in the size and shape of their beaks, with each beak being suited to, and used for, a different diet (Figure 17.11). How had the beaks of these finches come to differ in this way? Darwin wrote, "Seeing this gradation and diversity of structure in one small, intimately related group of birds, one might really fancy that from an original paucity of birds in this archipelago, one species had been taken and modified for different ends."*

There's an expression: Genius is 1% inspiration and 99% perspiration. Darwin's genius reflects a lot of perspiration. While on the *Beagle*, Darwin collected 1529 alcohol-preserved specimens and 3907 skins, bones, and dried specimens. He also took 2000 pages of notes on plants, animals, and geology. It's no wonder that when he wrote down his theory, he was able to support it with a wide variety of well-considered examples.

Darwin was also inspired by the work of two of his contemporaries, Charles Lyell and Thomas Malthus. Lyell, a geologist, argued that Earth's geological features were created not by major catastrophic events—the favored theory of the time—but by gradual processes that produced their effects over long time periods. For example, the formation of a deep canyon did not require a cataclysmic flood, but could result from a river's slow erosion of rock over millennia. Darwin realized this could be true for organisms as well: The accumulation of gradual changes over long periods could produce all the diversity of living organisms as well as all their remarkable features.

The economist Thomas Malthus was a second important influence for Darwin, and the one who led Darwin to his great idea on the cause of evolutionary change. Malthus observed that human populations grow much faster than available food supplies, and he concluded, with despair, that famine was an inevitable feature of human existence. Darwin applied Malthus's idea to the natural world and argued that, because there are not enough resources for all organisms to survive and to reproduce as much as they can, living organisms are involved in an intense "struggle for existence." As a result, organisms with advantageous traits leave more offspring than organisms with other traits, causing populations to change over time. To go back to the giraffe's long neck: Darwin argued that

*Charles Darwin, *The Voyage of the Beagle*, 1909.

(a) (b) (c)

FIGURE 17.11
The finches Darwin saw on the Galápagos Islands—now called Darwin's finches—show remarkable variation in the size and shape of their beaks. Each is suited to a different diet. (a) The cactus finch has a pointy beak that it uses to eat cactus pulp and flowers. (b) The large ground finch has a blunt, powerful beak that it uses to crack seeds. (c) The woodpecker finch has a woodpecker-like beak that it uses to drill holes in wood. It then uses a cactus spine to pry out insects.

ancestral giraffes with longer necks were better at reaching the high leaves on trees. Because longer-necked giraffes got more food, they were able to survive and leave more offspring than ancestral giraffes with shorter necks. This happened repeatedly over generations. Over time, there were more longer-necked giraffes in the giraffe population (Figure 17.9b). This process, which Darwin called **natural selection**, is the major driving force behind evolution.

MasteringPhysics®
TUTORIAL: Darwin and the Galapagos Islands
VIDEO: Galapagos Islands Overview
VIDEO: Galapagos Marine Iguana

CHECK YOURSELF

1. **If Lamarck had been correct and evolutionary change occurred through the inheritance of acquired characteristics, what trait might a bodybuilder pass to his offspring?**
2. **Many animals that live in the Arctic, such as Arctic hares, have white fur. How could natural selection explain the evolution of their white fur color?**

CHECK YOUR ANSWERS

1. If Lamarck were correct, the bodybuilder's children would inherit the increased muscle mass that the bodybuilder had acquired over a lifetime of weightlifting. Because Lamarck's theory turned out to be incorrect, however, the children will have to do their own bodybuilding.
2. Animals that were harder to see in their snowy environments had an advantageous trait—predators were less likely to spot them. Arctic hares with whiter fur were more likely to survive to adulthood, reproduce, and leave offspring. These offspring would also have inherited whiter fur. As a result, whiter fur became more common in the Arctic hare population. Over many generations, natural selection produced a white coat that matches the Arctic snow.

17.4 How Natural Selection Works

LEARNING OBJECTIVE
Explain how natural selection results in populations becoming adapted to their environments.

EXPLAIN THIS What does it mean to say that one rabbit has greater fitness than another?

Rabbits were introduced into Australia in 1859, when a man named Thomas Austin released 24 individuals onto his property in the southeastern part of the continent. The rabbits quickly became pests, devastating farmlands and natural habitats (Figure 17.12). Breeding "like rabbits," they spread across the continent in such large numbers that they were described as a "gray blanket" that covered the land. Many attempts were made to control the rabbit population, including the construction of an 1822-kilometer-long "rabbit-proof" fence—still the longest fence in the world. Unfortunately, by the time the fence was completed in 1907, the rabbits had already passed through. (The fence wouldn't have worked anyway—even after it was completed, rabbits would pile up so thickly behind it that some were eventually able to walk right over their companions' backs to the other side.)

MasteringPhysics®
TUTORIAL: Causes of Microevolution

In the early 1950s, the government decided to try to control the rabbit population by releasing myxoma virus, a virus deadly to rabbits. Initially, the virus was a wonder, killing more than 99.9% of infected rabbits. Within a few years, however, fewer rabbits were dying. What had happened? Within the original rabbit population, a small number of individuals happened to be resistant to the

(a)

(b)

FIGURE 17.12
(a) Rabbits introduced into Australia caused widespread destruction, including here on Phillip Island. (b) This photo shows the same area after rabbits were eradicated. The vegetation has grown back.

myxoma virus. These resistant individuals survived the disease and reproduced, producing more disease-resistant offspring (Figure 17.13). Over time, the number of disease-resistant rabbits increased, and the virus became less and less effective. The rabbit population had evolved resistance to the myxoma virus through natural selection.

Natural selection occurs when organisms with advantageous traits leave more offspring than organisms with other traits, causing populations to change over time. Let's look more carefully at the process of natural selection.

1. *Variation.* In any population of organisms, individuals have many traits that show **variation**—that is, they vary from individual to individual. In humans, some variable traits are height, hair color, hairstyle, foot size, and blood type.
2. *Heritability.* Many traits are determined at least partly by genes and so are **heritable**—that is, they are passed from parents to offspring. Which of the human traits listed above are heritable? All of them are heritable except hairstyle. Hairstyle is not heritable because it is not genetically determined.
3. *Natural selection.* Some variable heritable traits are advantageous. The organisms that possess these advantageous traits are able to leave more offspring than organisms without the advantageous traits. The **fitness** of an organism describes the number of offspring it leaves over its lifetime compared to other individuals in the population. An organism that leaves more offspring than other individuals in the population is said to have greater fitness.
4. *Adaptation.* Because organisms with advantageous traits leave more offspring, advantageous traits are "selected for" and become more common in a population. What is the result? The population evolves to become better adapted to its environment.

Figure 17.14 summarizes the process of natural selection. Note that, although natural selection acts on individuals within a population, allowing some individuals to leave more offspring than others, it is the population as a whole that evolves and becomes adapted to its environment.

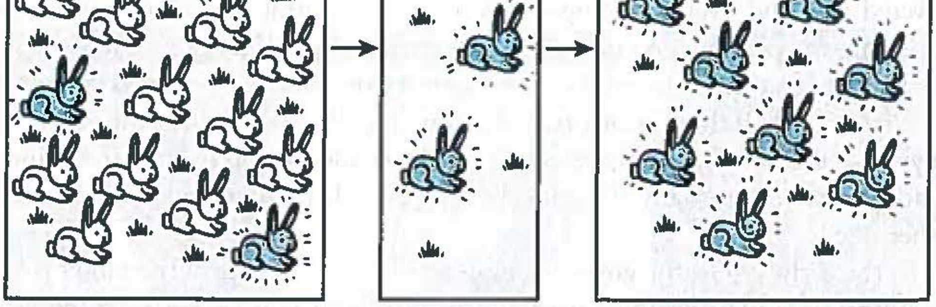

FIGURE 17.13
At first, the myxoma virus killed 99.9% of infected rabbits. However, a small number of naturally disease-resistant rabbits (blue) survived and reproduced, passing their myxoma-resistant genes to their offspring. The population became more resistant, and the virus became less effective.

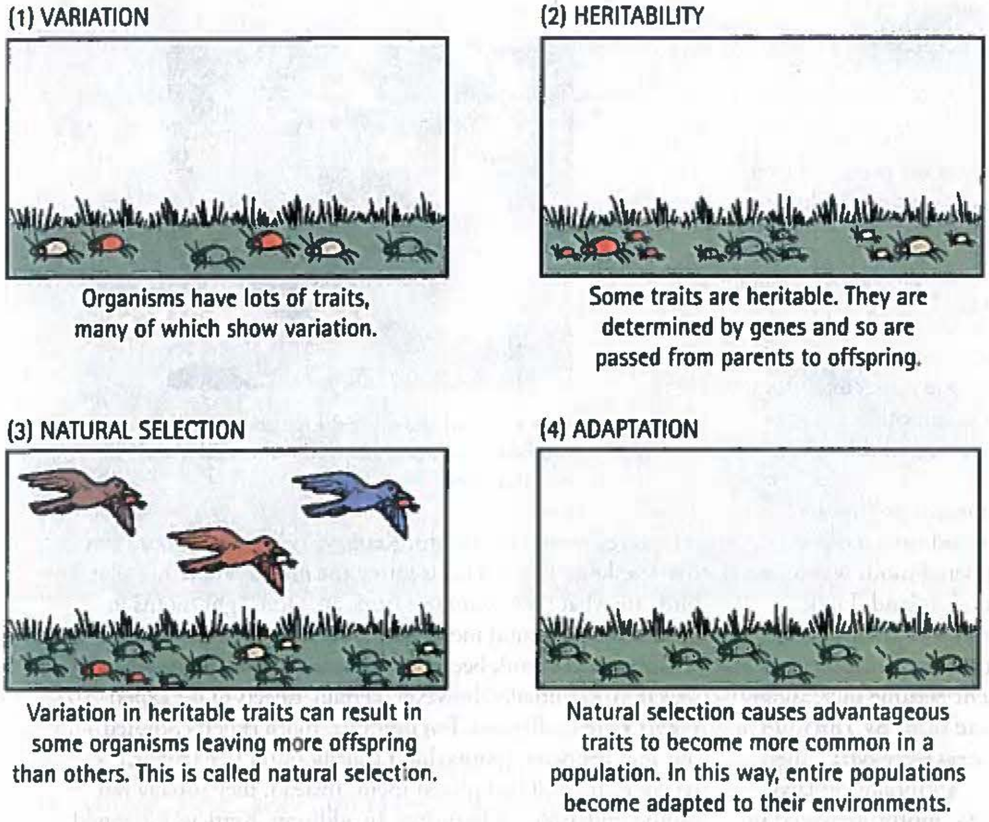

FIGURE 17.14
How natural selection works.

CHECK YOURSELF

1. (a) Which of these traits are variable in cats: fur color, tail length, number of eyes? (b) Which of the traits are heritable?
2. The cheetah is the fastest land animal on Earth. It can run 112 kilometers/hour (70 miles/hour)! Cheetahs prey on Thomson's gazelles that can run almost as fast, 80 kilometers/hour (50 miles/hour). How might natural selection have produced the cheetah's fast running speed?

CHECK YOUR ANSWERS

1. (a) Fur color varies among cats—there are tabby cats, black cats, gray cats, and so on. Tail length also varies—not all cats' tails are exactly the same length. But there is no variation in the number of eyes—all cats have two eyes. (b) All three traits are heritable because all are determined genetically.
2. Faster cheetahs were better at catching Thomson's gazelles. Being better at catching food made faster cheetahs better at surviving and reproducing. As a result, faster cheetahs left more offspring, which were also fast. This resulted in a cheetah population with faster individuals. Over many generations, natural selection produced the remarkably fast cheetah we know today.

HISTORY OF SCIENCE

The Peppered Moth

During the Industrial Revolution, coal was the primary fuel in England. Burning coal slathered dark soot on trees, rocks, and ground. And then a startling thing happened to the moths.

Peppered moths in England had always been light in color, with the scattering of dark peppery flecks that gave them their name. Their coloration made them hard to see in a habitat of lichen-covered trees and rocks. (Lichens are fungi that grow with photosynthetic algae or bacteria; they form crustlike growths on rocks, trees, and other surfaces.) It was believed that this camouflage protected the moths from birds, their main predators.

Can you find the moths? Light peppered moths are well camouflaged on lichen-covered trees.

As the Industrial Revolution progressed, pollution killed the lichens, leaving the trees first bare and then darkened with soot. In 1848, the first dark peppered moth was found in the industrial center of Manchester, England. Dark moths had probably always existed in the population, but they had been extremely rare. Over the next decades, as more coal burned and the environment became increasingly sooty, more and more dark moths were seen. By 1895, 98% of peppered moths in industrialized areas were dark. Then, in the second half of the 20th century, antipollution laws were passed and soot disappeared. Light moths increased in number, and today the dark moths have all but disappeared.

Did natural selection cause the coloration shifts in the peppered moth? Biologists hypothesized that in lichen-covered habitats, natural selection favored light moths because they were better camouflaged. In sooty habitats, natural selection favored dark moths. A series of experiments by Bernard Kettlewell tested this hypothesis. Kettlewell released equal numbers of marked dark and light moths in polluted and unpolluted areas. After a while, he tried to recapture the moths. In polluted areas, Kettlewell recaptured more dark moths than light moths, which suggested that dark moths had survived better. The opposite was true in unpolluted habitats, where he recaptured more light moths. Kettlewell also placed moths on tree trunks and filmed birds eating the moths. He found that birds ate what they could see: Birds ate more light moths in polluted habitats and more dark moths in unpolluted habitats.

Kettlewell's work became a classic example of natural selection. Eventually, however, certain aspects of his experiments were challenged. For example, moth experts pointed out that peppered moths don't usually sit on tree trunks, where Kettlewell had placed them. Instead, they usually rest on the undersides of branches. In addition, Kettlewell released the normally nocturnal moths during the daytime. This may have affected the moths' ability to find resting spots. Finally, Kettlewell used a mix of lab-raised and wild-caught moths, which could differ in their behavior. These doubts led Michael Majerus of Cambridge University to conduct a new set of experiments between 2001 and 2007. Majerus's work confirmed that bird predation was the key factor affecting the relative numbers of light and dark peppered moths. It is also interesting that a shift from light to dark forms in polluted areas (and back again, as pollution is cleaned up) has been reported in more than 70 other moth species in England and the United States alone.

LEARNING OBJECTIVE
Use examples to describe different kinds of adaptations found in living organisms.

17.5 Adaptation

EXPLAIN THIS Why do some birds have bright feathers despite the fact that the vivid colors make them more visible to predators?

Natural selection leads to the evolution of **adaptations**—traits that make organisms well suited to living and reproducing in their environments. The Check Yourself question in the preceding section gave an example of an adaptation—the cheetah's speed. The cheetah's speed helps it catch the food it needs to survive and reproduce.

Adaptations can relate to various aspects of an organism's life. Some adaptations help organisms survive. Survival is, after all, usually an important first step in successful reproduction. Survival requires that organisms be able to acquire food and other necessary resources. It also requires that organisms avoid becoming food for someone else (Figure 17.15). Anti-predator adaptations include camouflage, toxicity, or just the ability to hide or run away.

(a) (b)

FIGURE 17.15
Almost every organism has adaptations that help prevent it from becoming food for someone else. (a) The spines of this cactus prevent most animals from eating it. (b) When threatened, this octopus releases a cloud of dark ink that may confuse a predator long enough for the octopus to escape.

The peacock may be the organism with the most famous adaptation for attracting mates. The male peacock's great fan of colorful tail feathers not only is admired by people but, more important, impresses peahens.

Other adaptations have evolved to help organisms acquire mates. These include the beautiful feathers of male peacocks and birds of paradise (Figure 17.16a), the sexy "rib-bits" of male frogs, and the enchanting songs of many male birds. Males have evolved these "sexy" traits because females of the species find them attractive. In other species, females don't choose their mates based on attractive traits. Instead, males fight with other males to obtain mates. The adaptations of these males may include large size, great strength, or fighting structures such as antlers (Figure 17.16b). Natural selection that favors individuals best able to acquire mates is also called ***sexual selection***.

And speaking of bright colors—the bold colors of organisms such as wasps, coral snakes, and poison dart frogs evolved to warn potential predators that they are dangerous.

(a) (b)

FIGURE 17.16
Some adaptations for acquiring mates. (a) The beautiful feathers of this male bird of paradise (shown here displaying his wings) help attract female mates. (b) These male deer are fighting for control of territory as well as mates.

Finally, some adaptations relate to bearing and raising young. Figure 17.17 shows one such adaptation—parental care. Parental care evolved because natural selection favored organisms that were able to help their offspring survive and thrive. Parental care is found in many animals, including humans.

Natural selection has produced remarkable adaptations over time. Nature does not plan ahead—it does not plan to make a falcon or a polar bear. Instead, adaptations are built step by step, through the never-ending selection of the most successful forms.

FIGURE 17.17
Parental care occurs in many species. This male poison dart frog is carrying his tadpoles on his back.

When a male praying mantis (the smaller insect on top) mates with a female, he is in danger of having his head bitten off.

CHECK YOURSELF

Mating is very dangerous for a male praying mantis. Quite often, the female will eat him as he mates with her.

1. **What advantage does the female get from eating the male?**
2. **Would it be more advantageous ("adaptive") for the male not to mate at all?**

CHECK YOUR ANSWERS

1. **The female gets nutrients when she eats the male.**
2. **A male praying mantis that never mates is more likely to survive to old age. But, if he doesn't mate, he won't leave any offspring. Remember**

SCIENCE AND SOCIETY

Antibiotic-Resistant Bacteria

A patient is ill with pneumonia and gets a prescription for penicillin. After three days, he feels better and stops taking his pills. A few days later, his symptoms return. He quickly finds his pills and starts taking them again, but this time they have no effect. What happened? This frightening phenomenon is called *antibiotic resistance*. Antibiotic resistance is caused by natural selection: Penicillin killed most of the pneumonia bacteria, but a few penicillin-resistant bacteria survived. These bacteria multiplied, and the patient's infection came back—only this time, the bacteria are resistant to penicillin.

Antibiotics are wonder drugs. When penicillin, the first antibiotic, appeared, it dramatically cut the number of illnesses and deaths resulting from bacterial infections. After only a decade of use, however, the first penicillin-resistant bacterial strains appeared. Since then, antibiotic resistance has spread, with more and more bacterial populations becoming resistant to more and more different antibiotics. Diseases once easy to treat—tuberculosis, pneumonia, even common childhood ailments such as ear infections—are now often resistant to multiple antibiotics. In 2011 the World Health Organization reported that about 440,000 new cases of multi-drug-resistant tuberculosis appear each year, resulting in at least 150,000 deaths.

Some of the most dangerous antibiotic-resistant bacteria are found in hospitals, where the use of many different types of antibiotics allows widely resistant strains to evolve. The Centers for Disease Control reported that in 2005, methicillin-resistant *Staphylococcus aureus* (MRSA), a bacterial strain that is resistant to most of the antibiotics currently available, was responsible for more than 94,000 life-threatening infections and 18,650 deaths in the United States alone. And, some MRSA strains are beginning to show resistance to the antibiotic vancomycin, often considered "the drug of last resort." Another worrisome development is the emergence of MRSA in the wider community. Community-based MRSA infections usually start as skin infections and spread through skin-to-skin contact. Some of these cases turn into "flesh-eating" disease, and others are halted only by drastic measures such as amputation. Environments with a higher risk for community-based MRSA infections include athletic facilities, dorms, prisons, and day-care centers. Compared to people whose infections respond to antibiotics, people who have antibiotic-resistant infections require longer hospital stays and are more likely to die from their infections.

All antibiotic use has the potential of contributing to resistance. However, resistance has been greatly accelerated by the overuse of antibiotics. Under pressure from patients, physicians may prescribe antibiotics for illnesses that are not caused by bacteria. (Many common illnesses, such as colds, flus, and most sore throats, are caused by viruses.) These antibiotics select for resistance in the normal (non–disease-causing) bacterial populations in our bodies, making it possible for resistant genes to be transferred to disease-causing bacteria that later invade the body. The fact that patients sometimes stop taking their medications too soon contributes to the problem; this selects for antibiotic-resistant strains without providing the sustained dose that would actually kill all the bacteria. Antibiotics are also used heavily in the livestock industry, where animals are given antibiotics regularly—even when they are healthy—to promote growth. Unfortunately, this practice greatly promotes the evolution of antibiotic resistance. In recent years, reports of food-borne illnesses caused by antibiotic-resistant bacteria have become regular items in the news. For example, in August 2011, an outbreak of antibiotic-resistant salmonella in ground turkey caused at least 79 illnesses and one death.

What can be done about antibiotic resistance? First, humans must learn to use antibiotics wisely, taking them only when they are needed—that is, for bacterial infections—and then taking the entire course of treatment. Second, physicians and veterinarians can promote a socially responsible approach to antibiotics by educating patients and agriculturalists on the proper application of these drugs. Third, antibiotics should not be used to promote growth in livestock. In 2012, steps were finally taken to ban the agricultural use of certain antibiotics. Finally, since many antibiotics are less effective now because of resistance, scientists must search for new antibiotics to take the place of those that no longer do the job.

that adaptations are traits that make organisms good at living *and reproducing* in their environments. It's not enough to survive—you also have to reproduce! This male praying mantis may not have long to live, but at least he has a good chance of leaving offspring.

• • •

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LEARNING OBJECTIVE
Explain how an understanding of genetics produced insights about the mechanisms of evolution and the origin of genetic diversity.

17.6 Evolution and Genetics

• • •

So far, we've seen how natural selection acts on organisms' traits—giraffe neck length, cheetah speed, peppered moth color, and so on. Traits are only part of the story, though, because what gets passed from parents to offspring are not traits, but genes. The incorporation of modern genetics (see Chapter 16) into Darwin's theory of evolution took place in the middle of the twentieth century and produced many new insights about how populations evolve.

The focus on genes led to a description of evolution as *changes in the allele frequencies of genes over time. Allele frequencies* describe how common different alleles are in a population. For example, the peppered moths we discussed earlier have a light allele (*a*) and a dark allele (*A*) for color. A population with many light moths and few dark moths might have allele frequencies of 92% *a* and 8% *A*. As the habitat becomes more polluted, dark moths become more common, and the dark allele increases in frequency. In a polluted area, the allele frequencies might change to 5% *a* and 95% *A*.

We can describe natural selection in terms of allele frequencies as well: (1) There is variation in a gene when multiple alleles for that gene exist within a population. For example, in peppered moths there are two alleles for color, *A* and *a*. (2) A specific allele may give an organism an advantage that allows it to reproduce more than other organisms in the population. In a polluted habitat, for example, the *A* allele is advantageous. (3) As a result, more copies of the advantageous allele are passed to the next generation, and the frequency of the advantageous allele increases in the population. In a polluted habitat, the frequency of the *A* allele increases.

Notice that, although natural selection *affects* genes and allele frequencies, natural selection does not act *directly* on genes. Another way to say this is: Natural selection acts on an organism's phenotype (traits), not on its genotype (genes). To see why, let's go back to the peppered moth. In peppered moths, the dark allele (*A*) is dominant and the light allele (*a*) is recessive. This means that both *AA* moths and *Aa* moths have dark wings (Figure 17.21). Whether a bird is likely to eat the moth depends on the moth's phenotype (whether it is dark or light), not its genotype. A bird is equally likely to eat a dark moth whether it has genotype *AA* or *Aa*.

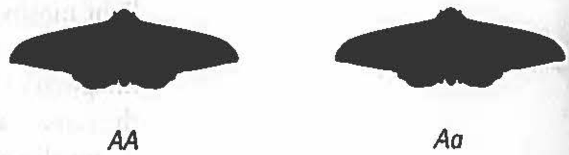

FIGURE 17.21
Natural selection acts on phenotype, not genotype. In the case of these two dark moths, it's the phenotype (dark color) that matters, not the genotype (*AA* versus *Aa*).

Where Variation Comes From

Natural selection cannot happen without variation. Furthermore, populations with more variation have a better chance of adapting to a changing environment. This is because with more variation, it is more likely that somewhere in the population there are alleles that will allow some individuals to survive under the new conditions. For instance, what would have happened to peppered moths during the Industrial Revolution if all the moths had been light and none were dark? In polluted areas, populations with only light moths might have died out. (In Chapter 21, we'll see that having many kinds of *species* in a habitat also increases the chance that at least some organisms will survive major changes in the environment.)

But where does variation come from? An understanding of genetics enabled biologists to answer this question. Genetic mutations (see Chapter 16) constantly create new variations within populations. For example, when a genetic mutation changes the amino acids in a protein, it may produce a new allele for a given gene. Sexual reproduction also contributes to variation by bringing together alleles for different traits in new combinations.

17.8 Evidence of Evolution

LEARNING OBJECTIVE
List and provide examples of the main kinds of evidence that support the theory of evolution.

EXPLAIN THIS How do corn on the cob, a dog's dewclaw, and the human hand provide evidence for evolution?

All scientific theories make predictions about what we should observe in nature (see Chapter 1). If these predictions are confirmed, the theory is supported. The theory of evolution has been tested repeatedly against observations of the natural world, and the evidence for evolution is overwhelming. Eight main kinds of evidence support the idea that evolution produced the diversity of life on Earth: (1) observations of natural selection in action, (2) artificial selection, (3) similarities in body structures, (4) vestigial organs, (5) DNA and molecular evidence, (6) patterns of development, (7) hierarchical organization of living things, (8) biogeography, and (9) fossils. We will look at the first eight topics here, and then consider fossils in Integrated Science 17C.

UNIFYING CONCEPT
- *The Scientific Method* Section 1.3

1. *Observations of natural selection in action.* In many cases, scientists have seen natural selection produce evolutionary changes in populations; they have observed and measured the actual changes in populations. Examples include some of the cases we have looked at: Australian rabbits evolved resistance to the myxoma virus, so that over time a smaller and smaller fraction of individuals died from the disease. Peppered moths evolved to become better camouflaged in their environments—dark moths became more and more common as habitats became polluted, and then became less and less common as pollution was cleaned up. Bacteria evolved resistance to certain antibiotics, so that these antibiotics no longer controlled infections. Scientists have also studied how the beaks of Darwin's finches evolve after a drought, how insects evolve resistance to pesticides, and natural selection in a wide variety of other populations.
2. *Artificial selection.* **Artificial selection** is the selective breeding of organisms with desirable traits in order to obtain organisms with similar traits. Humans artificially select for desirable traits in domesticated animals and crops all the time: We breed fast racehorses to try to get faster racehorses; different types of dogs to produce superior hunters, herders, or sled-pullers (Figure 17.29); and varieties of strawberries to grow the largest and sweetest fruit. In artificial selection, humans control the reproductive success of different organisms and bring about distinct evolutionary changes in populations over time. These changes can be dramatic—think how much a Chihuahua differs from the animal it is descended from, the wolf. Or look at Figure 17.30 to see the difference between the corn we eat today and teosinte, the plant from which corn was bred. Artificial selection has produced countless forms of domestic animals and crops, all with traits valued by humans.
3. *Similarities in body structures.* We see evidence of the evolutionary histories of species in the structures of their bodies. Consider, for example, the limbs of different mammals. Different mammals use their front limbs for different purposes: Humans use theirs as arms and hands for manipulating tools, cats use theirs to walk on, whales use theirs as flippers, and bats use theirs as wings. If each of these animals had originated independently, we would expect their limbs to look completely different. Each limb would have been designed from scratch to best perform its function. But, despite the different functions of human hands, cat legs, whale flippers, and bat wings, all these limbs show the same arrangement of bones (Figure 17.31). This suggests that the limbs were inherited from a common ancestor and then modified through natural selection for different functions.

FIGURE 17.29
Artificial selection has produced great diversity in dogs.

FIGURE 17.30
Corn (*below*), one of the most important agricultural crops in the world, was laboriously bred through artificial selection from teosinte (*above*). Teosinte has tiny cobs, only a few rows of kernels, and inedible hard coverings on its seeds.

A mouse and a whale are about as different as two mammals can be. Yet just about every bone in a mouse corresponds to a specific bone in a whale. These similarities suggest that mice and whales had a common ancestor and that their skeletons were modified over time by natural selection to fit different environments and ways of life.

MasteringPhysics®
TUTORIAL: Reconstructing Forelimbs

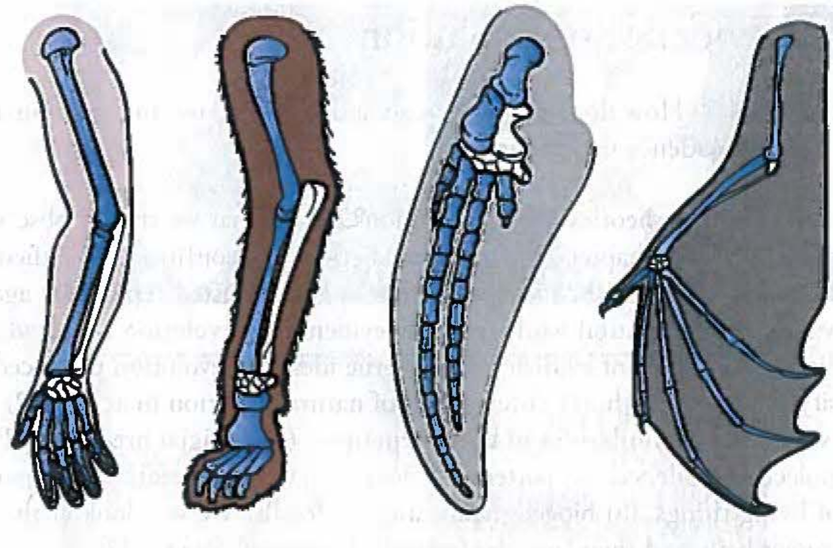

FIGURE 17.31
Although these mammalian limbs are used for different activities, they are composed of the same set of bones, evidence that they were inherited from a common ancestor.

4. *Vestigial organs.* An organism's evolutionary history often leaves traces in its body. Some organisms have vestigial organs. *Vestigial organs* are not functional—they are just the remains of an organ found in the organism's ancestor. For example, we think of snakes as legless. But did you know that certain snakes actually have tiny, partial hind legs? The tiny stubs have no purpose—they are just the remains of what once were bigger limbs. A snake's vestigial hind legs provide evidence that snakes evolved from animals with legs. In the same way, many blind cave species lack functional eyes in their lightless habitats but retain vestigial eyes (Figure 17.32). These vestigial organs suggest that cave species evolved from animals with eyes.
5. *DNA and molecular evidence.* The DNA of related species have similar nucleotide (ACGT) sequences. In fact, the more closely related two species are, the more similar their DNA sequences tend to be. This is true not only for DNA sequences that code for proteins, but even for sequences that have no known function. If each species on Earth had originated independently, would we expect to see similar noncoding DNA in related species? DNA similarity suggests that DNA did not originate independently in each species but was inherited from a common ancestor and then modified during evolution.
6. *Patterns of development.* Related species develop in similar ways. If each species on Earth had originated independently, we wouldn't expect these similarities in development. For example, even though humans have no tails, we go through a tailed stage, just like other vertebrates (Figure 17.33).
7. *Hierarchical organization of living things.* Darwin's theory of evolution explains Earth's diversity of species as originating through numerous speciation events. If this is the case, then we expect living things to be organized into hierarchical sets of "nested groups"—that is, "groups within groups." Each living species should have fewer traits in common with more distant relatives, and more traits in common with species that it split off from more recently. This is in fact how living things on Earth are organized. Humans, for example, share a backbone with other vertebrates such as fishes, amphibians, reptiles, and mammals; they share four limbs with terrestrial vertebrates such as amphibians, reptiles, and mammals but not with fish, which are more distantly related; they share a waterproof skin with reptiles and mammals

FIGURE 17.32
The Texas blind salamander lives in lightless caves. It has tiny vestigial eyes (dark dots in the photo) that are covered by skin.

A dog's dewclaw is a vestigial organ. The dewclaw is a digit that appears on the inside of the front paws. It does not reach the ground and has no function. It is just what remains of a formerly functional toe.

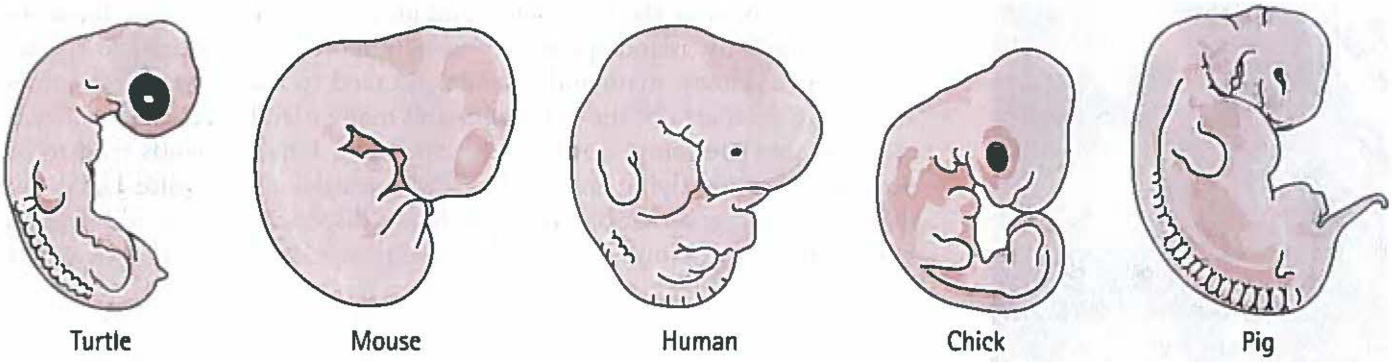

FIGURE 17.33
Related species go through similar stages in their development. The human embryo goes through a tailed stage just like the other vertebrates, even though humans don't have tails.

but not with amphibians, which are more distantly related; and they share the trait of nursing their young with milk with other mammals but not with the more distantly related reptiles. Living things fit into a hierarchical organization, as predicted by evolution. We do not see traits scattered across living things. For example, we do not see a backbone in vertebrates plus some worms and some insects and some snails. The characteristics that organisms have make sense based on their evolutionary history and relationships.

8. *Biogeography. Biogeography* is the study of how species are distributed on Earth. Biogeography is consistent with evolution: It supports the idea that organisms evolved in a certain place and then left descendants in the places where they were able to spread. Biogeography does not support the idea that organisms were specially designed to fit into a specific type of habitat and then distributed where these habitats occur on Earth. For example, even though the Arctic and Antarctic have similar environments, they are occupied by entirely different species (Figure 17.34). The same is true for New World tropical forests and Old World tropical forests.

What biogeography does show is that the ranges of many species are bounded by geographic barriers such as oceans or mountain ranges. For example, many organisms are restricted to a single continent. In addition, closely related species tend to be found close together, suggesting that they evolved in one place and then spread. For example, all of Darwin's finches

FIGURE 17.34
The Arctic and Antarctic, which have similar habitats, are occupied by very different species. Polar bears are found in the Arctic but not the Antarctic. Penguins are found in the Antarctic but not the Arctic.

are found in or near the Galápagos, and all the honeycreepers are found in Hawaii. Similarly, island species are usually most closely related to species found on the closest mainland. Islands also tend to have fewer species than an equally sized area of the mainland, and many island species are *endemic*, meaning they are found nowhere else on Earth. Finally, islands tend to be occupied by many flying animals but few terrestrial ones (Figure 17.35). All these points suggest that organisms were not dispersed purposefully around Earth, but instead evolved in one place and then left descendants where they were able to spread.

FIGURE 17.35
Why are terrestrial vertebrates rare or absent from islands, whereas flying species are common? This is the Hawaiian hoary bat, the only mammal found on Hawaii prior to human colonization of the islands.

CHECK YOURSELF

Why is the fact that many species found on islands resemble species found on the nearest mainland evidence for evolution?

CHECK YOUR ANSWER

This pattern suggests that island species evolved when some mainland individuals colonized the island and then evolved in isolation, rather than that species were distributed purposefully around the Earth.

LEARNING OBJECTIVE
Explain how fossils provide evidence of evolution.

Integrated Science 17C
EARTH SCIENCE

Fossils: Earth's Tangible Evidence of Evolution

EXPLAIN THIS Why do fossil whales have legs?

Evolution has left a record in Earth's rocks—fossils. Because we can date fossils from the age of the rock formations they belong to, we can follow the evolution of certain groups of organisms over time. For example, fossil whales show that whales are descended from hoofed mammals. Fossil whales also tell us how many key whale traits evolved. In Figure 17.36a, we can see how, over time, whale nostrils moved from the front of the skull to the top of the skull, forming a blowhole. Fossil whales also show how whales lost their hind legs as they became more and more adapted to an aquatic existence. The oldest whale fossils, such as the 50-million-year-old *Ambulocetus*, have large hind legs that were used both on land and for swimming (Figure 17.36b). *Ambulocetus* also has small hooves on its front legs, providing clear evidence that whales are descended from hoofed mammals. *Rhodocetus*, a 46-million-year-old fossil whale, shows reduced hind legs—these are not attached to the backbone and so could not have supported much weight. *Rhodocetus* also shows prominent tail muscles that would have been effective for swimming. In the 40-million-year-old *Dorudon*, hind limbs are present, but they are tiny: *Dorudon* was clearly a fully aquatic species. In modern whales, there is no evidence of hind limbs on the outside of the body, although tiny remnants of the pelvis and sometimes femurs remain inside the body.

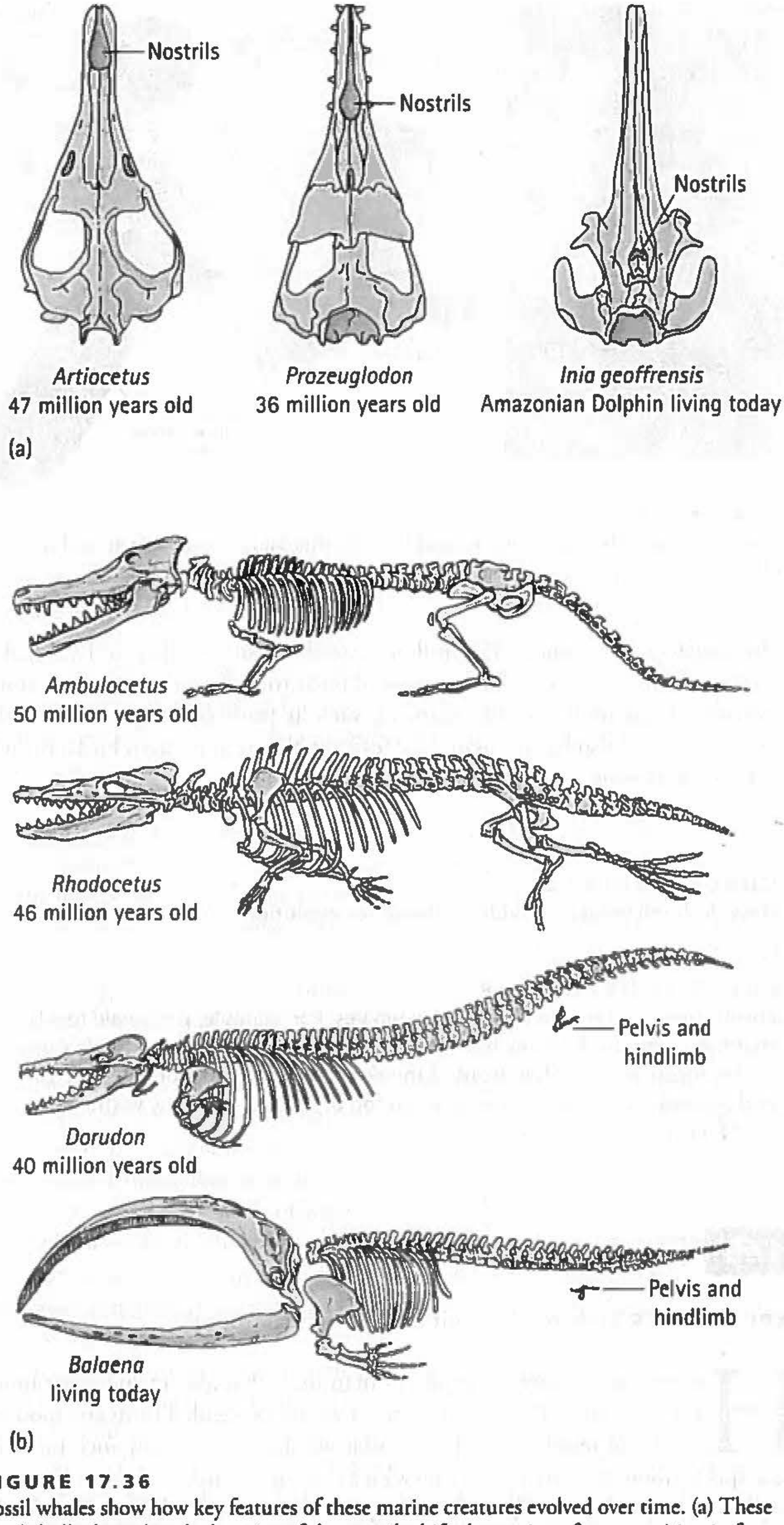

FIGURE 17.36
Fossil whales show how key features of these marine creatures evolved over time. (a) These fossil skulls show that the location of the nostrils shifted over time, from a position in front of the skull to a position on top of the skull—the "blowhole" seen in modern species. (b) Fossil whales also show the reduction and loss of hind legs over time.

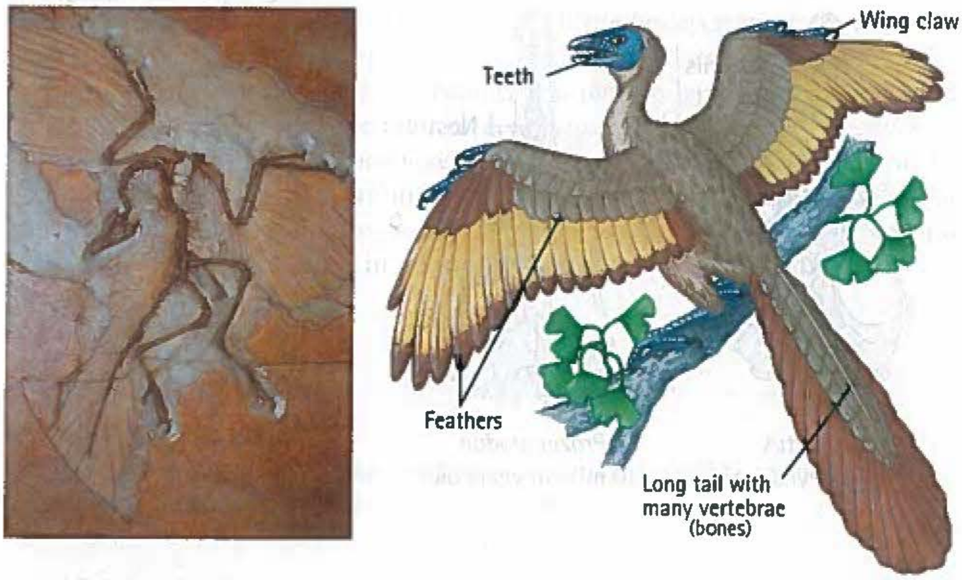

FIGURE 17.37
Archaeopteryx, an early bird, has features of both the dinosaurs it evolved from and modern birds.

You just learned that *Archaeopteryx*, the ancient bird, had clawed wings. Most birds today do not have claws on their wings, but there are a few exceptions—the most famous may be the hoatzin, which lives in tropical forests in the Amazon. Hoatzin chicks use their claws to move along branches. In addition, when threatened, they may drop from one tree, swim or move to another tree trunk, and then climb back up using their claws.

Archaeopteryx, the famous 150-million-year-old fossil bird (Figure 17.37), also shows intermediate traits in the evolution of birds from their dinosaur ancestors. *Archaeopteryx* has many birdlike features, such as feathers, wings, and a wishbone. However, it also has dinosaur-like features absent in modern birds, including claws on its wings, bones in its tail, and teeth.

CHECK YOURSELF
How do fossil whales provide evidence for evolution?

CHECK YOUR ANSWER
Fossils show how key traits evolved in whales. For example, the whale fossils that have been found show traits that are intermediate between the features of the ancestors (nostrils in front of the skull and large functional hind legs) and present-day whales (a blowhole on top of the skull and tiny vestigial hind limbs).

LEARNING OBJECTIVE
Describe some fossil hominids and what they reveal about the evolution of humans.

17.9 The Evolution of Humans

EXPLAIN THIS Is there a little bit of Neanderthal in you?

Humans are *primates*, a group of mammals that also includes the monkeys and apes. This does not mean we are descended from any modern species of monkey or ape, just that we share a common ancestor with these species more recently than we do with a dog, or a lizard, or a plant. Humans are also *hominids*, the group within the primates that includes modern *Homo sapiens* (our species) as well as some of our extinct relatives. Although humans are the only hominids in existence today, fossil hominids provide clues as to how humans evolved. A timeline of human evolution is shown in Figure 17.38.

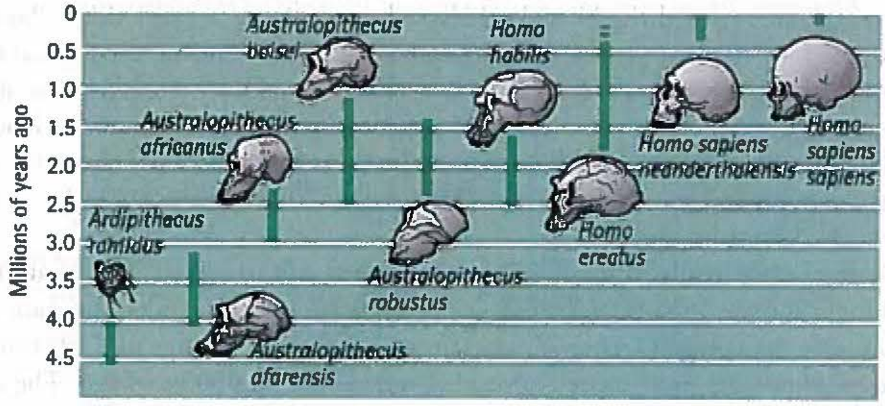

FIGURE 17.38
This timeline shows when certain hominid species existed on Earth. The skulls are all drawn to the same scale to show relative brain sizes.

Humans are not descended from any species of monkey or ape that is living today. However, we are more closely related to monkeys and apes than we are to other animals. *Descended from* and *related to* are entirely different.

Every creature alive now is equally evolved. Every creature alive today is the product of at least 3.5 billion years of evolution. Humans are not "more evolved" than any other species.

Some of the earliest hominids known belong to the group *Australopithecus.* Fossil *Australopithecus* have been found at multiple sites in Africa, where hominids are believed to have originated. "Lucy," the famous *Australopithecus afarensis* fossil shown in Figure 17.39, dates from 3.2 million years ago. When she was alive, Lucy stood 3 feet 8 inches tall and had a brain about the size of a chimpanzee's. However, the bones of Lucy's pelvis make it clear that she walked upright on two legs. In fact, older *Australopithecus* fossils show that an upright posture dates to at least 4 million years ago and therefore evolved long before increased brain size and intelligence.

Homo habilis is the earliest known species that belongs to the group *Homo,* which includes the species most closely related to modern humans. Some *Homo habilis* fossils are 2.2 million years old. *Homo habilis* had a larger brain than *Australopithecus. Homo habilis* also made stone tools—in fact, its scientific name means "handy man." Male *Homo habilis* were much larger than females. This is interesting because in other primates, such as gorillas and baboons, a big size difference between males and females is a sign that males fight each other for female mates.

Homo erectus lived from about 2 million years ago to about 400,000 years ago. *Homo erectus* had an even larger brain than *Homo habilis.* In fact, the brain of *Homo erectus* was not much smaller than that of modern humans. *Homo erectus* was a skilled toolmaker as well as the first hominid species to migrate out of Africa and spread into much of what is now Europe and Asia. Like *Homo habilis,* older *Homo erectus* fossils show that males were much larger than females. However, later fossils of the same species show a male–female size difference closer to that present in modern humans, suggesting the development of a more humanlike social system.

FIGURE 17.39
"Lucy," a fossil *Australopithecus afarensis,* stood upright and walked on two feet.

The Neanderthals—*Homo sapiens neanderthalensis*—are closely related to modern humans (Figure 17.40). They lived from about 200,000 years ago to about 30,000 years ago. Neanderthals had very thick arms and legs, and their brains were as large as those of modern humans. Archaeological finds show that Neanderthals were effective hunters, had complex burial rituals, and made use of medicinal plants. One question that remains unanswered is whether the Neanderthals had language. For thousands of years, modern humans coexisted with Neanderthals. However, Neanderthal populations disappeared as modern humans spread. Scientists are not sure why, although it seems likely that modern

In one of the most spectacular archaeological finds in centuries, skeletons of a tiny human relative were discovered on a remote Indonesian island in 2004. Nicknamed "hobbits," *Homo floresiensis* adults had skulls the size of grapefruits and were no bigger than 3-year-old modern children. *Homo floresiensis* lived alongside pygmy elephants, giant rodents, and Komodo dragons. Most amazing is the fact that they still occupied the island only 13,000 years ago, which means that they coexisted with our own species.

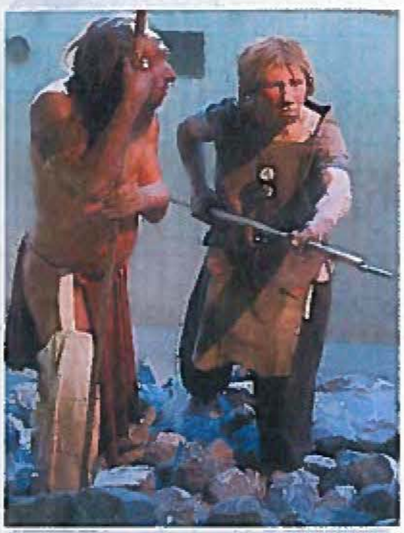

FIGURE 17.40
Neanderthals coexisted with modern humans and interbred with them. These reconstructions appear at the Neanderthal Museum in Mettmann, Germany.

humans outcompeted the Neanderthals and drove them to extinction. The development of modern genetic techniques has allowed scientists to collect information about the Neanderthals from a new source—DNA. Scientists are now attempting to sequence the Neanderthal genome from fossil remains. Genetic studies have already revealed that modern humans interbred with Neanderthals at some point in time; Neanderthal DNA accounts for at least 1%–4% of the genome of most humans.

The earliest fossils of modern humans, *Homo sapiens sapiens*, were found in Ethiopia and are 195,000 years old. Although anatomically modern humans are quite old, the cultural traits we associate with humans—things like art, music, and religion—are more recent, appearing only about 50,000 years ago. The reason for this gap between modern anatomy and modern behavior is the subject of continued debate.

CHECK YOURSELF

1. **Have multiple species of hominids ever coexisted on Earth? Do any hominids other than humans survive to this day?**
2. **What is the significance of the transition from a large male–female size difference in early *Homo erectus* fossils to a size difference closer to that of modern humans in later fossils of the same species?**
3. **What is the result of trillions and trillions of living things passing genetic traits to their offspring, here and there making an adaptive change, and surviving to today?**

CHECK YOUR ANSWERS

1. The timeline of hominid evolution shows that multiple species of hominids coexisted during much of hominid history. Today, however, humans are the only species of hominids in existence. The others have all died out.
2. A large size difference between males and females is a sign that males fought each other for female mates. This may have been true in early *Homo erectus*. More equal body sizes in later *Homo erectus* suggests that males and females had longer-term bonds, perhaps as they raised offspring together.
3. We and Earth's other living things are the result of this long and astounding journey!

For instructor-assigned homework, go to www.masteringphysics.com MP

SUMMARY OF TERMS (KNOWLEDGE)

Adaptations Evolved traits that make organisms well suited to living and reproducing in their environments.

Allopatric speciation Speciation that occurs after a geographic barrier divides a group of organisms into two isolated populations.

Artificial selection The selective breeding of organisms with desirable traits in order to produce offspring with the same traits.

Autotrophs Living organisms that convert inorganic molecules into food and organic molecules.

Evolution Inherited changes in populations of organisms over time.

Fitness The number of offspring an organism produces in its lifetime compared to other organisms in the population.

Gene flow The evolution of a population due to the movement of alleles into or out of the population.

Genetic drift The evolution of a population due to chance.

Heritable Description of traits that are passed from parents to offspring because they are at least partially determined by genes.

Heterotrophs Living organisms that obtain energy and organic molecules from other living organisms or other organic materials.

Natural selection The process in which organisms with heritable, advantageous traits leave more offspring than organisms with other traits, causing these advantageous traits to become more common in a population over time.

Speciation The formation of new species.

Species A group of organisms whose members can breed with one another but not with members of other species.

Sympatric speciation Speciation that occurs without geographic isolation.

Variation Differences in a trait from one individual to another.

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