Evolution

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An Introduction

One of the best feelings paleontologists can ever have is to realize that they have just found a fossil that will fill an empty space in our understanding of the history of life. Hans Thewissen got to enjoy that feeling one day as he dug a 49-million-year-old fossil out of a hillside in Pakistan. As he picked away the rocks surrounding the bones of a strange mammal, he suddenly realized what he had found: a whale with legs.

Left: The earliest whales, such as the 49-million-year-old *Ambulocetus*, still had legs. Above: Paleontologist Hans Thewissen has discovered many of the bones of *Ambulocetus*.

There were no whales three billion years ago. There were no mushrooms or trees, either, not to mention people. Paleontologists have scoured ancient rocks for signs of life, and, as far as they can tell, the Earth three billion years ago was home only to single-celled microbes. Some of those tiny organisms were tossed by ocean waves. Others formed slimy films on the seafloor. Others thrived in undersea chambers of boiling water heated by volcanoes. The whales, the mushrooms, the trees, and all the rest came later. That transformation of life occurred through the process known as evolution.

This book is an introduction to evolution, both to the process by which life evolves and to the pattern evolution has produced over life's history. It is also about how scientists study evolution. When Charles Darwin formulated the theory of evolution in the mid-1800s, the most sophisticated tool he could use was a crude light microscope. Today, scientists can study evolution by analyzing our DNA. They can probe the atoms of ancient rocks to determine the age of fossils. They can use powerful computers to apply new statistical equations to the diversity of life. They can observe evolution unfolding in their laboratories.

Evolution is the foundation of modern biology. But that doesn't mean that only biologists should know about it. Evolution underlies many of the most important issues society faces. We are witnessing a wave of extinctions the likes of which the Earth may not have seen for millions of years. Doctors are battling rapidly evolving bacteria and viruses. Evolution is also part of the answer to some of the biggest questions we all ask. How did we get here? What does it mean to be human? This book is intended for those who are not planning to be biologists—in other words, most people. It does not deal at length with the mathematics and the advanced experimental techniques evolutionary biologists use. But it does describe the key concepts in evolution with the help of graphs, diagrams, and other illustrations.

What Is Evolution?

The short answer is *descent with modification*. The patterns of this modification, and the mechanisms by which it unfolds, are what evolutionary biologists study. They have much left to learn—but, at this point in the history of science, there is no doubt that life has evolved and is still evolving.

The fundamental principles that make evolution possible are pretty straightforward. Organisms inherit traits from their ancestors because they receive a molecule called DNA from them (page 87). Cells use DNA as a guide to building biological molecules, and, when organisms reproduce, they make new copies of DNA for their offspring. Living things do not replicate their DNA perfectly, sometimes introducing errors in its sequence. Such errors are referred to as mutations (Chapter 6). A mutation may be lethal; it may be harmless; or it may be beneficial in some way. A beneficial mutation may help an organism to fight off diseases, to thrive in its environment, or to improve its ability to find mates.

Evolution takes place because mutated genes become more or less common over the course of generations. Many mutations eventually disappear, while others spread widely. Some mutations spread simply by chance. Others spread because they allow organisms to produce more offspring. This nonrandom spread of beneficial genes is known as natural selection. The effect of a mutation depends on more than just the mutation itself. It is also influenced by all the other genes an organism carries. The environment in which an organism lives can also have a huge effect. As a result, the same mutation to the same gene may be devastating in one individual and harmless in another. Depending on the particular circumstances, natural selection may favor a mutation or drive it to oblivion.

These processes are taking place all around us every day, and they have been transforming life ever since it began, some 3.5 billion years ago (Chapter 3). Charles Darwin argued that over such vast stretches of time, natural selection could have produced very complex organs, from the wings of birds to human eyes. Today, the weight of evidence overwhelmingly supports that conclusion (Chapter 8). Changes in organs are not the only adaptations that have emerged through evolution; behavior and even language have evolved (Chapter 14).

To trace the origin of these traits, evolutionary biologists reconstruct the tree of life (Chapter 4). Natural selection and other processes can make populations genetically distinct from one another. Over time, the populations become so different from one another they can be considered separate species (Chapter 9). One way to picture this process is to think of the populations as branches on a tree. When two populations diverge, a branch splits in two. As the branches diverged over and over again over billions of years (and sometimes joined back together), the tree of life emerged.

To reconstruct the tree, evolutionary biologists identify which species are closely related to each other. They do so by comparing anatomical traits and DNA among many different species. Close relatives share more traits inherited from their common ancestor. We humans have a bony skull, for example, as do all other mammals, as well as birds, reptiles, amphibians, and fishes (Chapter 4). We are more closely related to these animals than to animals without a skull, such as earthworms and ladybugs.

Biologists today not only understand what evolution is, but what it is not. Evolution is not a steady progress towards some particular goal. Our apelike ancestors did not evolve big brains because they "needed" them. The conditions in which they lived—searching for food on the African savanna in big social groups—favored genetic changes that led to bigger brains. The long-term process of evolution emerges from the way life works on a generation-to-generation scale.

Biologists also recognize that evolution does not make life perfect. All adaptations have shortcomings. Humans have evolved very large brains, which have allowed us to become nature's great thinkers (Chapter 14), but those big brains also make childbirth much more dangerous for human mothers than for other female primates. Evolution is imperfect because it does not invent things from scratch: it only modifies what already exists. There are only a limited number of beneficial mutations any particular organism can acquire, and so evolution can only produce new forms under tight constraints. Because mutations can have several different effects at once, evolution also faces trade-offs. This means that evolution, unfortunately, has left us susceptible to many diseases. But it also means that studying evolution can help researchers better understand—and perhaps even treat—those disorders (Chapter 13).

It's also a mistake to think that evolution produces a peaceful harmony in nature. There are many helpful partnerships in nature, such as the one between flowering plants and the insects that pollinate them (Chapter 11). But the same process by which species adapt to one another can also give rise to what looks to us like cruelty. Predators are exquisitely adapted to finding and killing prey. Parasites can devour their hosts from the inside out. Their adaptations are finely honed, allowing them to manipulate individual molecules within their hosts. Yet parasites and predators are not evil. They are just part of a dynamic balance that is constantly shifting, driving the diversification of life but also leading to extinctions.

The diversity of nature, in other words, is not eternally stable. More than 99 percent of all species that ever existed have become extinct, and, at some points in the Earth's history, millions of species have disappeared over a relatively short span of time. We may be at the start of another period of mass extinctions, this time caused by our own actions (Chapter 10).

Evidence and Evolution

Evolution is a process that takes place over time—from months to millions of years. It's not possible to track evolution from one millisecond to the next, even in a carefully designed experiment in the confines of a laboratory. Scientists have no choice but to reconstruct parts of the history of life by analyzing a wealth of clues.

In this respect, evolutionary biology is like many other sciences. Ecologists cannot keep track of every fish on a coral reef as they track population booms and busts. Instead, they have to make small measurements and then extrapolate to an estimate. Astronomers cannot track the movement of a single photon from the center of the Sun out into space. Instead, they must use what they know about photons, about hydrogen and the other gases that make up the Sun, to generate a hypothesis that they can test. In all these cases, scientists analyze evidence, form hypotheses, and then test those hypotheses with fresh evidence.

The evidence that evolutionary biologists gather comes in many forms. In laboratory experiments, for example, scientists can measure the effects of natural selection as it alters populations of bacteria, insects, or other fast-breeding organisms (page 118). It's much harder to estimate the strength of natural selection in the wild. Nevertheless, there are now thousands of examples of carefully documented cases of natural selection in our own lifetime. By comparing the genomes of different species, scientists can also observe how genetic changes make natural selection possible by producing new variations.

Over longer time scales, fossils illuminate the dark corners of life's history. Paleontologists have unearthed a record of fossil life that reaches back about 3.5 billion years. Life's many forms did not appear at once but rather emerged gradually. Single-celled microbes are the earliest known forms of life; the oldest known fossils of multicellular organisms are almost two billion years younger. The oldest known fossil traces of animals are only 635 million years old; the oldest fossils of mammals are only 200 million years old (Chapter 3).

Evolutionary biologists also study the similar traits that closely related species share. Humans have arms and bats have wings, for example, but a close look reveals that their bones form the same basic pattern. Both fossils and living organisms share traits inherited from their common ancestors. From these sorts of clues, scientists build hypotheses about how different species are related to one another. These hypotheses allow them to make new predictions about when

Many books about evolution include a separate chapter about the evolution of our own species, *Homo sapiens*. This book takes a different approach. Human evolution is not separate from the evolution of other species, and so humans are not isolated in a chapter of their own here. Instead, the story of human evolution is woven into most of the chapters in this book.

Here's a guide to the sections in which human evolution is discussed:

certain groups of species first arose in the history of life. As new evidence arises—new fossils, new comparisons of living species—biologists can see whether their hypotheses pass or fail new tests.

The best way to illustrate how scientists learn about evolution—by gathering many lines of evidence, from fossils to DNA; by understanding how evolution shapes everything about an organism, from how it moves to how it ages to how it behaves—is with a case study. So let's take a look at one of the most interesting of those cases: the origin of whales.

A Case of Evolution: Why Do Whales Have Blowholes?

Today, whales and dolphins have no legs. Their bodies are sculpted with the same sleek curves you can find on tunas and sharks, allowing them to use relatively little energy to shoot through the water. The tails of whales and dolphins narrow down to a small neck and then expand into flattened flukes, which they lift and lower to generate thrust. Sharks and tunas have similar tails, except that they move theirs from side to side.

Yet, unlike tunas and sharks, whales and dolphins must rise to the surface of the ocean in order to breathe. They do so by opening up a blowhole on the top of the head, which allows air to enter a passageway that leads to the lungs. Fishes, on the other hand, can usually get all the oxygen they need from the water. They pump water through their gills, and some of the dissolved oxygen passes into their blood vessels.

The differences keep piling up. Whales and dolphins have tiny bones embedded in their flesh just where the hips would be on a land vertebrate, but fishes have none. Fishes have relatively simple sets of muscles that form vertical blocks from head to tail, whereas whales and dolphins have long muscles that run horizontally down the length of their bodies. Whales and dolphins give birth to live young that cannot get their own food; instead, the young must drink milk produced by their mothers. Together, these differences make whales and dolphins starkly unlike the fishes. Those traits—and many others—are found only in mammals.


How did whales evolve? Clues come from everything from fossils to whale DNA.

Charles Darwin hypothesized that whales and dolphins descended from mammals on land and that their ancestors had gradually evolved into ocean-going animals without legs. But no one at the time had found a fossil from that transition, and it would take a very long time before someone did. In 1979, almost a century after Darwin died, a paleontologist from the University of Michigan named Philip Gingerich discovered in Pakistan a 50-million-year-old skull of a whale that appeared to be adapted to life on land. He found the fossil in rocks that had formed on a continent, rather than on the floor of an ocean, and the skull looked more like a dog's than a dolphin's. Gingerich knew that the animal was related to whales, however, because it shared several traits that are found today only in whales, such as a distinctive bony wall surrounding its ear. That whale is now known as *Pakicetus* ("whale of Pakistan" in Latin).

Thirteen years later, Hans Thewissen (a student of Gingerich's) traveled to a different part of Pakistan to look for mammals that lived a few million years after *Pakicetus*. One day he and his Pakistani colleagues happened across the fossil of a strange beast, and they slowly excavated its bones from the tail to the head. Its tail was massive, its legs were stubby, and its rear feet were shaped like paddles. Thewissen discovered that its head was long like an alligator's, but it had teeth with distinctive shapes that are found today only in the teeth of mammals. In fact, the teeth looked like those of *Pakicetus*. And when he excavated the bones around the ear, he discovered a distinctive bony wall around the ear—evidence that he had actually found a whale. He dubbed it *Ambulocetus*: the walking whale.

Thewissen's discovery was historic—it was the sort of animal that Darwin had predicted, and that many skeptics claimed could not have existed. But paleontologists do not stop with a single fossil. They have continued to dig up new fossils to understand the evolution of whales, and other scientists have looked for other kinds of evidence as well. In the mid-1990s geneticists began to sequence whale DNA and to compare it to the DNA of other animals. If whales were indeed mammals, then they should have DNA like the mammals that live on land. They do, in fact: all whales carry genetic markers found only in one group of land

The skeleton of *Ambulocetus* has traits that are found today only in whales. It also has legs and other adaptations found in land mammals.

mammals, known as the artiodactyls. This is a group that includes camels, cattle, hippopotamuses, and goats.

So how did an artiodactyl ancestor of whales go into the sea and lose its legs? To shed light on that question, paleontologists have searched for new fossils and have reanalyzed fossils discovered many years ago. In 2007, Thewissen and his colleagues published a study in which they argued that the closest relative of *Pakicetus* and other whales was a 47-million-year-old artiodactyl called *Indohyus*. They pointed to a set of traits in its skeleton that link it to whales, such as the distinctive ear bone. Yet, if you could see a living *Indohyus*, you might never guess at the kinship. *Indohyus* was a small, slender-legged creature that bore a striking resemblance to an African mammal known as a mouse deer.

Figure 1.1 is an evolutionary tree that illustrates how *Indohyus* and other fossil species are related to living whales. To draw this kind of tree, scientists identify key traits that are shared by groups of species and determine the most likely course of evolution that could have produced them. These trees help scientists to understand major evolutionary transformations, such as the transition of the ancestors of whales from land to sea. (For more on evolutionary trees, see Chapter 4.)

Indohyus and *Pakicetus* evolved when the ancestors of whales still had four long legs. They may have been adept swimmers, but probably no more so than mouse deer and many other land mammals are today. After their ancestors branched off, new whales evolved that were more adapted to life in water. *Ambulocetus*, which lived 49 million years ago along the coastline of what is now Pakistan, had short legs and massive feet. It probably swam like an otter, kicking its large feet and bending its tail. Another species from around the same age, *Rodhocetus*, looked more like a seal, being able only to drag itself around on land. All told, scientists have found more than 30 fossil species that mark the transition from land mammals to the living groups of whales and dolphins.

As whales adapted to the ocean, their legs gradually dwindled. Their forelimbs changed gradually from hooved limbs to flat flippers they used for steering. But evolution did not completely retool whales from the ground up. To breathe underwater, they did not reinvent gills (which had been lost long before by the early vertebrates that moved onto land). Instead, their nostrils shifted up along their skulls until they passed over the eyes.

It's almost certain that scientists will never be able to read the genes of 40-million-year-old whales, because DNA is too fragile to last for more than a few hundred thousand years. But it is possible to study the genes of living whales to learn about some of the genetic changes that turned four-legged land mammals into fishlike whales. Some of the most important genetic changes that take place during major evolutionary transitions change the timing of gene activity in embryos (Chapter 8).

When legs begin to develop on the embryos of humans or other land vertebrates, a distinctive set of genes become active. Thewissen and a team of embryologists discovered that these leg-building genes also become active in dolphin

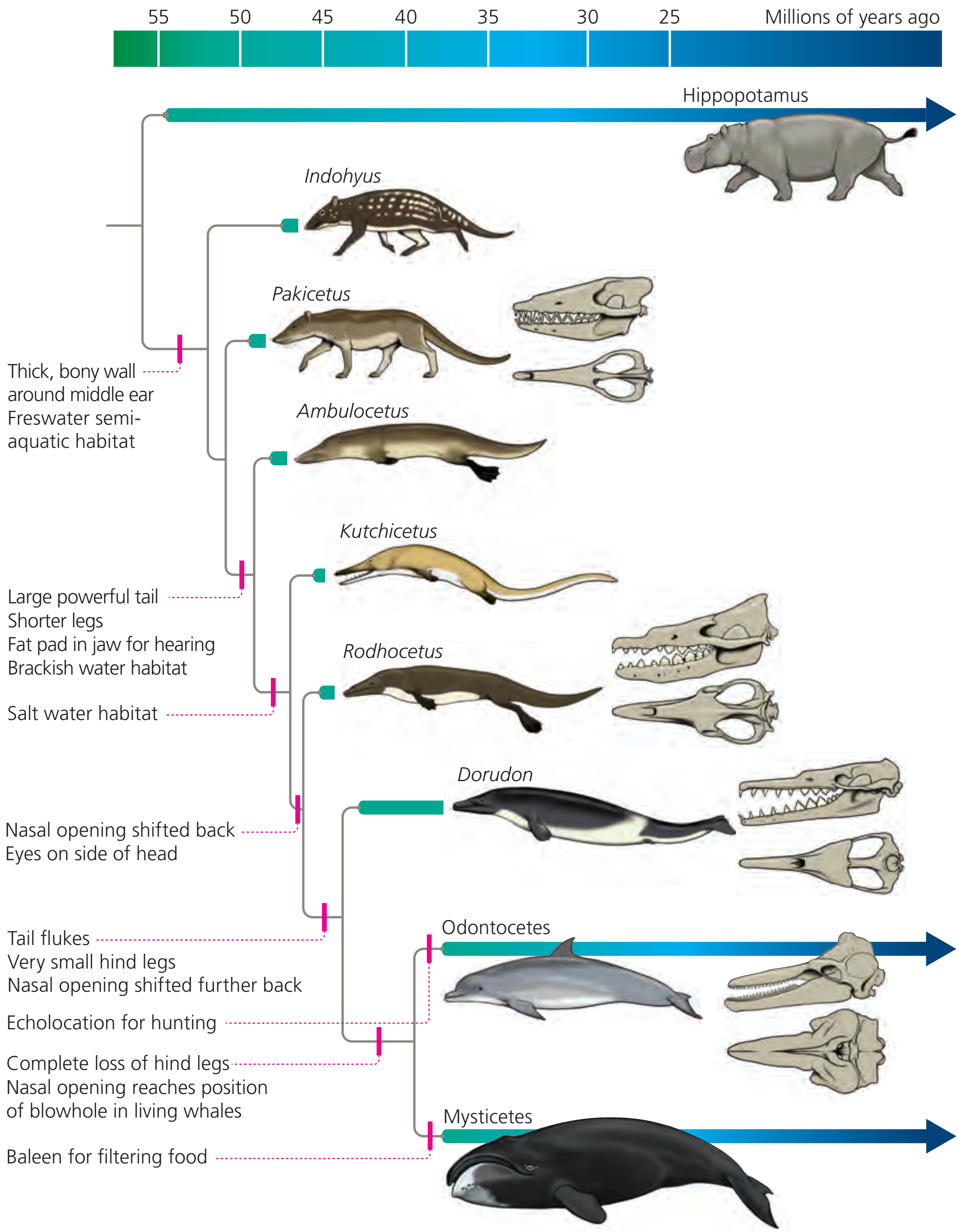

Figure 1.1 This diagram shows how some extinct species of early whales are related to living species. The animals illustrated here are only a fraction of the fossil whales paleontologists have discovered in recent decades. By studying fossils, paleontologists have been able to show how the traits found in living whales emerged gradually, not all at once.

embryos. They help build tiny buds of tissue, but these buds stop growing after a few weeks and then die back.

Fossils show that this change in the timing of gene activity took millions of years to complete. Some 40 million years ago, fully aquatic species had evolved. One species, called *Basilosaurus*, grew to be 50 feet long. But Gingerich and his colleagues have discovered a well-preserved *Basilosaurus* fossil that still had hind legs. Its legs were only as big as those of a human child, but they still retained ankles and toes.

Scientists can get clues about the origins of whales and dolpins not just from the shapes of their fossils, but from the individual atoms inside them. Living whales and dolphins can drink seawater, while land mammals can drink only freshwater. The two kinds of water are different in several ways, and not just because seawater is salty and freshwater is not. Both kinds of water contain oxygen atoms, but the oxygen atoms are slightly different. Like other elements, oxygen atoms are made up of a combination of negatively charged electrons, positively charged protons, and neutral neutrons. All oxygen atoms have eight protons, and most have eight neutrons. But a fraction of oxygen atoms on the Earth have extra neutrons. Scientists have observed that seawater has more oxygen atoms with 10 neutrons than freshwater. And animals that live on land and at sea reflect this difference in the oxygen atoms incorporated in their bones. Living whales and dolpins have a larger percentage of heavy oxygen in their bones than mammals that live on land.

Thewissen wondered if the oxygen atoms in ancient whale fossils might indicate where they lived. So he and his colleagues ground up tiny samples of ancient whale teeth and measured the ratio of light and heavy oxygen. They discovered that *Pakicetus* still drank freshwater. *Ambulocetus*, which belongs to a younger branch of the whale tree, had an intermediate ratio, suggesting that it was drinking brackish water near the shore, or a mix of freshwater and seawater. Younger fossil whales had the ratios you would expect in animals that drank seawater. The chemistry of these whales documents a transition from land to estuaries to the open ocean—the same transition documented in the changing shape of their skeletons.

The earliest lineages of whales are long extinct. The two lineages of whales alive today evolved from a common ancestor that lived about 35 million years ago. One lineage, known as the toothed whales, evolved muscles and special organs that they used to produce high-pitched sounds with their blowholes and to hear the echoes that bounced off animals and objects around them in the water. Today, dolphins and other toothed whales use these echoes to hunt for their prey.

The other living lineage, the baleen whales, lost their teeth and evolved huge, stiff pleats in their mouths that allowed them to swallow huge amounts of water, and to push it back out, straining out any fish or shrimp that the water contained. Scientists are now beginning to find important new clues to these two transitions. Fossils from about 25 million years ago show that the toothed ancestors of baleen whales probably grew small patches of baleen. Only later did their

Dolphins live in large groups and can communicate with each other. Their social life may have favored the evolution of big, powerful brains.

teeth disappear, much like hind legs of their ancestors. Baleen whales still carry genes for building teeth, but all of those genes have been disabled by mutations.

It's not just organs such as baleen and flippers that evolve. Every aspect of an organism may be sculpted by evolution. Consider, for example, the fact that whales can live to be very old. No one knows exactly how long they can live, but scientists have found some astonishing clues. In 2007, Eskimo hunters hunting off the coast of Alaska killed a bowhead whale that still had the tip of an antique harpoon lodged in its blubber. It was a kind of harpoon that had been used for only a few years around 1890, which means that the whale was about 130 years old when it was killed. In 1999, scientists examining the growth patterns in the teeth of a dead bowhead whale estimated that it was 211 years old. By contrast, the closest living relatives of whales on land have much shorter lives. Hippopotamuses are known to live up to 61 years; camels can live up to 35 years.

The lifespans of all species, ours included, are shaped by evolution (page 312). Animals face a trade-off between living long and having lots of offspring. Small animals that are commonly preyed on may grow up fast and die young. Thanks to their large size, whales don't face a lot of attacks by other animals. Bowhead whales, the longest-lived species, may also enjoy the extra luxury of little competition for food as they swim the frigid depths of the Arctic Ocean.

Aging is not the only threat to the health of whales, however. They are beset by parasites, including viruses, bacteria, single-celled protozoans, fungi, flukes, and sea lice. Not all of these parasites are harmful, though. Take an intestinal worm called *Anisakis*. It lives first in fishes. If a whale eats the fish, the worm becomes a parasite of the whale. It doesn't make the whale sick, however. It feeds harmlessly on the food the whale eats and lays its eggs in the whale's droppings. Some studies suggest that *Anisakis* have evolved molecules that they can use to hide from their host's immune system, so that they can stay safe and their hosts don't get sick. Scientists have discovered that the most closely related species of *Anisakis* often live inside the most closely related species of whales. This mirror-like pattern suggests that the evolution of *Anisakis* has been closely tracking the evolution of its hosts for millions of years (Chapter 11).

We don't have this long history with *Anisakis*. And so, if we happen to eat a fish infected with *Anisakis* (in a bad piece of sushi, for example), things sometimes go badly. The worm does not get the normal signals it would use in a whale to guide its journey to the intestines. Instead, it drills a hole in the stomach and crawls out into the abdominal cavity. It wanders around aimlessly, causing excruciating pain and dangerous infections. (Chapter 13 explores other insights that evolution offers about diseases.)

Biologists have long been impressed with the size and complexity of whale brains. Aside from humans, dolphins have the biggest brains in proportion to their body of any animals. Dolphins can also use their oversized brains to solve remarkably complicated puzzles that scientists make for them. A number of studies suggest that big brains evolved in dolphins as a way to solve a particular kind of natural puzzle: figuring out how to thrive in a large social group. Dozens of dolphins live together, forming alliances and competing for mates. They communicate with each other with high-frequency squeaks, and each dolphin can tell all the other dolphins apart by their whistles. Natural selection appears to have favored dolphins with extra brainpower for processing social information. The same process appears to have driven the expansion of brain size in primates as well, culminating in our own extraordinarily oversized brains (page 344).

Unfortunately, 50 million years of evolution has not prepared whales and dolphins very well for life in a human-dominated world. In the 1800s, sailors crisscrossed the world to hunt big whales for their oil and baleen. (The oil was used for lamps and the baleen for corset stays.) Many species of whales came perilously close to extinction before the whale-oil industry collapsed and laws were passed to protect the surviving animals. Because whales are so long-lived, they reproduce slowly, and so their populations have not expanded very much toward their previous levels over the past 100 years. Animals that have only small populations are at greater risk of extinction, in part because diseases can spread more effectively through small populations, and in part because small populations have little genetic variability, making them more susceptible to genetic disorders. Scientists are analyzing the DNA of whales to understand the risks they face from over-


Whale hunting in the nineteenth century nearly drove many species of whales extinct.

hunting and to determine how best to preserve them from extinction (page 235). Unfortunately, whales and dolphins also face other risks. Pollution and heavy fishing in the Yangtze River drove the Chinese river dolphin to extinction in 2006.

Learning about the evolution of whales makes them all the more fascinating. We can discover a dense tapestry of history on display in the living things with which we share the planet. As Charles Darwin wrote at the end of *The Origin of Species*, "There is grandeur in this view of life, with its several powers, having been breathed into a few forms or into one; and that, whilst this planet has gone cycling on according to the fixed law of gravity, from so simple a beginning endless forms most beautiful and most wonderful have been, and are being evolved."

TO SUM UP...

- **Evolution is descent with modification.**
- **Evolution produces complex adaptations, but it does not move towards a particular goal.**
- **Evolutionary biologists test hypotheses about evolution with many different lines of evidence.**
- **Whales evolved from land mammals about 50 million years ago. Evolution has shaped many aspects of their biology, from their behavior to their aging.**