CHAPTER TWO

THE EVIDENCE FOR BIOLOGICAL EVOLUTION

Many areas of science have produced support for biological evolution.

Many kinds of evidence have contributed to scientific understanding of biological evolution. Some of this evidence — such as the fossils of long-extinct animals and the geographical distribution of species — was familiar to scientists in the 19th century or earlier. Other forms of evidence — such as comparisons of DNA sequences — became available only in the 20th and 21st centuries.

The evidence for evolution comes not just from the biological sciences but also from both historical and modern research in anthropology, astrophysics, chemistry, geology, physics, mathematics, and other scientific disciplines, including the behavioral and social sciences. Astrophysics and geology have demonstrated that the Earth is old enough for biological evolution to have resulted in the species seen today. Physics and chemistry have led to dating methods that have established the timing of key evolutionary events. Studies of other species have revealed not only the physical but also the behavioral continuities among species. Anthropology has provided new insights into human origins and the interactions between biology and cultural factors in shaping human behaviors and social systems.

As in every active area of science, many questions remain unanswered. Biologists continue to study the evolutionary relationships among organisms, the genetic changes that affect the form and function of organisms, the effects of organisms on Earth's physical environment, the evolution of intelligence and social behaviors, and many other fascinating subjects. But in each case they are asking specific questions to learn more about *how*, not *whether*, evolution has occurred and is continuing to occur. They are investigating and further elucidating the mechanisms that produce evolutionary change and the consequences of that change.

Biological evolution is part of a compelling historical narrative that scientists have constructed over the last few centuries. The narrative begins with the formation of the universe, the solar system, and the Earth, which resulted in the conditions necessary for life to evolve. While many questions remain about the origins of life on this planet, the appearance of life set in motion a process of biological evolution that continues to this day. Today, new chapters in the narrative are being uncovered through the study of the genetic processes responsible for evolutionary change.

The origins of the universe, our galaxy, and our solar system produced the conditions necessary for the evolution of life on Earth.

The picture of Earth's place in the cosmos changed as much in the 20th century as it did in the 16th and 17th centuries following Copernicus's then controversial suggestion that the Sun, not the Earth, was at the center of the known universe. In the 1920s a new telescope at the Mount Wilson Observatory outside Los Angeles revealed that many of the faint smudges of light scattered across the night sky are not nebulae within our own Milky Way galaxy. Rather, they are separate galaxies, each containing many billions of stars. By studying the light emitted by these stars, astrophysicists arrived at another remarkable conclusion: The galaxies are receding from each other in every direction, which implies that the universe is expanding.

This observation led to the hypothesis first proposed by the Belgian astronomer and Roman Catholic priest Georges Lemaître that the universe originated in an event known as the "Big Bang." According to this idea, all of the energy and matter in the universe initially were compressed into an infinitesimally small, infinitely dense, and infinitely hot object known as a singularity, about which scientists still know very little. The universe then began to expand. As it did, the universe cooled to the point that the elementary particles that today form the matter of the universe became stable. The occurrence of the Big Bang, and the time that has elapsed since then, implied that matter in deep space should be at a particular temperature — a prediction confirmed by ground-

For ten consecutive days, the Hubble Space Telescope focused on a small patch of sky near the Big Dipper, revealing hundreds of galaxies never seen before.

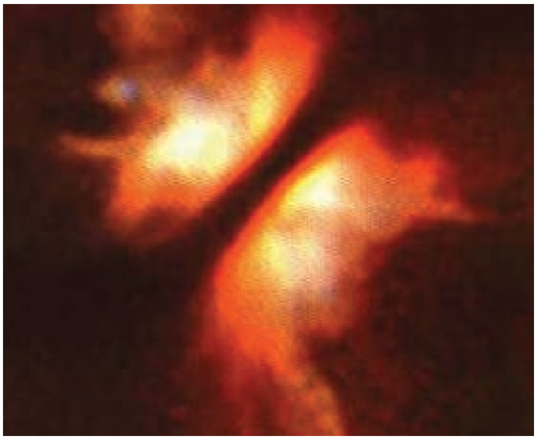
based microwave radio telescopes. Later observations with satellites showed that the background radiation in the universe has exactly the properties that would be predicted from the Big Bang.

As the universe expanded, the matter in it gathered, by way of gravity and other processes that are not yet fully understood, into immense structures that became galaxies. Within these structures, much smaller clumps of matter collapsed into whirling clouds of gas and dust. When the matter in the center of an individual cloud became sufficiently compressed by gravity, the hydrogen atoms in that cloud began to fuse into helium atoms, giving off visible light and other radiation — the origin of a star.

Astrophysicists also have found that some stars form in the middle of a flattened spinning disk of matter. The gas and dust within such disks can aggregate into small grains, and these grains can form larger bodies called planetesimals. Computer simulations have indicated that planetesimals can coalesce into planets and other objects (such as moons and asteroids) orbiting a star. Our own solar system is likely to have formed in this way, and careful measurements have detected large planets orbiting stars in other parts of the Milky Way. These findings imply that billions of planets are orbiting the many billions of stars in our galaxy.

Astrophysicists and geologists have developed a variety of ways to measure the ages of the universe, our galaxy, the solar system, and the Earth. By measuring

A dark disk of dust and gas bisects a glowing star in this photograph from the Hubble Space Telescope. Such disks appear to provide the raw materials for the formation of planetesimals that combine to form planets and other orbiting bodies.



the distances between galaxies and the speeds with which they are separating, astronomers can calculate how much time has passed since the Big Bang. Increasingly accurate ways of measuring these quantities indicate that the universe is approximately 14 billion years old. Another way to estimate the universe's age, using measurements of the background radiation left behind by the Big Bang, produces similar results. Other observations and calculations suggest that our galaxy began to form a few hundred million years after the Big Bang, so the Milky Way is almost as old as the universe itself.

Our solar system formed within the Milky Way more recently. Measurements of radioactive elements in meteorites, which are the remnants of the materials that formed the solar system, indicate that our planet formed between 4.5 billion and 4.6 billion years ago. Asteroids and comets bombarded Earth after it formed, repeatedly melting the surface. Recent calculations show that one of

Radiometric Dating

According to modern cosmology, the particles that constitute ordinary matter (protons, neutrons, and electrons) formed when the universe cooled after the Big Bang. These particles then came together to form hydrogen atoms, helium atoms, and small amounts of the next heavier element in the periodic table, lithium.

All the other elements in the universe were formed inside stars like the Sun and inside exploding stars known as supernovas. Through the addition of neutrons to lighter elements, nuclear reactions produced heavier elements. Supernovas dispersed these elements into interstellar space. Mixed with the hydrogen, helium, and lithium from the Big Bang, these elements formed our solar system.

Some atoms are radioactive, meaning that they naturally decay into other radioactive and nonradioactive atoms by emitting subatomic particles and energy. Each radioactive **nuclide** has a characteristic half-life, which is the amount of time it takes for half of the atoms in a sample to decay. Radioactive atoms therefore act as internal clocks for materials. By comparing the amount of a radioactive element in a material to the amount of its decay product, researchers can determine when the material formed. These measurements have yielded ages for the Earth, the Moon, meteorites, and the solar system. All of these measurements indicate that these objects are billions of years old.

Some who oppose the teaching of evolution try to cast doubt on radiometric age measurements. Radiometric dating is the product of more than a century of ingenious research and represents one of the most well-substantiated achievements of modern science.

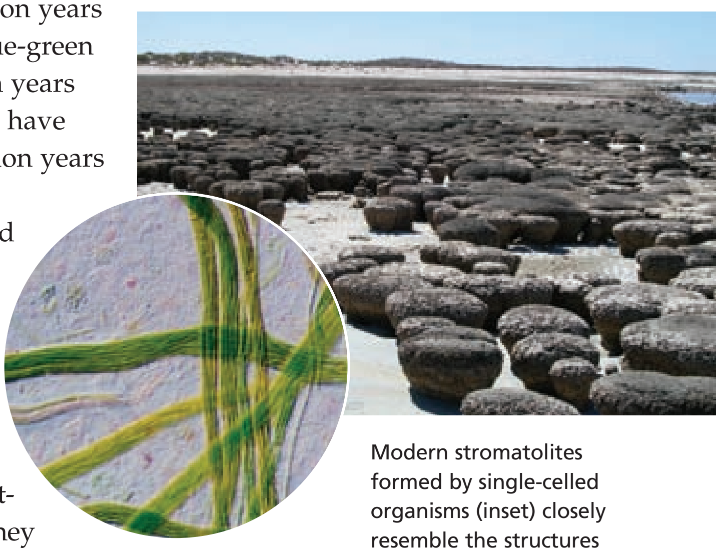
[**Nuclide:** *An atom with a particular number of protons and neutrons in its nucleus. An element is defined by the number of protons in its nucleus. Nuclides that have the same number of protons but different numbers of neutrons are isotopes of that element.*]

the objects to hit Earth was so large — about the size of Mars — that it splashed material into Earth's orbit that coalesced to form the Moon. The oldest rocks brought back from the Moon have ages measured to be 4.4 billion to 4.5 billion years. The oldest solid materials found on Earth are zircon crystals that formed 4.4 billion years ago. Rocks older than 3.5 billion years have been found on all the Earth's continents.

Living things appeared in the first billion years of Earth's history.

Evidence from the most ancient fossils reveals that life has existed on Earth for most of our planet's history. Paleontologists working in Western Australia have discovered layered rocks known as stromatolites that appear to have resulted from the actions of bacteria at least 3.4 billion years ago, and fossils of cyanobacteria (also known as blue-green algae) have been determined to be nearly 3.5 billion years old. Other chemical evidence suggests that life may have originated much earlier, within a few hundred million years of when Earth's surface finally cooled.

Figuring out how life began is both an exciting and a challenging scientific problem. No fossil evidence of life forms older than 3.5 billion years has yet been found. Re-creating conditions that led to those earliest organisms is difficult because much remains unknown about the chemical and physical characteristics of the early Earth. Nevertheless, researchers have been developing hypotheses of how self-replicating organisms could form and begin to evolve, and they have tested the plausibility of these hypotheses in laboratories. While none of these hypotheses has yet achieved consensus, some progress has been made on these fundamental questions.



Modern stromatolites formed by single-celled organisms (inset) closely resemble the structures formed by some of Earth's earliest living things.

Since the 1950s hundreds of laboratory experiments have shown that Earth's simplest chemical compounds, including water and volcanic gases, could have reacted to form many of the molecular building blocks of life, including the molecules that make up proteins, DNA, and cell membranes. Meteorites from outer space also contain some of these chemical building blocks, and astronomers using radio telescopes have found many of these molecules in interstellar space.

For life to begin, three conditions had to be met. First, groups of molecules that could reproduce themselves had to come together. Second, copies of these molecular assemblages had to exhibit variation, so that some were better able to take advantage of resources and withstand challenges in the environment. Third, the variations had to be heritable, so that some variants would increase in number under favorable environmental conditions.

No one yet knows which combination of molecules first met these conditions, but researchers have shown how this process might have worked by studying a molecule known as **RNA.** Researchers recently discovered that some RNA molecules can greatly increase the rate of specific chemical reactions, including the replication of parts of other RNA molecules. If a molecule like RNA could reproduce itself (perhaps with the assistance of other molecules), it could form the basis for a very simple living organism. If such self-replicators were packaged within chemical vesicles or membranes, they might have formed "protocells"— early versions of very simple cells. Changes in these molecules could lead to variants that, for example, replicated more efficiently in a particular environment. In this way, natural selection would begin to operate, creating opportunities for protocells that had advantageous molecular innovations to increase in complexity.

[**RNA:** *Ribonucleic acid. A molecule related to DNA that consists of nucleotide subunits strung together in chains. RNA serves a number of cellular functions, including providing a template for the synthesis of proteins and catalyzing certain biochemical reactions.*]

Constructing a plausible hypothesis of life's origins will require that many questions be answered. Scientists who study the origin of life do not yet know which sets of chemicals could have begun replicating themselves. Even if a living cell could be made in the laboratory from simpler chemicals, it would not prove that nature followed the same pathway billions of years ago on the early Earth. But the principles underlying life's chemical origins, as well as plausible chemical details of the process, are subject to scientific investigation in the same ways that all other natural phenomena are. The history of science shows that even very difficult questions such as how life originated may become amenable to solution as a result of advances in theory, the development of new instrumentation, and the discovery of new facts.

The fossil record provides extensive evidence documenting the occurrence of evolution.

Early in the 19th century, naturalists observed that fossils occur in a particular order in layers of **sedimentary** rock. Older materials are deposited more deeply and thus lie closer to the bottom of sedimentary rock than more recently deposited sediments, although older rocks can sometimes lie above younger rocks where large upheavals in the Earth's crust have taken place.

[**Sedimentary:** *Rocks formed of particles deposited by water, wind, or ice.*]

Fossils that closely resemble contemporary organisms appear in relatively young sediments, while fossils that only distantly resemble contemporary organisms occur in older sediments. Based on these observations, many naturalists, including Charles Darwin's grandfather, proposed that organisms had changed over time. But Darwin and Alfred Russel Wallace were the first to identify natural selection as the driving force behind evolution, or what Darwin termed "descent with modification."

When Darwin published *On the Origin of Species* in 1859, paleontology was still a rudimentary science. Sedimentary rocks from many time periods were unknown or had been inadequately studied. Darwin spent almost 20 years gathering evidence that supported his idea before making it public, but he also carefully considered evidential problems for his view, such as the inadequacy of the fossil record and the rarity of intermediate forms between some major groups of organisms at that time.

A near complete skeleton of a transitional bird-like fossil that was discovered in China and reported in 2006.

In the century and a half since then, paleontologists have found many intermediate forms that were not known in Darwin's time. In a variety of locations, sedimentary rocks that are between 540 million and 635 million years old contain traces of soft-bodied multicellular organisms, and fossilized tracks in earlier sediments hint at the existence of wormlike creatures as long ago as 1 billion years. Some of these organisms are likely to be the intermediate forms between the single-celled organisms that were Earth's sole inhabitants for the first 2 or more billion years of life's history and the hard-bodied organisms that appear in abundance in the fossil record beginning about 540 million years ago. Similarly, many of the organisms that appeared during this period were transitional forms between earlier soft-bodied organisms and major evolutionary lineages such as the fishes, arthropods, and mollusks that have survived to the present day.

As described at the beginning of this document, *Tiktaalik* is a notable transitional form between fish and the early tetrapods that lived on land. Fossils from about 330 million years ago document the evolution of large amphibians from the early tetrapods. Well-preserved skeletons from rocks that are 230 million years old show dinosaurs evolving from a lineage of reptiles. A long-standing example of a transitional form is *Archaeopteryx,* a 155-million-year-old fossil that has the skeleton of a small dinosaur but also feathers and wings. More birdlike fossils from China that are about 110 million years old have smaller tails and clawed appendages. In the more recent fossil record, the evolutionary paths of many modern organisms, such as whales, elephants, armadillos, horses, and humans, have been uncovered.

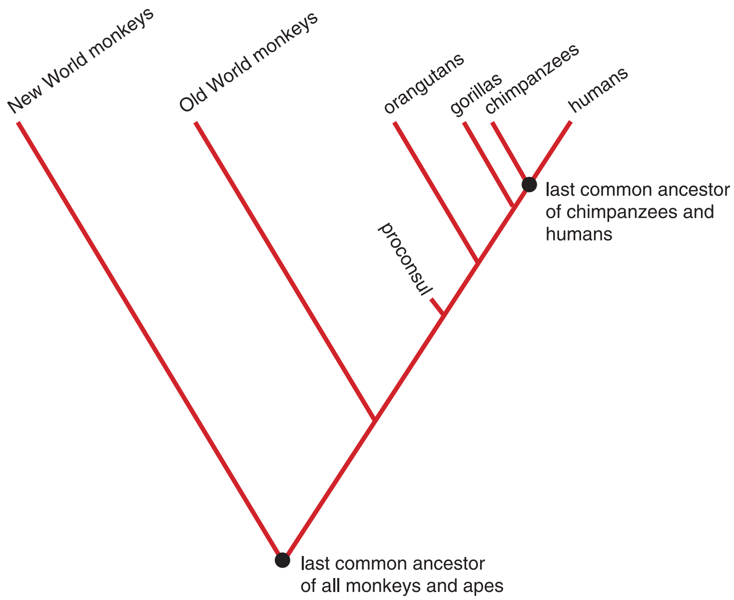
Common structures and behaviors often demonstrate that species have evolved from common ancestors.

Each species that lives on Earth today is the product of an evolutionary lineage — that is, it arose from a preexisting species, which itself arose from a preexisting species, and so on back through time. For any two species living today, their evolutionary lineages can be traced back in time until the two lineages intersect. At that intersection is the species that was the most recent common ancestral species of the two modern species. (Sometimes, this common ancestral species is referred to as the common ancestor, but this term refers to a group of organisms rather than to a single ancestor.) For example, the common ancestor of humans and chimpanzees was a species estimated to have lived 6 to 7 million years ago, whereas the common ancestor of humans and the puffer fish was an ancient fish that lived in the Earth's oceans more than 400 million years ago. *Thus, humans are not descended from chimpanzees or from any other ape living today but from a species that no longer exists.* Nor are humans descended from the species of fish that live today but, rather, from the species of fish that gave rise to the early tetrapods.

Modern chimpanzees, other great apes, and humans are descended from a common ancestor that is now extinct.

If the common ancestor of two species lived relatively recently, those two species are likely to have more physical features and behaviors in common than two species with a more distant common ancestor. Humans are thus far more similar to chimps than they are to fish. Nevertheless, all organisms share some common traits because they all share common ancestors at some point in the past. For example, based on accumulating fossil and molecular evidence, the common ancestor of humans, cows, whales, and bats was likely a small mammal that lived about 100 million years ago. The descendants of that common ancestor have undergone major changes, but their skeletons remain strikingly similar. A person writes, a cow walks, a whale swims, and a bat flies with structures built of bones that are different in detail but similar in general structure and relation to each other.

Evolutionary biologists call similar structures that derive from common ancestry "homologies." Comparative anatomists investigate such homologies, not only in bone structure but also in other parts of the body, and work out

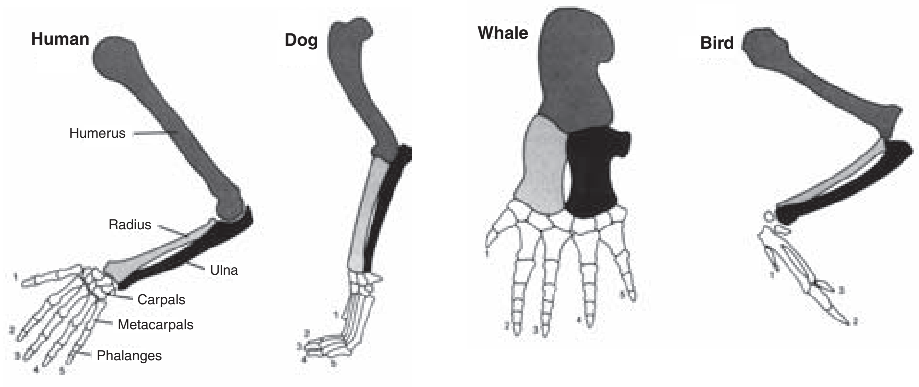


The last common ancestor of all monkeys and apes lived about 40 million years ago. Proconsul was a species that lived about 17 million years ago. The most recent species ancestral to both humans and chimpanzees lived 6 to 7 million years ago.

evolutionary relationships from degrees of similarity. Using the same logic, other biologists examine similarities in the functions of different organs, in the development of embryos, or in behaviors among different kinds of organisms. These investigations provide evidence about the evolutionary pathways that connect today's organisms to their common ancestors. Hypotheses based on this evidence then can be tested by examining the fossil record.

Sometimes, separate lineages independently evolve similar features, known as "analogous" structures, which look like homologies but result from common environments rather than common ancestry. For example, dolphins are aquatic mammals that have evolved from terrestrial mammals over the past 50 million

Though dolphins (left) are more closely related to humans than they are to sharks (right), they have evolved bodies adapted to an aquatic environment. This is an example of analogous structures.



The bones in the forelimbs of terrestrial and some aquatic vertebrates are remarkably similar because they have all evolved from the forelimbs of a common ancestor. This is an example of homologous structures.

years. In evolutionary terms, dolphins are as distant from fish as are mice or humans. But they have evolved streamlined bodies that closely resemble the bodies of fish, sharks, and even extinct dinosaurs known as ichthyosaurs. These kinds of evidence from many different fields of biology allow evolutionary biologists to discern whether physical and behavioral similarities are the product of common descent or are independent responses to similar environmental challenges.

Evolution accounts for the geographic distribution of many plants and animals.

The diversity of life is almost unimaginable. Many millions of species live on, in, and above the Earth, each occupying its own ecological setting or niche. Some species, such as humans, dogs, and rats, can live in a wide range of environments. Others are extremely specialized. One species of a fungus grows exclusively on the rear portion of the covering on the wings of a single species of beetle that is found only in some caves in southern France. The larvae of the fly *Drosophila carcinophila* can develop only in specialized grooves beneath the flaps of the third pair of oral appendages of a land crab that is found solely on certain islands in the Caribbean.

The occurrence of biological evolution both explains this diversity and accounts for its distribution. Consider,

The volcanic birth of the Hawaiian Islands in the Pacific Ocean over 2,000 miles from the nearest continent allowed one or a small number of windblown drosophilid flies such as the example pictured to evolve into more than 500 species in the islands' specialized environments. This rampant speciation was made possible in part because many of the environments in which they evolved were largely free of insect competitors and predators.

for example, the drosophilid flies of the Hawaiian Islands. More than 500 species of flies belonging to the genera *Drosophila* and the closely related *Scaptomyza* exist only in Hawaii. These Hawaiian species comprise about a quarter of all the species in these genera worldwide, and far more species than are found in a similar-sized area anywhere else on Earth. Why do so many different kinds of flies live exclusively in Hawaii?

The geological and biological history of Hawaii provides an answer. The Hawaiian Islands consist of the tops of mid-ocean volcanoes and have never been connected to any body of land. The islands formed as the Pacific tectonic plate moved over a "hot spot" where upwelling molten rock from the Earth's interior heats the Earth's crust. The newest islands are the tallest, while older islands progressively erode and eventually sink beneath the water. Thus, the oldest landmass in the chain, Kure Atoll, rose from the Pacific about 30 million years ago, while the youngest, the "Big Island" of Hawaii, is only about 500,000 years old and still has considerable ongoing volcanic activity.

All of the native plants and animals of the Hawaiian Islands — that is, those existing on the islands before the arrival of humans 1,200 to 1,600 years ago — are descended from organisms that made their way through the air or the water from the surrounding continents and from distant islands to the initially barren islands. In the case of the Hawaiian drosophilids, several lines of evidence, especially from DNA, indicate that all of the native *Drosophila* and *Scaptomyza* species are descended from a single ancestral species that colonized the islands millions of years ago.

These initial colonizers encountered conditions that were very favorable to rapid **speciation**. Individual species repeatedly served as ancestors for multiple other species as groups of flies occupied habitats with different elevations, precipitation, soils, and plants. In addition, small groups of flies — or in some cases perhaps a single fertilized female — periodically flew or were carried to other islands, where they gave rise to new species. Many new species were able to occupy ecological niches that on the continents already would have been filled by other species. For example, many Hawaiian drosophilids lay eggs in decaying leaves on the ground, an ecological niche that is filled by insects and other organisms on the continents but in the Hawaiian Islands was almost empty.

[**Speciation:** *The evolutionary processes through which new species arise from existing species.*]

The mammals that have lived in North and South America provide another good example of how evolution accounts for the distribution of species. These two continents were connected as part of a much larger landmass during the early evolution of the mammals. But the breakup of that landmass caused North and South America to separate, after which their respective mammals evolved in different directions. The mammals that evolved in South America include such modern-day groups as anteaters, sloths, opossums, and armadillos, according to the fossil record. In North America, horses, bats, wolves, and

When tectonic forces joined North and South America, mammals that had evolved in South America, such as the armadillo, migrated north.

the saber-toothed cat were among the many species that evolved. Then, about 3 million years ago, North and South America were reconnected as a consequence of the movement of the Earth's tectonic plates. Mammals of South American origin, such as armadillos, porcupines, and opossums, migrated north. Meanwhile, many kinds of North American mammals, including deer, raccoons, mountain lions, bears, and dogs, eventually made their way across the isthmus to the south.

Molecular biology has confirmed and extended the conclusions about evolution drawn from other forms of evidence.

Charles Darwin and other 19th-century biologists arrived at their conclusions despite knowing almost nothing about the molecular basis of life. Since then, the ability to examine biological molecules in detail has provided an entirely new form of evidence about the mechanisms and historical pathways of evolution. This new evidence has fully confirmed the general conclusions drawn from the fossil record, the geographic distribution of species, and other types of observations. In addition, it has provided a wealth of new information about the evolutionary relationships among species and about how evolution occurs.

DNA is passed from one generation to the next directly from a parent to its offspring (in asexually reproducing organisms) or through the union of DNA-containing sperm and egg cells (in sexually reproducing organisms). As discussed earlier, the sequence of nucleotides in DNA can change from one generation to the next because of mutations; if these changes give rise to beneficial traits, the new DNA sequences are likely to spread within a population

The Picture-Winged Drosophilids

The drosophilid flies of Hawaii provide an excellent example of "adaptive radiation," in which an ancestral species gives rise to a very large number of new species in a relatively short time. Evolutionary biologists have focused particular attention on a group of about 100 drosophilid species that have characteristic pigmented markings on their large wings. Known as the picture-winged drosophilids, these species carry within them a remarkable biological record of the group's evolutionary history.

[**Chromosome:** *A double stranded DNA molecule that contains a series of specific genes along its length. In most sexually reproducing organisms, chromosomes occur in pairs, with one member of the pair being inherited from each parent.*]

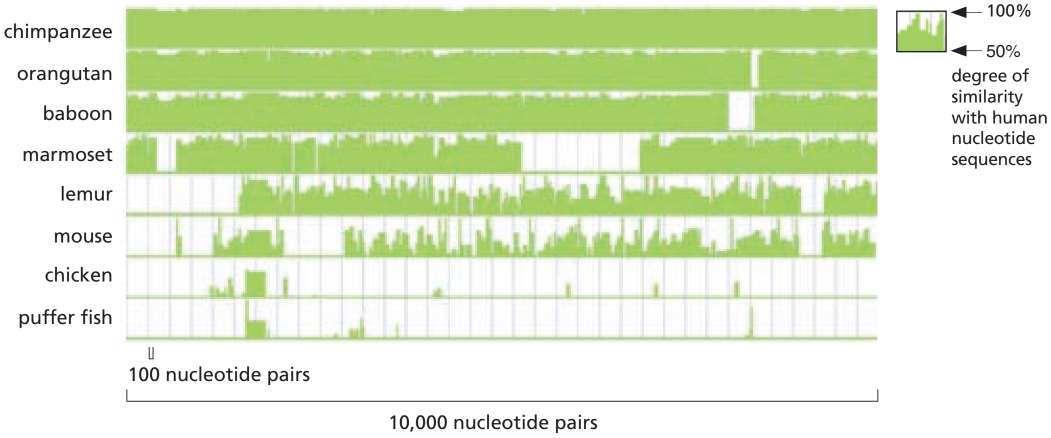
Cells in the salivary glands of all *Drosophila* larvae contain special chromosomal structures known as polytene chromosomes. Easily visible through a microscope, these polytene chromosomes display hundreds of alternating dark and light bands of different sizes. These banding patterns make it especially easy to detect a kind of chromosomal rearrangement known as an inversion. Sometimes, a mistake during the duplication of DNA can cause a segment of the chromosome to be flipped. The result is a rearranged chromosome in which a section of the chromosome, with its characteristic light and dark bands, has a reversed orientation. Many inversions of this type have occurred in different segments of chromosomes in different species of flies.

As individual species of drosophilids on the Hawaiian islands have diversified to form multiple species, researchers have used the resulting changes in banding patterns to reconstruct the sequence in which existing species of drosophilids moved from older islands to newer islands and gave rise to new species. For example, the "Big Island" of Hawaii, which is the youngest in the island chain, currently has 26 species of picture-winged drosophilids. By examining the specific chromosome inversions in these colonizing species and comparing them with species that live on islands that are older, researchers have determined that flies on the Big Island have all originated from 19 separate colonizations of the island by a small group of flies (or perhaps single fertilized female flies) from one of the older islands.

Photograph of a polytene chromosome from a Drosophila *larva shows two breakpoints (indicated by solid bars) where a portion of the chromosome is inverted compared to the same chromosome in other species.*

over multiple generations. In addition, neutral mutations that have no effect on the traits of an organism can be maintained within a population as DNA passes between generations. As a result, DNA contains a record of past genetic changes, including the changes responsible for evolutionary adaptations.

By comparing the DNA sequences of two organisms, biologists can uncover the genetic changes that have occurred since those organisms shared a common ancestor. If two species have a relatively recent common ancestor, their DNA sequences will be more similar than the DNA sequences for two species that share a distant common ancestor. For example, the DNA sequences of humans, which vary to a small degree among individuals and populations



The gene that, when mutated, causes cystic fibrosis in humans is very similar to the corresponding gene in chimpanzees but is less similar to the corresponding gene in organisms that are less closely related to humans. The height of the green bars shows the similarity of the gene in other organisms to the human gene over a span of 10,000 nucleotides.

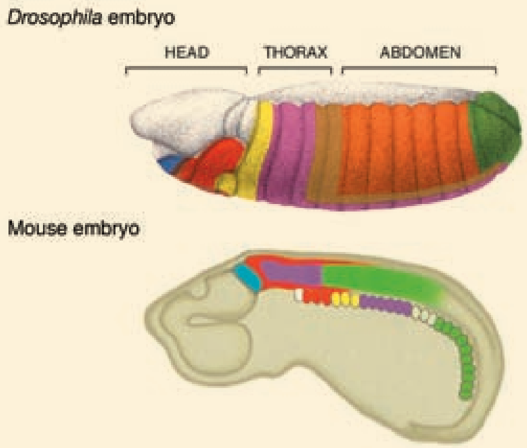
of people, on average differ by just a few percent from those of chimpanzees, reflecting our relatively recent common ancestry. But human DNA sequences are increasingly different from those of the baboon, mouse, chicken, and puffer fish, reflecting our increasing evolutionary distance from each of those organisms. Even greater differences in DNA sequences are found when comparing humans to flies, worms, and plants. Yet similarities in DNA sequences can be seen across all living forms, despite the amount of time that has elapsed since

The Evolution of Limbs in Early Tetrapods

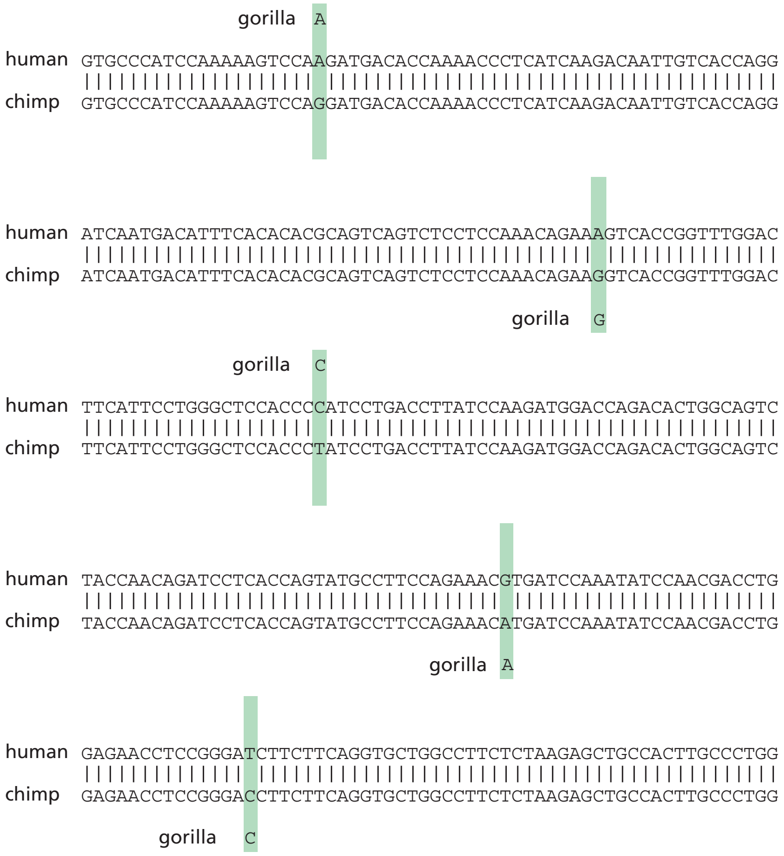
Molecular biologists have been discovering DNA regions that control the formation of body parts during development. Some of the most important of these DNA regions are known as *Hox* genes.

Humans and all other mammals have 39 *Hox* genes. Individual *Hox* genes control the function of other types of genes, and the same *Hox* gene can control different sets of genes in different parts of the body.

Hox genes are also involved in the development of many different anatomical features, including limbs, the spine, the digestive system, and the reproductive tract in diverse species of both invertebrate and vertebrate animals. For example, as illustrated in the figure (right side of page), the same *Hox* genes that control the development of body parts in the fruit fly *Drosophila* also control the development of body parts in mice and other mammals. Colors indicate the activity of the same *Hox* gene in both kinds of organisms.



Hox genes also direct the formation of fins in fish and limbs in land-dwelling vertebrates. They are expressed in different patterns in limbed animals, resulting in the formation of fingers and toes. Changes in the expression of these genes were likely involved in the evolution of the early tetrapods, such as *Tiktaalik.*



Comparison of the human and chimp DNA sequences for the gene that encodes the hormone leptin (which is involved in the metabolism of fats) reveals only five differences in 250 nucleotides. Where the human and chimpanzee sequences differ, the corresponding nucleotide in the gorilla (shaded bars) can be used to derive the nucleotide that likely existed in the common ancestor of humans, chimpanzees, and gorillas. In two cases, the gorilla and human nucleotides match, while in the other three cases, the gorilla and chimpanzee sequences are the same. The common ancestor of the gorilla, chimpanzee, and human is most likely to have had the nucleotide that is the same in two of the three modern-day organisms because this would require just one DNA change rather than two.

they had common ancestors. Even humans and bacteria share some similarity in DNA sequences in certain genes, and these similarities correspond to molecular systems with similar functions. Biological evolution thus explains why other organisms can be studied to understand biological processes critical to human life. Indeed, much of the biomedical research carried out today is based on the biological commonalities of all living things.

The study of biological molecules has done more than document the evolutionary relationships among organisms. It also can reveal how genetic changes produce new traits in organisms over the course of evolutionary history. For example, molecular biologists have been examining the function of regulatory proteins that cause other genes in a cell to turn on and off as an organism develops from a fertilized egg. Small changes in these proteins, in the DNA regions to which these proteins attach, or even, as recently discovered, in small RNA molecules can have dramatic effects on the anatomy and function of an organism. Such changes could be responsible for some of the major evolutionary innovations that have occurred over time, such as the development of limbs from fins in early tetrapods. Moreover, biologists have discovered that very similar sets of regulatory proteins occur in organisms as different as flies, mice, and humans, despite the many millions of years that separate these organisms from their common ancestors. The DNA evidence suggests that the basic mechanisms controlling biological form became established before or during the evolution of multicellular organisms and have been conserved with little modification ever since.

Biological evolution explains the origin and history of our species.

Study of all the forms of evidence discussed earlier in this booklet has led to the conclusion that humans evolved from ancestral primates. In the 19th century, the idea that humans and apes had common ancestors was a novel one, and it was hotly debated among scientists in Darwin's time and for years after.

The Evolution of Whales, Dolphins, and Porpoises

Fossils of Dorudon, *found in Egypt and dating to approximately 40 million years ago, document a critical transition in the evolution of modern whales. Because it had evolved from a mammal that lived on land,* Dorudon *still had vestigial traces of hind limbs, feet, and toes (the small bones at the base of the tail), even though it lived in the water and used its long powerful tail to swim.*

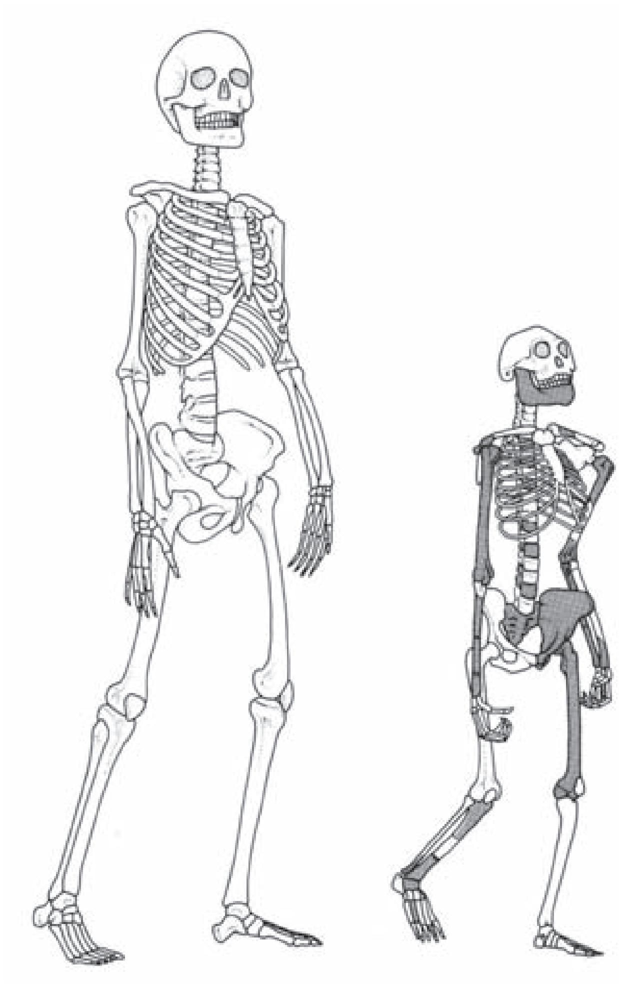
The combination of fossil and molecular evidence enables biologists to construct much more detailed evolutionary histories than have been possible in the past. For example, recent fossil discoveries in Asia have revealed a succession of organisms that, beginning about 50 million years ago, moved from life on land first to hunt and then to live continuously in marine environments. This fossil evidence accords with recent genetic findings that whales, dolphins, and porpoises are descended from a group of terrestrial mammals known as artiodactyls, which today includes such animals as sheep, goats, and giraffes. Most recently, studies of regulatory networks in the DNA of modern porpoises have revealed the molecular changes that caused the ancestors of these organisms to lose their hind limbs and develop more streamlined bodies. All of these forms of evidence support each other and add fascinating details to the understanding of evolution.

More than 3.5 million years ago, two hominids walked upright across a field of newly fallen volcanic ash in eastern Africa. The footprints were covered by a subsequent ashfall until 1978, when they were unearthed by paleontologists. The Laetoli footprints, named after the site where they were found, are very early evidence of upright walking, a key acquisition in the lineage leading to humans.

But today there is no scientific doubt about the close evolutionary relationships between humans and all other primates. Using the same scientific methods and tools that have been employed to study the evolution of other species, researchers have compiled a large and increasing number of fossil discoveries and compelling new molecular evidence that clearly indicate that the same forces responsible for the evolution of all other life forms on Earth account for the biological evolution of human characteristics.

Based on the strength of evidence from DNA comparisons, the common ancestor of humans and chimpanzees lived approximately 6 to 7 million years ago in Africa. The evolutionary tree leading from this ancestral species to modern humans contains a number of side branches, representing populations and species that eventually went extinct. At various times in the past, the planet appears to have been populated by several human-like species.

About 4.1 million years ago, a species appeared in Africa that paleontologists place in the genus *Australopithecus,* which means “southern ape.” (A member of the genus was first discovered in southern Africa, although other fossils, including an almost complete skeleton of a 3-year-old female, have been found in eastern Africa.) The brain of an adult of this genus was about the same size as that of modern apes (as documented by the size of fossil

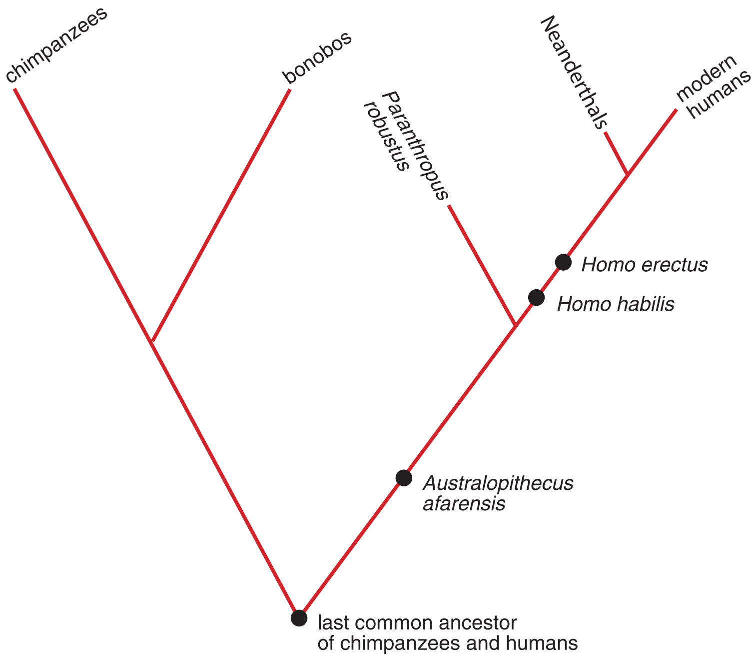


In the drawing at right, the skeleton of Lucy, exemplar of an adult member of the species *Australopithecus afarensis* (with shaded bones representing those that were recovered), dates from the same geological period when the Laetoli footprints were made. For comparison, the skeleton of a modern human stands beside her.

skulls), and it appears to have spent part of its life climbing in trees, as indicated by its short legs and features of its upper limbs. But *Australopithecus* also walked upright, as humans do. Footprints left by one of the earliest *Australopithecus* species have been discovered preserved with remarkable clarity in hardened volcanic ash.

About 2.3 million years ago, the earliest species of *Homo*, the genus to which all modern humans belong, evolved in Africa. This species is known as *Homo habilis* ("handy" or "skillful man"). Its average brain size, as determined from skulls that postdate 2 million years ago, was probably about 50 percent larger than that of earlier *Australopithecus*. The earliest stone tools appear about 2.6 million years ago.

About 1.8 million years ago, a more evolved species, *Homo erectus* ("upright man") appeared. This species spread from Africa to Eurasia. The subsequent fossil record includes the skeletal remains of additional species within the genus *Homo*. The more recent species generally had larger brains than the earlier ones.



A number of species, of which only *Australopithecus afarensis*, *Homo habilis*, and *Homo erectus* are shown here, are thought to represent evolutionary links between modern humans and the more ancient species that was the common ancestor of chimpanzees, bonobos (a close relative of chimpanzees), and modern humans. Other closely related species on the human side of the family tree are known from the fossil record. *Paranthropus robustus* and Neanderthals are extinct evolutionary lineages now represented only by fossils.

Evidence shows that anatomically modern humans (*Homo sapiens* —“wise” or “knowing man”) with bodies and brains like ours, evolved in Africa from earlier forms of humans. The earliest known fossil of a modern human is less than 200,000 years old. The members of this group dispersed throughout Africa and, more recently, into Asia, Australia, Europe, and the Americas, replacing earlier populations of humans then living in some parts of the world. ■