Science and Creationism

A View from the National Academy of Sciences

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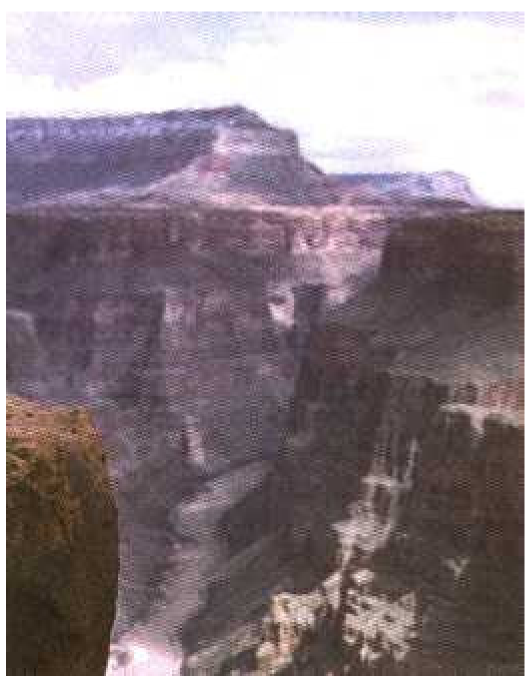


Preface

In his preface to the original 1984 version of this document, Frank Press, my predecessor as president of the National Academy of Sciences, called attention to a pair of illustrations similar to the ones on the front and back of this booklet. The first is a photograph of Earth from space—the one on this booklet was taken by the GOES 7 satellite in 1992 as it passed over Earth and captured in graphic detail Hurricane Andrew. The second shows a map of the world prepared during the 7th century by the scholar Isidore of Seville. As Press pointed out, both illustrations reflect the efforts of humans to understand the natural world. "How then," he wrote, "can the two views be so different? The answer lies at the very heart of the nature of this system of study we call science."

Since those words were written, the mapping of Earth has provided further powerful examples of how science and science-based technologies progress. Beginning in the early 1990s, a network of satellites has allowed anyone with a hand-held receiver to know his or her position on Earth to within a few feet. This Global Positioning System* (GPS) now is being used to locate vessels lost at sea, study plate tectonics, trace open routes through crowded city streets, and survey Earth's surface. Yet the technology originated with a purely scientific objective—the desire to build extremely accurate clocks to test Einstein's theory of relativity.

The tremendous success of science in explaining natural phenomena and fostering technological innovation arises from its focus on explanations that can be inferred from confirmable data. Scientists seek to relate one natural phenomenon to another and to recognize the causes and effects of phenomena. In this way, they have developed explanations for the changing of the seasons, the movements of the sun and stars, the structure of matter, the shaping of mountains and valleys, the changes in the positions of continents over time, the history of life on Earth, and many other natural occurrences. By the same means, scientists have also deciphered which substances in our environment are harmful to humans and which are not, developed cures for diseases, and generated the knowledge needed to produce innumerable labor-saving devices.

The concept of biological evolution is one of the most important ideas ever generated by the application of scientific methods to the natural world. The evolution of all the organisms that live on Earth today from ancestors that lived in the past is at the core of genetics, biochemistry, neurobiology, physiology, ecology, and other biological disciplines. It helps to explain the emergence of new infectious diseases, the development of antibiotic resistance in bacteria, the agricultural relationships among wild and domestic plants and animals, the composition of Earth's atmosphere, the molecular machinery of the cell, the similarities between human beings and other primates, and countless other features of the biological and physical world. As the great geneticist and evolutionist Theodosius Dobzhansky wrote in 1973, "Nothing in biology makes sense except in the light of evolution."

Nevertheless, the teaching of evolution in our schools remains controversial. Some object to it on the grounds that evolution contradicts the accounts of origins given in the first two chapters of Genesis. Some wish to see "creation science"—which posits that scientific evidence exists to prove that the universe and living things were specially created in their present form—taught together with evolution as two alternative scientific theories.

Scientists have considered the hypotheses proposed by creation science and have rejected them because of a lack of evidence. Furthermore, the claims of creation science do not refer to natural causes and cannot be subject to meaningful tests, so they do not qualify as scientific hypotheses. In 1987 the U.S. Supreme Court ruled that creationism is religion, not science, and cannot be advocated in public school classrooms. And most major religious groups have concluded that the concept of evolution is not at odds with their descriptions of creation and human origins.

This new edition of *Science and Creationism: A View from the National Academy of Sciences* is a companion volume to a publication released in 1998 by the Academy, *Teaching About Evolution and the Nature of Science*. That longer document is addressed to the teachers, educators, and policymakers who design, deliver, and oversee classroom instruction in biology. It summarizes the overwhelming observational evidence for evolution and explains how science differs from other human endeavors. It also suggests effective ways of teaching the subject and offers sample teaching exercises, curriculum guides, and "dialogues" among fictional teachers discussing the difficulties of presenting evolution in the classroom.

This new edition of *Science and Creationism* has a somewhat different purpose. It, too, summarizes key aspects of several of the most important lines of the evidence supporting evolution. But it also describes some of the positions taken by advocates of creation science and presents an analysis of these claims. As such, this document lays out for a broader audience the case against presenting religious concepts in science classes. Both this document, and the earlier *Teaching About Evolution and the Nature of Science,* are freely available online at the Academy website (www.nap.edu).

Scientists, like many others, are touched with awe at the order and complexity of nature. Indeed, many scientists are deeply religious. But science and religion occupy two separate realms of human experience. Demanding that they be combined detracts from the glory of each.

Bruce Alberts

President

National Academy of Sciences

Introduction

Science is a particular way of knowing about the world. In science, explanations are limited to those based on observations and experiments that can be substantiated by other scientists. Explanations that cannot be based on empirical evidence are not a part of science.

In the quest for understanding, science involves a great deal of careful observation that eventually produces an elaborate written description of the natural world. Scientists communicate their findings and conclusions to other scientists through publications, talks at conferences, hallway conversations, and many other means. Other scientists then test those ideas and build on preexisting work. In this way, the accuracy and sophistication of descriptions of the natural world tend to increase with time, as subsequent generations of scientists correct and extend the work done by their predecessors.

Progress in science consists of the development of better explanations for the causes of natural phenomena. Scientists never can be sure that a given explanation is complete and final. Some of the hypotheses advanced by scientists turn out to be incorrect when tested by further observations or experiments. Yet many scientific explanations have been so thoroughly tested and confirmed that they are held with great confidence.

The theory of evolution is one of these well-established explanations. An enormous amount of scientific investigation since the mid-19th century has converted early ideas about evolution proposed by Darwin and others into a strong and well-supported theory. Today, evolution is an extremely active field of research, with an abundance of new discoveries that are continually increasing our understanding of how evolution occurs.

This booklet considers the science that supports the theory of evolution, focusing on three categories of scientific evidence:

- Evidence for the origins of the universe, Earth, and life
- Evidence for biological evolution, including findings from paleontology, comparative anatomy, biogeography, embryology, and molecular biology
- Evidence for human evolution

At the end of each of these sections, the positions held by advocates of "creation science" are briefly presented and analyzed as well.

The theory of evolution has become the central unifying concept of biology and is a critical component of many related scientific disciplines. In contrast, the claims of creation science lack empirical support and cannot be meaningfully tested. These observations lead to two fundamental conclusions: the teaching of evolution should be an integral part of science instruction, and creation science is in fact not science and should not be presented as such in science classes.

Terms Used in Describing the Nature of Science

Fact: In science, an observation that has been repeatedly confirmed and for all practical purposes is accepted as "true." Truth in science, however, is never final, and what is accepted as a fact today may be modified or even discarded tomorrow.

Hypothesis: A tentative statement about the natural world leading to deductions that can be tested. If the deductions are verified, it becomes more probable that the hypothesis is correct. If the deductions are incorrect, the original hypothesis can be abandoned or modified. Hypotheses can be used to build more complex inferences and explanations.

Law: A descriptive generalization about how some aspect of the natural world behaves under stated circumstances.

Theory: In science, a well-substantiated explanation of some aspect of the natural world that can incorporate facts, laws, inferences, and tested hypotheses.

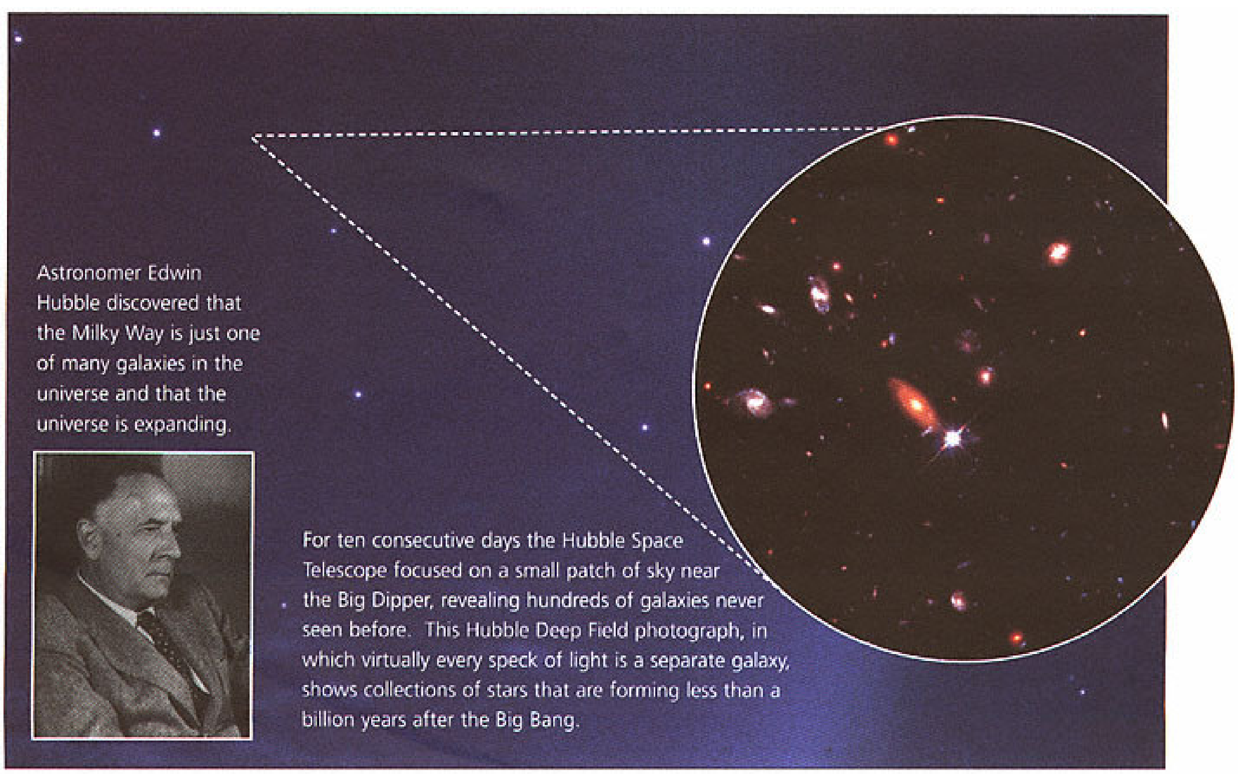
The contention that evolution should be taught as a "theory, not as a fact" confuses the common use of these words with the scientific use. In science, theories do not turn into facts through the accumulation of evidence. Rather, theories are the end points of science. They are understandings that develop from extensive observation, experimentation, and creative reflection. They incorporate a large body of scientific facts, laws, tested hypotheses, and logical inferences. In this sense, evolution is one of the strongest and most useful scientific theories we have.

The Origin of the Universe, Earth, and Life

The term "evolution" usually refers to the biological evolution of living things. But the processes by which planets, stars, galaxies, and the universe form and change over time are also types of "evolution." In all of these cases there is change over time, although the processes involved are quite different.

In the late 1920s the American astronomer Edwin Hubble made a very interesting and important discovery. Hubble made observations that he interpreted as showing that distant stars and galaxies are receding from Earth in every direction. Moreover, the velocities of recession increase in proportion with distance, a discovery that has been confirmed by numerous and repeated measurements since Hubble's time. The implication of these findings is that the universe is expanding.

Hubble's hypothesis of an expanding universe leads to certain deductions. One is that the universe was more condensed at a previous time. From this deduction came the suggestion that all the currently observed matter and energy in the universe were initially condensed in a very small and infinitely hot mass. A huge explosion, known as the Big Bang, then sent matter and energy expanding in all directions.

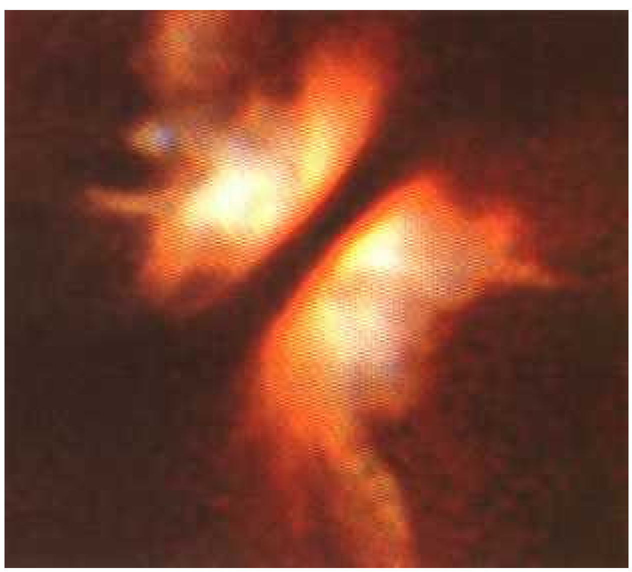


This Big Bang hypothesis led to more testable deductions. One such deduction was that the temperature in deep space today should be several degrees above absolute zero. Observations showed this deduction to be correct. In fact, the Cosmic Microwave Background Explorer (COBE) satellite launched in 1991 confirmed that the background radiation field has exactly the spectrum predicted by a Big Bang origin for the universe.

As the universe expanded, according to current scientific understanding, matter collected into clouds that began to condense and rotate, forming the forerunners of galaxies. Within galaxies, including our own Milky Way galaxy, changes in pressure caused gas and dust to form distinct clouds. In some of these clouds, where there was sufficient mass and the right forces, gravitational attraction caused the cloud to collapse. If the mass of material in the cloud was sufficiently compressed, nuclear reactions began and a star was born.

Some proportion of stars, including our sun, formed in the middle of a flattened spinning disk of material. In the case of our sun, the gas and dust within this disk collided and aggregated into small grains, and the grains formed into larger bodies called planetesimals ("very small planets"), some of which reached diameters of several hundred kilometers. In successive stages these planetesimals coalesced into the nine planets and their numerous satellites. The rocky planets, including Earth, were near the sun, and the gaseous planets were in more distant orbits.

The ages of the universe, our galaxy, the solar system, and Earth can be estimated using modem scientific methods. The age of the universe can be derived from the observed relationship between the velocities of and the distances separating the galaxies. The velocities of distant galaxies can be measured very accurately, but the measurement of distances is more uncertain. Over the past few decades, measurements of the Hubble expansion have led to estimated ages for the universe of between 7 billion and 20 billion years, with the most recent and best measurements within the range of 10 billion to 15 billion years.



A disk of dust and gas, appearing as a dark band in this Hubble Space Telescope photograph, bisects a glowing nebula around a very young star in the constellation Taurus. Similar disks can be seen around other nearby stars and are thought to provide the raw material for planets.

The age of the Milky Way galaxy has been calculated in two ways. One involves studying the observed stages of evolution of different-sized stars in globular clusters. Globular clusters occur in a faint halo surrounding the center of the Galaxy, with each cluster containing from a hundred thousand to a million stars. The very low amounts of elements heavier than hydrogen and helium in these stars indicate that they must have formed early in the history of the Galaxy, before large amounts of heavy elements were created inside the initial generations of stars and later distributed into the interstellar medium through supernova explosions (the Big Bang itself created primarily hydrogen and helium atoms). Estimates of the ages of the stars in globular clusters fall within the range of 11 billion to 16 billion years.

A second method for estimating the age of our galaxy is based on the present abundances of several long-lived radioactive elements in the solar system. Their abundances are set by their rates of production and distribution through exploding

supernovas. According to these calculations, the age of our galaxy is between 9 billion and 16 billion years. Thus, both ways of estimating the age of the Milky Way galaxy agree with each other, and they also are consistent with the independently derived estimate for the age of the universe.

Radioactive elements occurring naturally in rocks and minerals also provide a means of estimating the age of the solar system and Earth. Several of these elements decay with half lives between 700 million and more than 100 billion years (the half life of an element is the time it takes for half of the element to decay radioactively into another element). Using these time-keepers, it is calculated that meteorites, which are fragments of asteroids, formed between 4.53 billion and 4.58 billion years ago (asteroids are small "planetoids" that revolve around the sun and are remnants of the solar nebula that gave rise to the sun and planets). The same radioactive time-keepers applied to the three oldest lunar samples returned to Earth by the Apollo astronauts yield ages between 4.4 billion and 4.5 billion years, providing minimum estimates for the time since the formation of the moon.

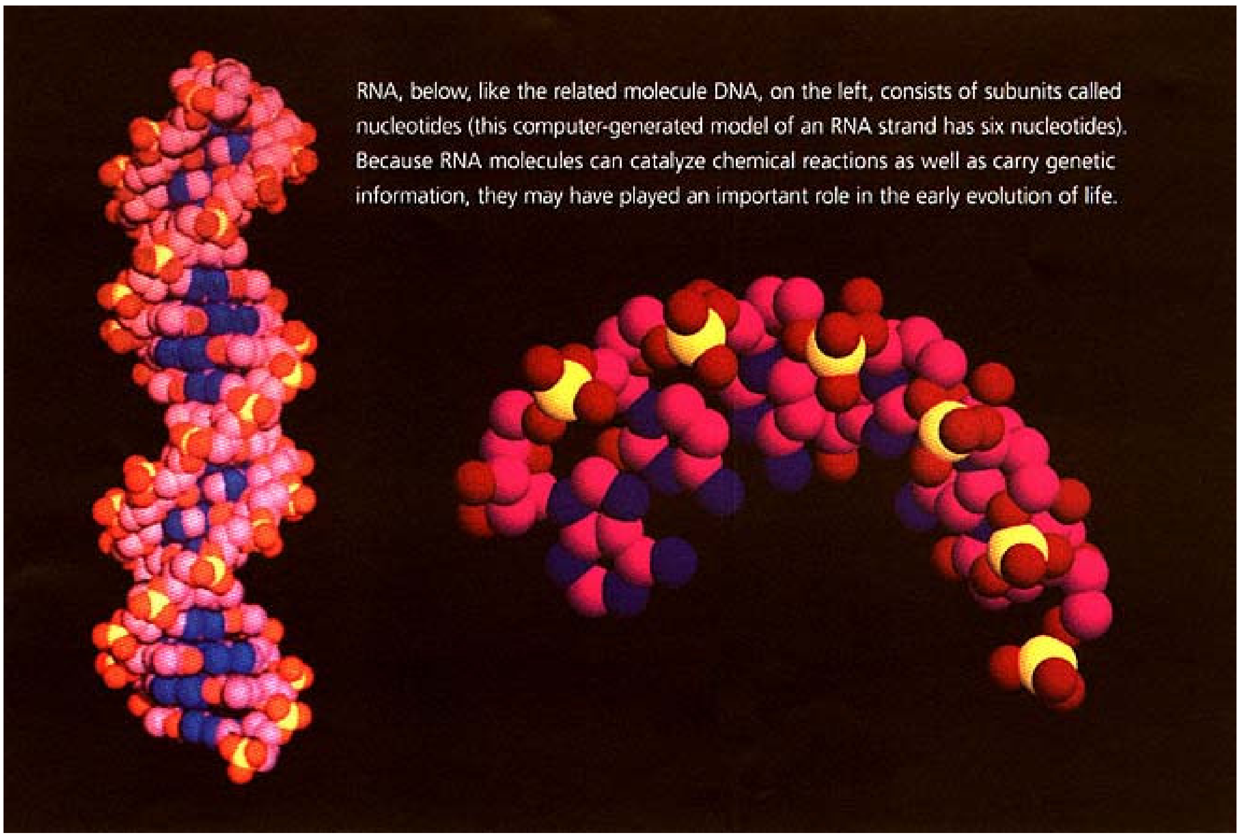
The oldest known rocks on Earth occur in northwestern Canada (3.96 billion years), but well-studied rocks nearly as old are also found in other parts of the world. In Western Australia, zircon crystals encased within younger rocks have ages as old as 4.3 billion years, making these tiny crystals the oldest materials so far found on Earth.

The best estimates of Earth's age are obtained by calculating the time required for development of the observed lead isotopes in Earth's oldest lead ores. These estimates yield 4.54 billion years as the age of Earth and of meteorites, and hence of the solar system.

The origins of life cannot be dated as precisely, but there is evidence that bacteria-like organisms lived on Earth 3.5 billion years ago, and they may have existed even earlier, when the first solid crust formed, almost 4 billion years ago. These early organisms must have been simpler than the organisms living today. Furthermore, before the earliest organisms there must have been structures that one would not call "alive" but that are now components of living things. Today, all living organisms store and transmit hereditary information using two kinds of molecules: DNA and RNA. Each of these molecules is in turn composed of four kinds of subunits known as nucleotides. The sequences of nucleotides in particular lengths of DNA or RNA, known as genes, direct the construction of molecules known as proteins, which in turn catalyze biochemical reactions, provide structural components for organisms, and perform many of the other functions on which life depends. Proteins consist of chains of subunits known as amino acids. The sequence of nucleotides in DNA and RNA therefore determines the sequence of amino acids in proteins; this is a central mechanism in all of biology.

Experiments conducted under conditions intended to resemble those present on primitive Earth have resulted in the production of some of the chemical components of proteins, DNA, and RNA. Some of these molecules also have been detected in meteorites from outer space and in interstellar space by astronomers using radio-telescopes. Scientists have concluded that the "building blocks of life" could have been available early in Earth's history.

An important new research avenue has opened with the discovery that certain molecules made of RNA, called ribozymes, can act as catalysts in modem cells. It previously had been thought that only proteins could serve as the catalysts required to carry out specific biochemical functions. Thus, in the early prebiotic world, RNA molecules could have been "autocatalytic"—that is, they could have replicated themselves well before there were any protein catalysts (called enzymes).


RNA, below, like the related molecule DNA, on the left, consists of subunits called nucleotides (this computer-generated model of an RNA strand has six nucleotides). Because RNA molecules can catalyze chemical reactions as well as carry genetic information, they may have played an important role in the early evolution of life.

Laboratory experiments demonstrate that replicating autocatalytic RNA molecules undergo spontaneous changes and that the variants of RNA molecules with the greatest autocatalytic activity come to prevail in their environments. Some scientists favor the hypothesis that there was an early "RNA world," and they are testing models that lead from RNA to the synthesis of simple DNA and protein molecules. These assemblages of molecules eventually could have become packaged within membranes, thus making up "protocells"—early versions of very simple cells.

For those who are studying the origin of life, the question is no longer whether life could have originated by chemical processes involving nonbiological components. The question instead has become which of many pathways might have been followed to produce the first cells.

Will we ever be able to identify the path of chemical evolution that succeeded in initiating life on Earth? Scientists are designing experiments and speculating about how early Earth could have provided a hospitable site for the segregation of

molecules in units that might have been the first living systems. The recent speculation includes the possibility that the first living cells might have arisen on Mars, seeding Earth via the many meteorites that are known to travel from Mars to our planet.

Of course, even if a living cell were to be made in the laboratory, it would not prove that nature followed the same pathway billions of years ago. But it is the job of science to provide plausible natural explanations for natural phenomena. The study of the origin of life is a very active research area in which important progress is being made, although the consensus among scientists is that none of the current hypotheses has thus far been confirmed. The history of science shows that seemingly intractable problems like this one may become amenable to solution later, as a result of advances in theory, instrumentation, or the discovery of new facts.

Creationist Views of the Origin of the Universe, Earth, and Life

Many religious persons, including many scientists, hold that God created the universe and the various processes driving physical and biological evolution and that these processes then resulted in the creation of galaxies, our solar system, and life on Earth. This belief, which sometimes is termed "theistic evolution," is not in disagreement with scientific explanations of evolution. Indeed, it reflects the remarkable and inspiring character of the physical universe revealed by cosmology, paleontology, molecular biology, and many other scientific disciplines.

The advocates of "creation science" hold a variety of viewpoints. Some claim that Earth and the universe are relatively young, perhaps only 6,000 to 10,000 years old. These individuals often believe that the present physical form of Earth can be explained by "catastrophism," including a worldwide flood, and that all living things (including humans) were created miraculously, essentially in the forms we now find them.

Other advocates of creation science are willing to accept that Earth, the planets, and the stars may have existed for millions of years. But they argue that the various types of organisms, and especially humans, could only have come about with supernatural intervention, because they show "intelligent design."

In this booklet, both these "Young Earth" and "Old Earth" views are referred to as "creationism" or "special creation."

There are no valid scientific data or calculations to substantiate the belief that Earth was created just a few thousand years ago. This document has summarized the vast amount of evidence for the great age of the universe, our galaxy, the solar system, and Earth from astronomy, astrophysics, nuclear physics, geology, geochemistry, and geophysics. Independent scientific methods consistently give an age for Earth and the solar system of about 5 billion years, and an age for our galaxy and the universe that is two to three times greater. These conclusions make the origin of the universe as a whole intelligible, lend coherence to many different branches of science, and form the core conclusions of a remarkable body of knowledge about the origins and behavior of the physical world.

Nor is there any evidence that the entire geological record, with its orderly succession of fossils, is the product of a single universal flood that occurred a few thousand years ago, lasted a little longer than a year, and covered the highest mountains to a depth of several meters. On the contrary, intertidal and terrestrial deposits demonstrate that at no recorded time in the past has the entire planet been under water. Moreover, a universal flood of sufficient magnitude to form the sedimentary rocks seen today, which together are many kilometers thick, would require a volume of water far greater than has ever existed on and in Earth, at least since the formation of the first known solid crust about 4 billion years ago. The belief that Earth's sediments, with their fossils, were deposited in an orderly sequence in a year's time defies all geological observations and physical principles concerning sedimentation rates and possible quantities of suspended solid matter.

Geologists have constructed a detailed history of sediment deposition that links particular bodies of rock in the crust of Earth to particular environments and processes. If petroleum geologists could find more oil and gas by interpreting the record of sedimentary rocks as having resulted from a single flood, they would certainly favor the idea of such a flood, but they do not. Instead, these practical workers agree with academic geologists about the nature of depositional environments and geological time. Petroleum geologists have been pioneers in the recognition of fossil deposits that were formed over millions of years in such environments as meandering rivers, deltas, sandy barrier beaches, and coral reefs.

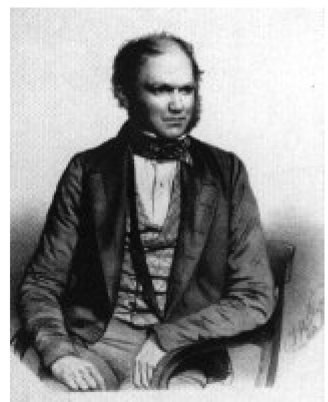
The example of petroleum geology demonstrates one of the great strengths of science. By using knowledge of the natural world to predict the consequences of our actions, science makes it possible to solve problems and create opportunities using technology. The detailed knowledge required to sustain our civilization could only have been derived through scientific investigation.

The arguments of creationists are not driven by evidence that can be observed in the natural world. Special creation or supernatural intervention is not subjectable to meaningful tests, which require predicting plausible results and then checking these results through observation and experimentation. Indeed, claims of "special creation" reverse the scientific process. The explanation is seen as unalterable, and evidence is sought only to support a particular conclusion by whatever means possible.

Evidence Supporting Biological Evolution

Along path leads from the origins of primitive "life," which existed at least 3.5 billion years ago, to the profusion and diversity of life that exists today. This path is best understood as a product of evolution.

Contrary to popular opinion, neither the term nor the idea of biological evolution began with Charles Darwin and his foremost work, *On the Origin of Species by Means of Natural Selection* (1859). Many scholars from the ancient Greek philosophers on had inferred that similar species were descended from a common ancestor. The word "evolution" first appeared in the English language in 1647 in a nonbiological connection, and it became widely used in English for all sorts of progressions from simpler beginnings. The term Darwin most often used to refer to biological evolution was "descent with modification," which remains a good brief definition of the process today.



Darwin proposed that evolution could be explained by the differential survival of organisms following their naturally occurring variation—a process he termed "natural selection." According to this view, the offspring of organisms differ from one another and from their parents in ways that are heritable—that is, they can pass on the differences genetically to their own offspring. Furthermore, organisms in nature typically produce more offspring than can survive and reproduce given the constraints of food, space, and other environmental resources. If a particular offspring has traits that give it an advantage in a particular environment, that organism will be more likely to survive and pass on those traits. As differences accumulate over generations, populations of organisms diverge from their ancestors.

Charles Darwin arrived at many of his insights into evolution by studying the variations among species on the Galápagos Islands off the coast of Ecuador.

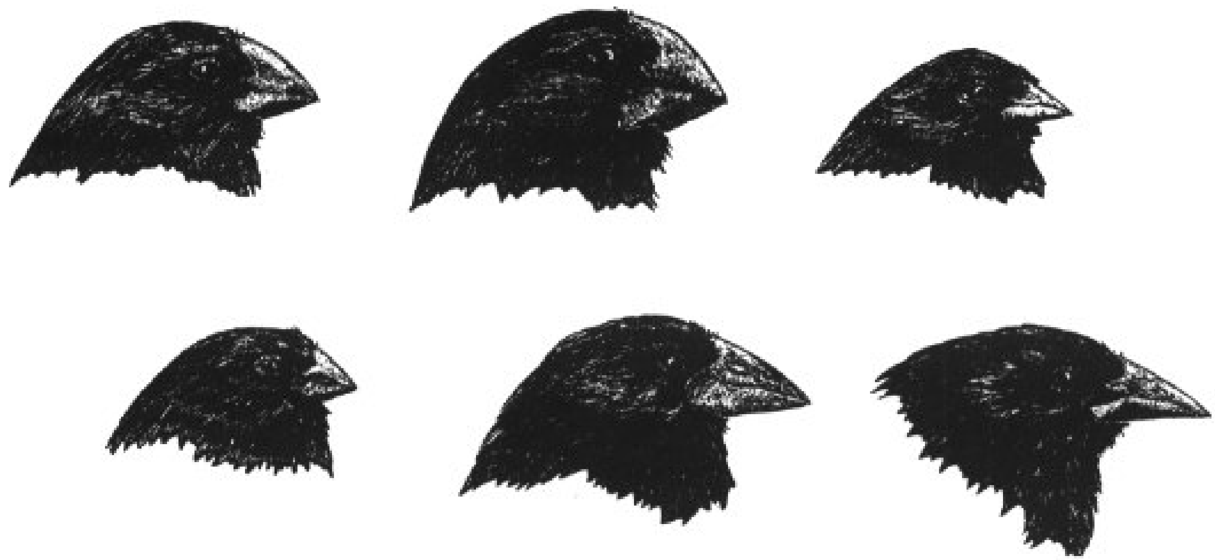
Darwin's original hypothesis has undergone extensive modification and expansion, but the central concepts stand firm. Studies in genetics and molecular biology—fields unknown in Darwin's time—have explained the occurrence of the hereditary variations that are essential to natural selection. Genetic variations result from changes, or mutations, in the nucleotide sequence of DNA, the molecule that genes are made from. Such changes in DNA now can be detected and described with great precision.

Genetic mutations arise by chance. They may or may not equip the organism with better means for surviving in its environment. But if a gene variant improves adaptation to the environment (for example, by allowing an organism to make better use of an available nutrient, or to escape predators more effectively—such as through stronger legs or disguising coloration), the organisms carrying that gene are more likely to survive and reproduce than those without it. Over time, their descendants will tend to increase, changing the average characteristics of the population. Although the genetic variation on which natural selection works is based on random or chance elements, natural selection itself produces "adaptive" change—the very opposite of chance.

Scientists also have gained an understanding of the processes by which new species originate. A new species is one in which the individuals cannot mate and produce viable descendants with individuals of a preexisting species. The split of one species into two often starts because a group of individuals becomes geographically separated from the rest. This is particularly apparent in distant remote islands, such as the Galápagos and the Hawaiian archipelago, whose great distance from the Americas and Asia means that arriving colonizers will have little or no opportunity to mate with individuals remaining on those continents. Mountains, rivers, lakes, and other natural barriers also account for geographic separation between populations that once belonged to the same species.

Once isolated, geographically separated groups of individuals become genetically differentiated as a consequence of mutation and other processes, including natural selection. The origin of a species is often a gradual process, so that at first the reproductive isolation between separated groups of organisms is only partial, but it eventually becomes complete. Scientists pay special attention to these intermediate situations, because they help to reconstruct the details of the process and to identify particular genes or sets of genes that account for the reproductive isolation between species.

A particularly compelling example of speciation involves the 13 species of finches studied by Darwin on the Galápagos Islands, now known as Darwin's finches. The ancestors of these finches appear to have immigrated from the South American mainland to the Galápagos. Today the different species of finches on the island have distinct habitats, diets, and behaviors, but the mechanisms involved in speciation continue to operate. A research group led by Peter and Rosemary Grant of Princeton University has shown that a single year of drought on the islands can drive evolutionary changes in the finches. Drought diminishes supplies of easily



The different species of finches on the Galápagos Islands, now known as Darwin's finches, have different-sized beaks that have evolved to take advantage of distinct food sources.

cracked nuts but permits the survival of plants that produce larger, tougher nuts. Droughts thus favor birds with strong, wide beaks that can break these tougher seeds, producing populations of birds with these traits. The Grants have estimated that if droughts occur about once every 10 years on the islands, a new species of finch might arise in only about 200 years.

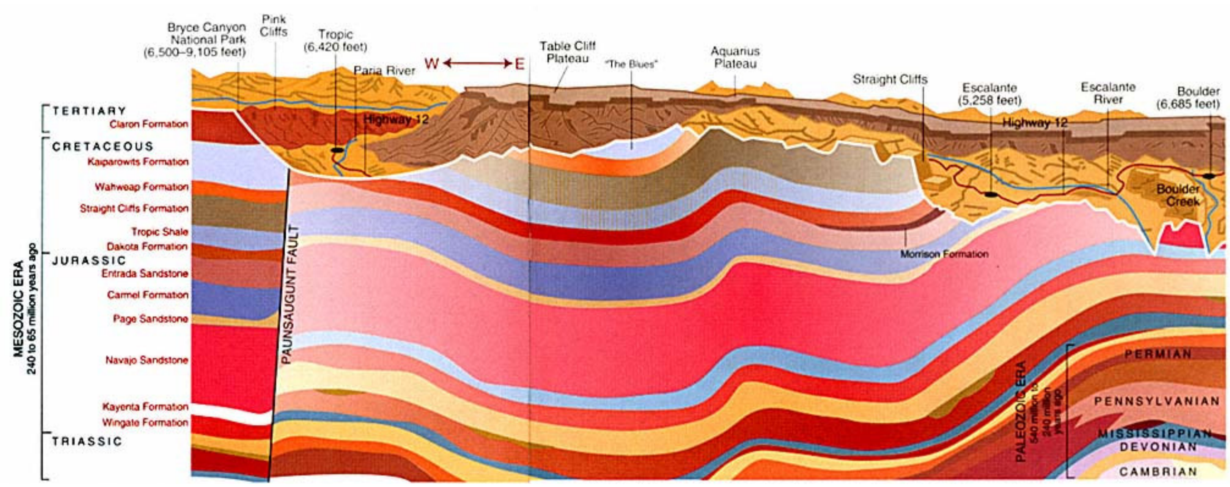
The following sections consider several aspects of biological evolution in greater detail, looking at paleontology, comparative anatomy, biogeography, embryology, and molecular biology for further evidence supporting evolution.

The Fossil Record

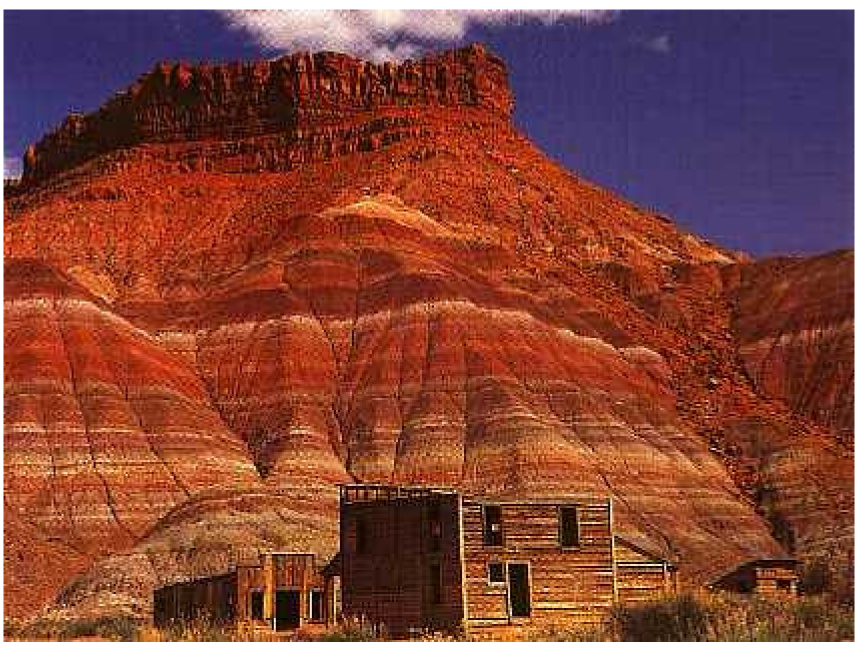
Although it was Darwin, above all others, who first marshaled convincing evidence for biological evolution, earlier scholars had recognized that organisms on Earth had changed systematically over long periods of time. For example, in 1799 an engineer named William Smith reported that, in undisrupted layers of rock, fossils occurred in a definite sequential order, with more modern-appearing ones closer to the top. Because bottom layers of rock logically were laid down earlier and thus are older than top layers, the sequence of fossils also could be given a chronology from oldest to youngest. His findings were confirmed and extended in the 1830s by the paleontologist William Lonsdale, who recognized that fossil remains of organisms from lower strata were more primitive than the ones above. Today, many thousands of ancient rock deposits have been identified that show corresponding successions of fossil organisms.

Thus, the general sequence of fossils had already been recognized before Darwin conceived of descent with modification. But the paleontologists and geologists before Darwin used the sequence of fossils in rocks not as proof of biological evolution, but as a basis for working out the original sequence of rock strata that had been structurally disturbed by earthquakes and other forces.

In Darwin's time, paleontology was still a rudimentary science. Large parts of the geological succession of stratified rocks were unknown or inadequately studied.



A geological cross section of the Grand Staircase-Escalante National Monument in Utah shows layers of sedimentary rock. These layers reveal deposits laid down over millions of years. Older fossils are found in the lower layers, revealing the succession of organisms over time



Weathering has exposed layers of sedimentary rock near the Paria River in Utah

Darwin, therefore, worried about the rarity of intermediate forms between some major groups of organisms.

Today, many of the gaps in the paleontological record have been filled by the research of paleontologists. Hundreds of thousands of fossil organisms, found in well-dated rock sequences, represent successions of forms through time and manifest many evolutionary transitions. As mentioned earlier, microbial life of the simplest type was already in existence 3.5 billion years ago. The oldest evidence of more complex organisms (that is, eucaryotic cells, which are more complex than bacteria) has been discovered in fossils sealed in rocks approximately 2 billion years old. Multicellular organisms, which are the familiar fungi, plants, and animals, have been found only in younger geological strata. The following list presents the order in which increasingly complex forms of life appeared:

Life Form	Millions of Years Since First Known Appearance (Approximate)
Microbial (procaryotic cells)	3,500
Complex (eucaryotic cells)	2,000
First multicellular animals	670
Shell-bearing animals	540
Vertebrates (simple fishes)	490
Amphibians	350
Reptiles	310
Mammals	200
Nonhuman primates	60
Earliest apes	25
Australopithecine ancestors of humans	5
Modern humans	0.15 (150,000 years

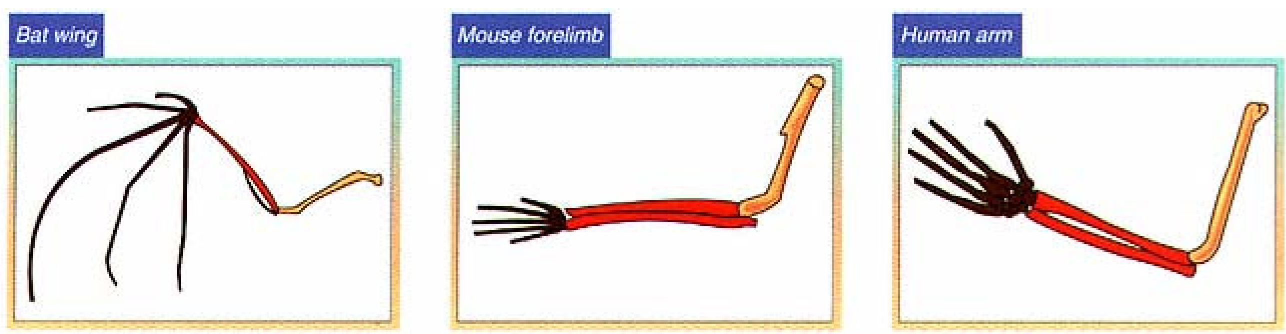
So many intermediate forms have been discovered between fish and amphibians, between amphibians and reptiles, between reptiles and mammals, and along the primate lines of descent that it often is difficult to identify categorically when the transition occurs from one to another particular species. Actually, nearly all fossils can be regarded as intermediates in some sense; they are life forms that come between the forms that preceded them and those that followed.

The fossil record thus provides consistent evidence of systematic change through time—of descent with modification. From this huge body of evidence, it can be predicted that no reversals will be found in future paleontological studies. That is, amphibians will not appear before fishes, nor mammals before reptiles, and no complex life will occur in the geological record before the oldest eucaryotic cells. This prediction has been upheld by the evidence that has accumulated until now: no reversals have been found.

Common Structures

Inferences about common descent derived from paleontology are reinforced by comparative anatomy. For example, the skeletons of humans, mice, and bats are strikingly similar, despite the different ways of life of these animals and the diversity of environments in which they flourish. The correspondence of these animals, bone by bone, can be observed in every part of the body, including the limbs; yet a person writes, a mouse runs, and a bat flies with structures built of bones that are different in detail but similar in general structure and relation to each other.

Scientists call such structures homologies and have concluded that they are best explained by common descent. Comparative anatomists investigate such homologies, not only in bone structure but also in other parts of the body, working out relationships from degrees of similarity. Their conclusions provide important inferences about the details of evolutionary history, inferences that can be tested by comparisons with the sequence of ancestral forms in the paleontological record.



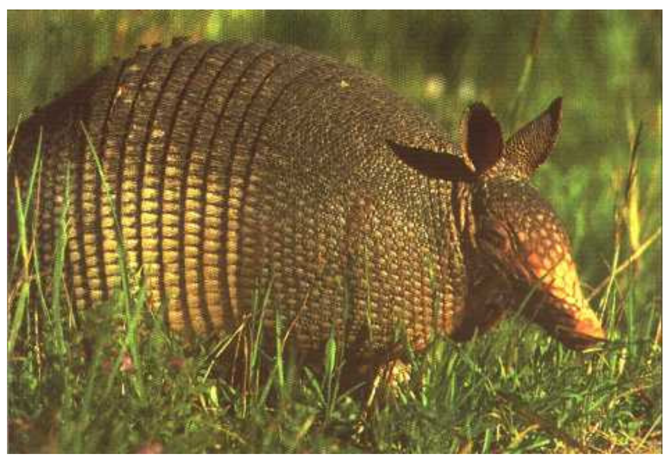
A bat wing, a mouse forelimb, and a human arm serve very different purposes, but they have the same basic components The similarities arise because all three species share a common four-limbed vertebrate ancestor

The mammalian ear and jaw are instances in which paleontology and comparative anatomy combine to show common ancestry through transitional stages. The lower jaws of mammals contain only one bone, whereas those of reptiles have several. The other bones in the reptile jaw are homologous with bones now found in the mammalian ear. Paleontologists have discovered intermediate forms of mammal-like reptiles (Therapsida) with a double jaw joint—one composed of the bones that persist in mammalian jaws, the other consisting of bones that eventually became the hammer and anvil of the mammalian ear.

The Distribution of Species

Biogeography also has contributed evidence for descent from common ancestors. The diversity of life is stupendous. Approximately 250,000 species of living plants, 100,000 species of fungi, and one million species of animals have been described and named, each occupying its own peculiar ecological setting or niche; and the census is far from complete. Some species, such as human beings and our companion the dog, can live under a wide range of environments. Others are amazingly specialized. One species of a fungus (*Laboulbenia*) grows exclusively on the rear portion of the covering wings of a single species of beetle (*Aphaenops cronei*) found only in some caves of 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 only on certain Caribbean islands.

How can we make intelligible the colossal diversity of living beings and the existence of such extraordinary, seemingly whimsical creatures as the fungus, beetle, and fly described above? And why are island groups like the Galápagos so often inhabited by forms similar to those on the nearest mainland but belonging to different species? Evolutionary theory explains that biological diversity results from the descendants of local or migrant predecessors becoming adapted to their diverse environments. This explanation can be tested by examining present species and local fossils to see whether they have similar structures, which would indicate how one is derived from the other. Also, there should be evidence that species without an established local ancestry had migrated into the locality.

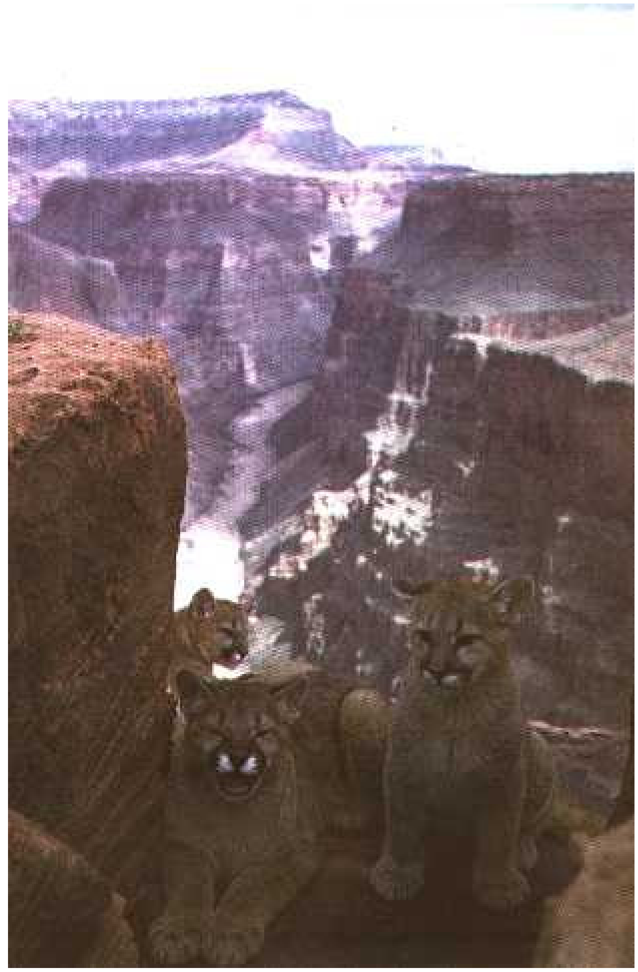


Wherever such tests have been carried out, these conditions have been confirmed. A good example is provided by the mammalian populations of North and South America, where strikingly different native organisms evolved in isolation until the emergence of the isthmus of Panama approximately 3 million years ago. Thereafter, the armadillo, porcupine, and opossum—mammals of South American origin—migrated north, along with many other species of plants and animals, while the mountain lion and other North American species made their way across the isthmus to the south.

The evidence that Darwin found for the influence of geographical distribution on the evolution of organisms has become stronger with advancing knowledge. For example, approximately 2,000 species of flies belonging to the genus *Drosophila* are now found throughout the world. About one-quarter of them live only in Hawaii.

Until about 3 million years ago, North and South America were separated by a wide expanse of water, so mammals on the two continents evolved separately. After the isthmus of Panama formed, armadillos and opossums migrated north, and mountain lions migrated south. These movements are documented in the fossil record.

More than a thousand species of snails and other land mollusks also are found only in Hawaii. The biological explanation for the multiplicity of related species in remote localities is that such great diversity is a consequence of their evolution from a few common ancestors that colonized an isolated environment. The Hawaiian Islands are far from any mainland or other islands, and on the basis of geological evidence they never have been attached to other lands. Thus, the few colonizers that reached the Hawaiian Islands found many available ecological niches, where they could, over numerous generations, undergo evolutionary change and diversification. No mammals other than one bat species lived in the Hawaiian Islands when the first human settlers arrived; similarly, many other kinds of plants and animals were absent.



The Hawaiian Islands are not less hospitable than other parts of the world for the absent species. For example, pigs and goats have multiplied in the wild in Hawaii, and other domestic animals also thrive there. The scientific explanation for the absence of many kinds of organisms, and the great multiplication of a few kinds, is that many sorts of organisms never reached the islands, because of their geographic isolation. Those that did reach the islands diversified over time because of the absence of related organisms that would compete for resources.

Similarities During Development

Embryology, the study of biological development from the time of conception, is another source of independent evidence for common descent. Barnacles, for instance, are sedentary crustaceans with little apparent similarity to such other crustaceans as lobsters, shrimps, or copepods. Yet barnacles pass through a free-swimming larval stage in which they look like other crustacean larvae. The similarity of larval stages supports the conclusion that all crustaceans have homologous parts and a common ancestry.

Similarly, a wide variety of organisms from fruit flies to worms to mice to humans have very similar sequences of genes that are active early in development. These genes influence body segmentation or orientation in all these diverse groups. The presence of such similar genes doing similar things across such a wide range of organisms is best explained by their having been present in a very early common ancestor of all of these groups.

New Evidence from Molecular Biology

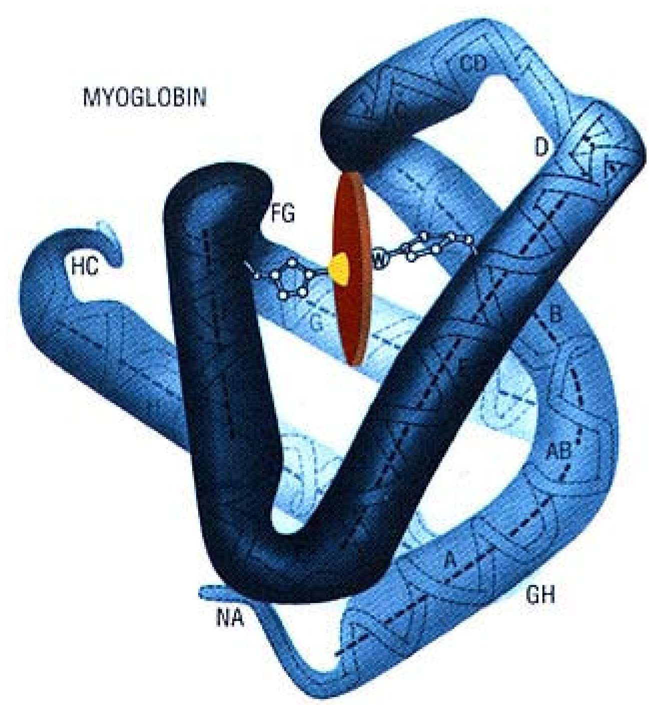
The unifying principle of common descent that emerges from all the foregoing lines of evidence is being reinforced by the discoveries of modern biochemistry and molecular biology.

The code used to translate nucleotide sequences into amino acid sequences is essentially the same in all organisms. Moreover, proteins in all organisms are invariably composed of the same set of 20 amino acids. This unity of composition

and function is a powerful argument in favor of the common descent of the most diverse organisms.

In 1959, scientists at Cambridge University in the United Kingdom determined the three-dimensional structures of two proteins that are found in almost every multicelled animal: hemoglobin and myoglobin. Hemoglobin is the protein that carries oxygen in the blood. Myoglobin receives oxygen from hemoglobin and stores it in the tissues until needed. These were the first three-dimensional protein structures to be solved, and they yielded some key insights. Myoglobin has a single chain of 153 amino acids wrapped around a group of iron and other atoms (called "heme") to which oxygen binds. Hemoglobin, in contrast, is made of up four chains: two identical chains consisting of 141 amino acids, and two other identical chains consisting of 146 amino acids. However, each chain has a heme exactly like that of myoglobin, and each of the four chains in the hemoglobin molecule is folded exactly like myoglobin. It was immediately obvious in 1959 that the two molecules are very closely related.

During the next two decades, myoglobin and hemoglobin sequences were determined for dozens of mammals, birds, reptiles, amphibians, fish, worms, and molluscs. All of these sequences were so obviously related that they could be compared with confidence with the three-dimensional structures of two selected standards—whale myoglobin and horse hemoglobin. Even more significantly, the differences between sequences from different organisms could be used to construct a family tree of hemoglobin and myoglobin variation among organisms. This tree agreed completely with observations derived from paleontology and anatomy about the common descent of the corresponding organisms.



Myoglobin, which stores oxygen in muscles, consists of a chain of 153 amino acids wrapped around an oxygen-binding molecule. The sequence of amino acids in myoglobin vanes from species to species, revealing the evolutionary relationships among organisms.

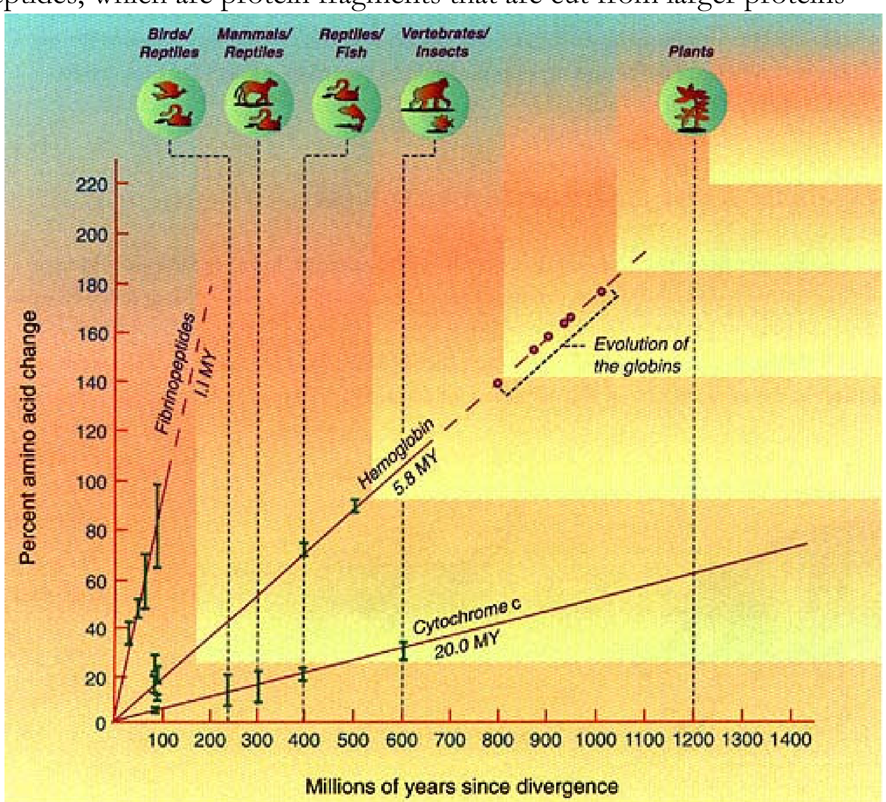
Similar family histories have been obtained from the three-dimensional structures and amino acid sequences of other proteins, such as cytochrome *c* (a protein engaged in energy transfer) and the digestive proteins trypsin and chymotrypsin. The examination of molecular structure offers a new and extremely powerful tool for studying evolutionary relationships. The quantity of information is potentially huge—as large as the thousands of different proteins contained in living organisms, and limited only by the time and resources of molecular biologists.

As the ability to sequence the nucleotides making up DNA has improved, it also has become possible to use genes to reconstruct the evolutionary history of organisms. Because of mutations, the sequence of nucleotides in a gene gradually changes over time. The more closely related two organisms are, the less different their DNA will be. Because there are tens of thousands of genes in humans and other organisms, DNA contains a tremendous amount of information about the evolutionary history of each organism.

Genes evolve at different rates because, although mutation is a random event, some proteins are much more tolerant of changes in their amino acid sequence than

are other proteins. For this reason, the genes that encode these more tolerant, less constrained proteins evolve faster The average rate at which a particular kind of gene or protein evolves gives rise to the concept of a "molecular clock." Molecular clocks run rapidly for less constrained proteins and slowly for more constrained proteins, though they all time the same evolutionary events.

The figure on this page compares three molecular clocks: for cytochrome *c* proteins, which interact intimately with other macromolecules and are quite constrained in their amino acid sequences; for the less rigidly constrained hemoglobins, which interact mainly with oxygen and other small molecules; and for fibrinopeptides, which are protein fragments that are cut from larger proteins (fibrinogens) when blood clots. The clock for fibrinopeptides runs rapidly; 1 percent of the amino acids change in a little longer than 1 million years. At the other extreme, the molecular clock runs slowly for cytochrome *c*; a 1 percent change in amino acid sequence requires 20 million years. The hemoglobin clock is intermediate.



The concept of a molecular clock is useful for two purposes. It determines evolutionary relationships among organisms, and it indicates the time in the past when species started to diverge from one another. Once the clock for a particular gene or protein has been calibrated by reference to some event whose time is known, the actual chronological time when all other events occurred can be determined by examining the protein or gene tree.

Species that diverged longer ago have more differences in their corresponding proteins, reflecting changes in the amino acids over time. Proteins evolve at different rates depending on the constraints imposed by their functions. Cytochrome c, a protein involved in energy transfer, is tightly constrained and changes slowly. Fibrinopeptides, which are involved in blood clotting, are much less constrained, with hemoglobin an intermediate case. The estimates for times of divergence shown here are based on 1971 data and have changed slightly since then *(see "The Fossil Record" table).*

An interesting additional line of evidence supporting evolution involves sequences of DNA known as "pseudogenes." Pseudogenes are remnants of genes that no longer function but continue to be carried along in DNA as excess baggage. Pseudogenes also change through time, as they are passed on from ancestors to descendants, and they offer an especially useful way of reconstructing evolutionary relationships.

With functioning genes, one possible explanation for the relative similarity between genes from different organisms is that their ways of life are similar—for example, the genes from a horse and a zebra could be more similar because of their similar habitats and behaviors than the genes from a horse and a tiger. But this possible explanation does not work for pseudogenes, since they perform no function. Rather, the degree of similarity between pseudogenes must simply reflect their evolutionary relatedness. The more remote the last common ancestor of two organisms, the more dissimilar their pseudogenes will be.

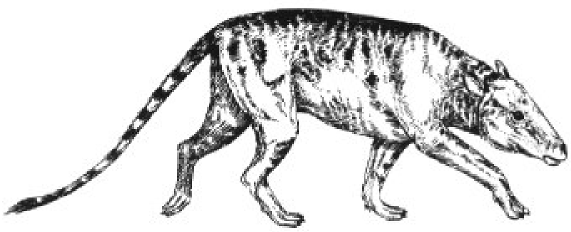
The evidence for evolution from molecular biology is overwhelming and is growing quickly. In some cases, this molecular evidence makes it possible to go beyond the paleontological evidence. For example, it has long been postulated that whales descended from land mammals that had returned to the sea. From anatomical and paleontological evidence, the whales' closest living land relatives seemed to be the even-toed hoofed mammals (modem cattle, sheep, camels, goats, etc.).

Recent comparisons of some milk protein genes (beta-casein and kappa-casein) have confirmed this relationship and have suggested that the closest land-bound living relative of whales may be the hippopotamus. In this case, molecular biology has augmented the fossil record.

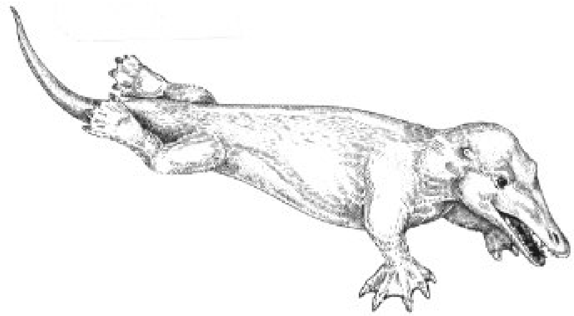
Creationism and the Evidence for Evolution

Some creationists cite what they say is an incomplete fossil record as evidence for the failure of evolutionary theory. The fossil record was incomplete in Darwin's time, but many of the important gaps that existed then have been filled by subsequent paleontological research. Perhaps the most persuasive fossil evidence for evolution is the consistency of the sequence of fossils from early to recent. Nowhere on Earth do we find, for example, mammals in Devonian (the age of fishes) strata, or human fossils coexisting with dinosaur remains. Undisturbed strata with simple unicellular organisms predate those with multicellular organisms, and invertebrates precede vertebrates;

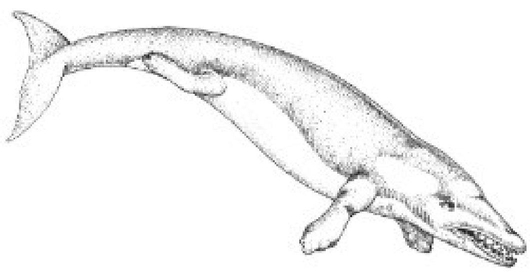
nowhere has this sequence been found inverted. Fossils from adjacent strata are more similar than fossils from temporally distant strata. The most reasonable scientific conclusion that can be drawn from the fossil record is that descent with modification has taken place as stated in evolutionary theory.



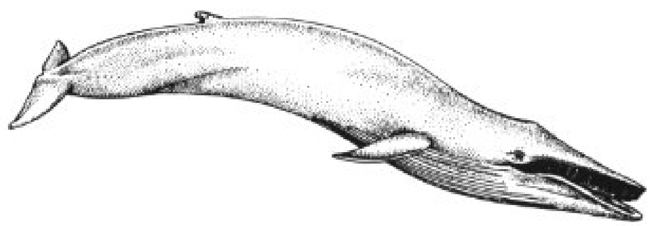
Mammakian land ancestor



Ambulocetus



Rodhocetus



Balaenoptera (modern Blue whale)

Special creationists argue that "no one has seen evolution occur." This misses the point about how science tests hypotheses. We don't see Earth going around the sun or the atoms that make up matter. We "see" their consequences. Scientists infer that atoms exist and Earth revolves because they have tested predictions derived from these concepts by extensive observation and experimentation.

Furthermore, on a minor scale, we "experience" evolution occurring every day. The annual changes in influenza viruses and the emergence of antibiotic-resistant bacteria are both products of evolutionary forces. Indeed, the rapidity with which organisms with short generation times, such as bacteria and viruses, can evolve under the influence of their environments is of great medical significance. Many laboratory experiments have shown that, because of mutation and natural selection, such microorganisms can change in specific ways from those of immediately preceding generations.

On a larger scale, the evolution of mosquitoes resistant to insecticides is another example of the tenacity and adaptability of organisms under environmental stress. Similarly, malaria parasites have become resistant to the drugs that were used extensively to combat them for many years. As a consequence, malaria is on the increase, with more than 300 million clinical cases of malaria occurring every year.

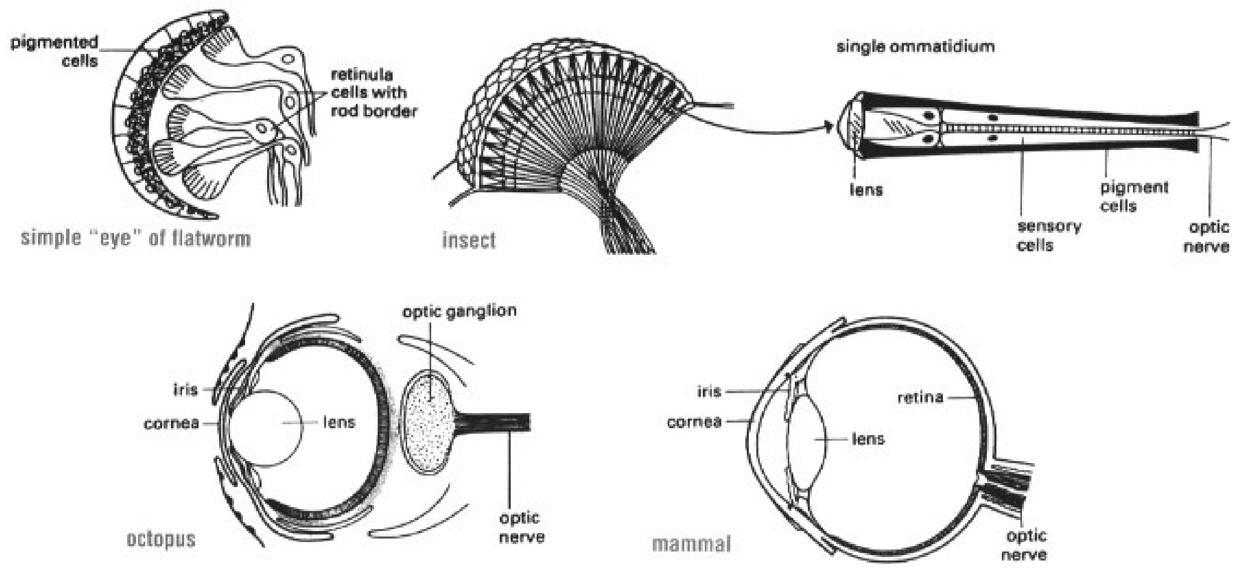
Molecular evolutionary data counter a recent proposition called "intelligent design theory." Proponents of this idea argue that structural complexity is proof of the direct hand of God in specially creating organisms as they are today. These arguments echo those of the 18th century cleric William Paley who held that the vertebrate eye, because of its intricate organization, had been specially designed in its present form by an omnipotent Creator. Modem-day intelligent design proponents argue that molecular structures such as DNA, or molecular processes such as

the many steps that blood goes through when it clots, are so irreducibly complex that they can function only if all the components are operative at once. Thus, proponents of intelligent design say that these structures and processes could not have evolved in the stepwise mode characteristic of natural selection.

However, structures and processes that are claimed to be "irreducibly" complex typically are not on closer inspection. For example, it is incorrect to assume that a complex structure or biochemical process can function only if all its components are present and functioning as we see them today. Complex biochemical systems can be built up from simpler systems through natural selection. Thus, the "history" of a protein can be traced through simpler organisms. Jawless fish have a simpler hemoglobin than do jawed fish, which in turn have a simpler hemoglobin than mammals.

The evolution of complex molecular systems can occur in several ways. Natural selection can bring together parts of a system for one function at one time and then, at a later time, recombine those parts with other systems of components to produce a system that has a different function. Genes can be duplicated, altered, and then amplified through natural selection. The complex biochemical cascade resulting in blood clotting has been explained in this fashion.

Similarly, evolutionary mechanisms are capable of explaining the origin of highly complex anatomical structures. For example, eyes may have evolved independently many times during the history of life on Earth. The steps proceed from a simple eye spot made up of light-sensitive retinula cells (as is now found in the flatworm), to formation of individual photosensitive units (ommatidia) in insects with light focusing lenses, to the eventual formation of an eye with a single lens focusing images onto a retina. In humans and other vertebrates, the retina consists not only of photoreceptor cells but also of several types of neurons that begin to analyze the visual image. Through such gradual steps, very different kinds of eyes have evolved, from simple light-sensing organs to highly complex systems for vision.



Eyes evolved over many millions of years from simple organs that can detect light.

Human Evolution

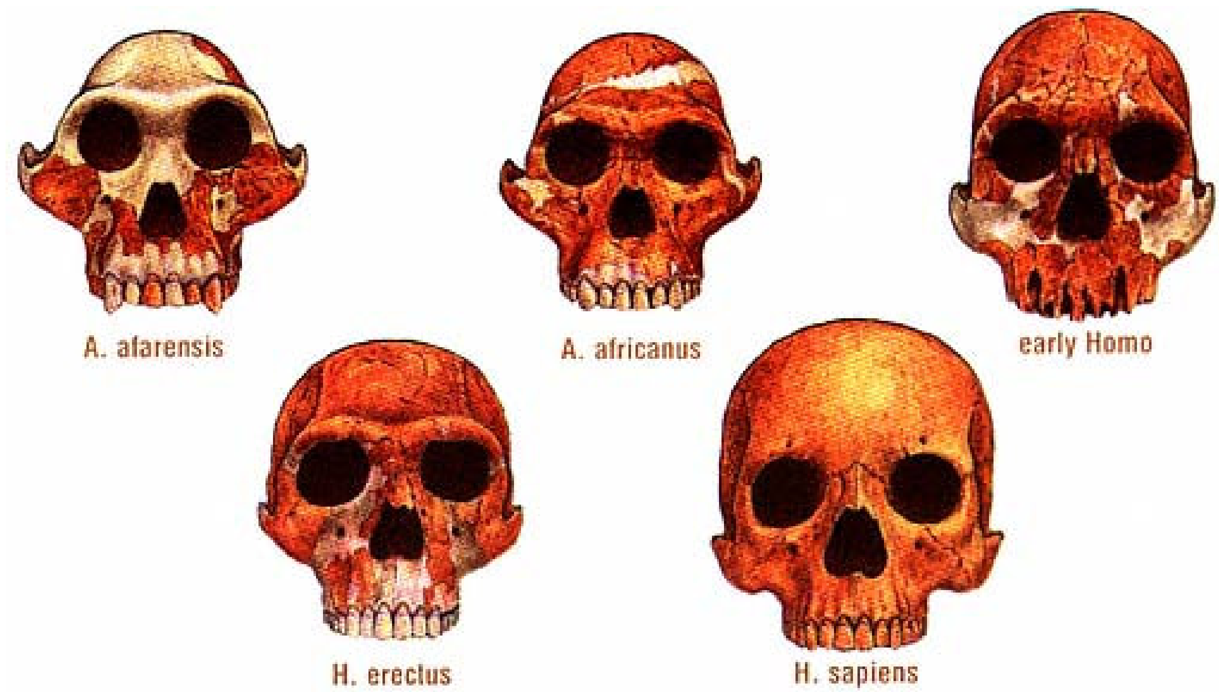
Studies in evolutionary biology have led to the conclusion that human beings arose from ancestral primates. This association was hotly debated among scientists in Darwin's day. But today there is no significant scientific doubt about the close evolutionary relationships among all primates, including humans.

Many of the most important advances in paleontology over the past century relate to the evolutionary history of humans. Not one but many connecting links—intermediate between and along various branches of the human family tree—have been found as fossils. These linking fossils occur in geological deposits of intermediate age. They document the time and rate at which primate and human evolution occurred.

Scientists have unearthed thousands of fossil specimens representing members of the human family. A great number of these cannot be assigned to the modem human species, *Homo sapiens*. Most of these specimens have been well dated, often by means of radiometric techniques. They reveal a well-branched tree, parts of which trace a general evolutionary sequence leading from ape-like forms to modem humans.

Paleontologists have discovered numerous species of extinct apes in rock strata that are older than four million years, but never a member of the human family at that great age. *Australopithecus,* whose earliest known fossils are about four million years old, is a genus with some features closer to apes and some closer to modem humans. In brain size, *Australopithecus* was barely more advanced than apes. A number of features, including long arms, short legs, intermediate toe structure, and features of the upper limb, indicate that the members of this species spent part of the time in trees. But they also walked upright on the ground, like humans. Bipedal tracks of *Australopithecus* have been discovered, beautifully preserved with those of other extinct animals, in hardened volcanic ash. Most of our *Australopithecus* ancestors died out close to two-and-a-half million years ago, while other *Australopithecus* species, which were on side branches of the human tree, survived alongside more advanced hominids for another million years.

Distinctive bones of the oldest species of the human genus, *Homo,* date back to rock strata about 2.4 million years old. Physical anthropologists agree that *Homo* evolved from one of the species of *Australopithecus.* By two million years ago, early members of *Homo* had an average brain size one-and-a-half times larger than that of *Australopithecus,* though still substantially smaller than that of modem humans. The shapes of the pelvic and leg bones suggest that these early *Homo* were not part-time climbers like *Australopithecus* but walked and ran on long legs, as modem humans do. Just as *Australopithecus* showed a complex of ape-like, human-like, and intermediate features, so was early *Homo* intermediate between *Australopithecus* and modem humans in some features, and dose to modem humans in other respects. The earliest



Early hominids, such as members of the *Australopithecus afarensis* species that lived about 3 million years ago, had smaller brains and larger faces than species belonging to the genus *Homo,* which first appeared about 2.4 million years ago. White parts of the skulls are reconstructions, and the skulls are not all on the same scale.

stone tools are of virtually the same age as the earliest fossils of *Homo.* Early *Homo,* with its larger brain than *Australopithecus,* was a maker of stone tools.

The fossil record for the interval between 2.4 million years ago and the present includes the skeletal remains of several species assigned to the genus *Homo.* The more recent species had larger brains than the older ones. This fossil record is complete enough to show that the human genus first spread from its place of origin in Africa to Europe and Asia a little less than two million years ago.

Distinctive types of stone tools are associated with various populations. More recent species with larger brains generally used more sophisticated tools than more ancient species.

Molecular biology also has provided strong evidence of the close relationship between humans and apes. Analysis of many proteins and genes has shown that humans are genetically similar to chimpanzees and gorillas and less similar to orangutans and other primates.

DNA has even been extracted from a well-preserved skeleton of the extinct human creature known as Neanderthal, a member of the genus *Homo* and often considered either as a subspecies of *Homo sapiens* or as a separate species. Application of the molecular clock, which makes use of known rates of genetic mutation, suggests that Neanderthal's lineage diverged from that of modem *Homo sapiens* less than half a million years ago, which is entirely compatible with evidence from the fossil record.

Based on molecular and genetic data, evolutionists favor the hypothesis that modem *Homo sapiens,* individuals very much like us, evolved from more archaic humans about 100,000 to 150,000 years ago. They also believe that this transition occurred in Africa, with modem humans then dispersing to Asia, Europe, and eventually Australasia and the Americas.

Discoveries of hominid remains during the past three decades in East and South Africa, the Middle East, and elsewhere have combined with advances in molecular biology to initiate a new discipline—molecular paleoanthropology. This field of inquiry is providing an ever-growing inventory of evidence for a genetic affinity between human beings and the African apes.

Opinion polls show that many people believe that divine intervention actively guided the evolution of human beings. Science cannot comment on the role that supernatural forces might play in human affairs. But scientific investigations have concluded that the same forces responsible for the evolution of all other life forms on Earth can account for the evolution of human beings.

Conclusion

Science is not the only way of acquiring knowledge about ourselves and the world around us. Humans gain understanding in many other ways, such as through literature, the arts, philosophical reflection, and religious experience. Scientific knowledge may enrich aesthetic and moral perceptions, but these subjects extend beyond science's realm, which is to obtain a better understanding of the natural world.

The claim that equity demands balanced treatment of evolutionary theory and special creation in science classrooms reflects a misunderstanding of what science is and how it is conducted. Scientific investigators seek to understand natural phenomena by observation and experimentation. Scientific interpretations of facts and the explanations that account for them therefore must be testable by observation and experimentation.

Creationism, intelligent design, and other claims of supernatural intervention in the origin of life or of species are not science because they are not testable by the methods of science. These claims subordinate observed data to statements based on authority, revelation, or religious belief.

Documentation offered in support of these claims is typically limited to the special publications of their advocates. These publications do not offer hypotheses subject to change in light of new data, new interpretations, or demonstration of error. This contrasts with science, where any hypothesis or theory always remains subject to the possibility of rejection or modification in the light of new knowledge.

No body of beliefs that has its origin in doctrinal material rather than scientific observation, interpretation, and experimentation should be admissible as science in any science course. Incorporating the teaching of such doctrines into a science curriculum compromises the objectives of public education. Science has been greatly successful at explaining natural processes, and this has led not only to increased understanding of the universe but also to major improvements in technology and public health and welfare. The growing role that science plays in modem life requires that science, and not religion, be taught in science classes.

Appendix

Frequently Asked Questions

What is evolution?

Evolution in the broadest sense explains that what we see today is different from what existed in the past. Galaxies, stars, the solar system, and Earth have changed through time, and so has life on Earth.

Biological evolution concerns changes in living things during the history of life on Earth. It explains that living things share common ancestors. Over time, biological processes such as natural selection give rise to new species. Darwin called this process "descent with modification," which remains a good definition of biological evolution today.

Isn't evolution just an inference?

No one saw the evolution of one-toed horses from three-toed horses, but that does not mean that we cannot be confident that horses evolved. Science is practiced in many ways besides direct observation and experimentation. Much scientific discovery is done through indirect experimentation and observation in which inferences are made, and hypotheses generated from those inferences are tested.

For instance, particle physicists cannot directly observe subatomic particles because the particles are too small. They make inferences about the weight, speed, and other properties of the particles based on other observations. A logical hypothesis might be something like this: If the weight of this particle is Y, when I bombard it, X will happen. If X does not happen, then the hypothesis is disproved. Thus, we can learn about the natural world even if we cannot directly observe a phenomenon—and that is true about the past, too.

In historical sciences like astronomy, geology, evolutionary biology, and archaeology, logical inferences are made and then tested against data. Sometimes the test cannot be made until new data are available, but a great deal has been done to help us understand the past. For example, scorpionflies (*Mecoptera*) and true flies (*Diptera*) have enough similarities that entomologists consider them to be closely related. Scorpionflies have four wings of about the same size, and true flies have a large front pair of wings but the back pair is replaced by small club-shaped structures. If two-winged flies evolved from scorpionfly-like ancestors, as comparative

anatomy suggests, then an intermediate true fly with four wings should have existed—and in 1976 fossils of such a fly were discovered. Furthermore, geneticists have found that the number of wings in flies can be changed through mutations in a single gene.

Something that happened in the past is thus not "off limits" for scientific study. Hypotheses can be made about such phenomena, and these hypotheses can be tested and can lead to solid conclusions.

Furthermore, many key mechanisms of evolution occur over relatively short periods and can be observed directly—such as the evolution of bacteria resistant to antibiotics.

Evolution is a well-supported theory drawn from a variety of sources of data, including observations about the fossil record, genetic information, the distribution of plants and animals, and the similarities across species of anatomy and development. Scientists have inferred that descent with modification offers the best scientific explanation for these observations.

Is evolution a fact or a theory?

The theory of evolution explains how life on Earth has changed. In scientific terms, "theory" does not mean "guess" or "hunch" as it does in everyday usage. Scientific theories are explanations of natural phenomena built up logically from testable observations and hypotheses. Biological evolution is the best scientific explanation we have for the enormous range of observations about the living world.

Scientists most often use the word "fact" to describe an observation. But scientists can also use fact to mean something that has been tested or observed so many times that there is no longer a compelling reason to keep testing or looking for examples. The occurrence of evolution in this sense is a fact. Scientists no longer question whether descent with modification occurred because the evidence supporting the idea is so strong.

Don't many famous scientists reject evolution?

No. The scientific consensus around evolution is overwhelming. Those opposed to the teaching of evolution sometimes use quotations from prominent scientists out of context to claim that scientists do not support evolution. However, examination of the quotations reveals that the scientists are actually disputing some aspect of *how* evolution occurs, not *whether* evolution occurred. For example, the biologist Stephen Jay Gould once wrote that "the extreme rarity of transitional forms in the fossil record persists as the trade secret of paleontology." But Gould, an accomplished paleontologist and eloquent educator about evolution, was arguing about *how* evolution takes place. He was discussing whether the rate of change of species is slow and gradual or whether it takes place in bursts after long periods when little change occurs—an idea known as punctuated equilibrium. As Gould writes in response, "This quotation, although accurate as a partial citation, is dishonest in leaving out the following explanatory material showing my true purpose—to discuss rates of evolutionary change, not to deny the fact of evolution itself." Gould defines punctuated equilibrium as follows:

Punctuated equilibrium is neither a creationist idea nor even a non-Darwinian evolutionary theory about sudden change that produces a new species all at once in a single generation. Punctuated equilibrium accepts the conventional idea that new species form over hundreds or thousands of generations and through an extensive series of intermediate stages. But geological time is so long that even a few thousand years may appear as a mere "moment" relative to the several million years of existence for most species. Thus, rates of evolution vary enormously and new species may appear to arise "suddenly" in geological time, even though the time involved would seem long, and the change very slow, when compared to a human lifetime.

If humans evolved from apes, why are there still apes?

Humans did not evolve from modem apes, but humans and modem apes shared a common ancestor, a species that no longer exists. Because we share a recent common ancestor with chimpanzees and gorillas, we have many anatomical, genetic, biochemical, and even behavioral similarities with these African great apes. We are less similar to the Asian apes—orangutans and gibbons—and even less similar to monkeys, because we share common ancestors with these groups in the more distant past.

Evolution is a branching or splitting process in which populations split off from one another and gradually become different. As the two groups become isolated from each other, they stop sharing genes, and eventually genetic differences increase until members of the groups can no longer interbreed. At this point, they have become separate species. Through time, these two species might give rise to new species, and so on through millennia.

Why can't we teach creation science in my school?

The courts have ruled that "creation science" is actually a religious view. Because public schools must be religiously neutral under the U.S. Constitution, the courts have held that it is unconstitutional to present creation science as legitimate scholarship.

In particular, in a trial in which supporters of creation science testified in support of their view, a district court declared that creation science does not meet the tenets of science as scientists use the term (*McLean v. Arkansas Board of Education*). The Supreme Court has held that it is illegal to require that creation science be taught when evolution is taught (*Edwards v. Aguillard*). In addition, district courts have decided that individual teachers cannot advocate creation science on their own (*Peloza v. San Juan Capistrano School District* and *Webster v. New Lennox School District*).(See *Teaching About Evolution and the Nature of Science,* Appendix A. National Academy of Sciences, Washington, D.C. 1998.)

Teachers' organizations such as the National Science Teachers Association, the National Association of Biology Teachers, the National Science Education Leadership Association, and many others also have rejected the science and pedagogy of creation science and have strongly discouraged its presentation in the public schools. In addition, a coalition of religious and other organizations has noted in "A Joint Statement of Current Law" that "in science class, [schools] may present

only genuinely scientific critiques of, or evidence for, any explanation of life on Earth, but not religious critiques (beliefs unverifiable by scientific methodology)." (See *Teaching About Evolution and the Nature of Science,* Appendices B and C, National Academy of Sciences, Washington, D.C., 1998.)

Some argue that "fairness" demands the teaching of creationism along with evolution. But a science curriculum should cover science, not the religious views of particular groups or individuals.

If evolution is taught in schools, shouldn't creationism be given equal time?

Some religious groups deny that microorganisms cause disease, but the science curriculum should not therefore be altered to reflect this belief. Most people agree that students should be exposed to the best possible scholarship in each field. That scholarship is evaluated by professionals and educators in those fields. Scientists as well as educators have concluded that evolution—and only evolution—should be taught in science classes because it is the only *scientific* explanation for why the universe is the way it is today.

Many people say that they want their children to be exposed to creationism in school, but there are thousands of different ideas about creation among the world's people. Comparative religions might comprise a worthwhile field of study, but not one appropriate for a science class. Furthermore, the U.S. Constitution states that schools must be religiously neutral, so legally a teacher cannot present any particular creationist view as being more "true" than others.

Recommended Readings

Evolution

Dawkins, Richard1996*Climbing Mount Improbable,*W.W. Norton: New York and London. An authoritative and elegant account of the evolutionary explanation of the "design" of organisms.

Fortey, Richard1998*Life: A Natural History of the First Four BillionYears of Life on Earth,*Alfred P. Knopf: New York. A lively account of the history of life on Earth.

Gould, Stephen J.1992*The Panda's Thumb,*W.W. Norton: New York. Gould's *Natural History* columns have been collected into a series of books including *Hen's Teeth and Horses Toes, An Urchin in the Storm, Eight Little Piggies, The Flamingo g Smile, and Bully for Brontosaurus.* All are good popular introductions to the basic ideas behind evolution, and extremely readable.

Homer, John R., and Edwin Dobb1997*Dinosaur Lives: Unearthing anEvolutionary Saga,*HarperCollins: New York. What it's like to uncover fossilized bones, eggs, and more, plus Homer's views on dinosaurs.

Howells, W.W.1997*Getting Here: The Story of Human Evolution,*Compass Press: Washington, D.C.A very readable survey of human evolution by one of the fathers of physical anthropology.

Johanson, Donald C., Lenora Johanson, and Blake Edgar1994*Ancestors:In Search of Human Origins,*Villard Books: New York. The companion volume to Johanson's NOVA series, "In Search of Human Origins."

Mayr, Ernst1991*One Long Argument: Charles Darwin and the Genesisof Modern Evolutionary Thought,*Harvard University Press: Cambridge, MA.An easily understandable distillation of Charles Darwin's scientific contributions.

National Academy of Sciences1998*Teaching About Evolution and theNature of Science,*National Academy Press: Washington, DC.An engaging, conversational, and well-structured framework for understanding and teaching evolution.

Nesse, Randolph, and George C. Williams1996*Why We Get Sick: TheNew Science of Darwinian Medicine,*Vintage Books: New York. The principle of natural selection as applied to modern-day health and disease. Helps to illustrate evolution as an ongoing phenomenon.

Tattersall, Ian1998*Becoming Human,*Harcourt Brace: New York. A description of the current state of understanding about the differences between Neanderthals and *Homo sapiens.*

Weiner, Jonathan1994*The Beak of the Finch: A Story of Evolutionin Our Time,*Alfred P. Knopf: New York. Discussion of basic evolutionary principles and how they are illustrated by ongoing evolution on the Galápagos Islands.

Whitfield, Philip1993*From So Simple a Beginning,*Macmillan: New York. A large-format, beautifully illustrated book explaining evolution from genetic, fossil, and geological perspectives. A good general introduction for nonspecialists.

Zimmer, Carl1999*At the Water's Edge: Macroevolution and the Transformationof Life,*Free Press: New York. Some creatures moved from water to land (the evolution land vertebrates) and others from land to water (the evolution of whales from land animals). Zimmer clearly explains these two events in the history of vertebrates and what might have brought them about.

Evolution: Books for Children and Young Adults

Cole, Joanna, and Juan Carlos Barberis1987*The Human Body: How WeEvolved,*Illustrated by Walter Gaffney-Kessell, William Morrow and Company: New York. This book traces the evolution of humans, from early prehistoric ancestors to modem tool-users. Grades 4-7.

Lauber, Patricia, and Douglas Henderson1994*How Dinosaurs Came toBe,*Simon and Schuster: New York. A description of the ancestors to the dinosaurs. Grades 4-7.

Matsen, Brad, and Ray Troll1994*Planet Ocean: A Story of Life, theSea, and Dancing to the Fossil Record,*10 Speed Press: Berkeley, CA. Whimsically illustrated tour of history for older kids and adults. Grades junior high to high school.

McNulty, Faith1999*How Whales Walked into the Sea,*Illustrated by Ted Lewin, Scholastic Trade: New York. This wonderfully illustrated book describes the evolution of whales from land mammals. Grades K-3.

Stein, Sara1986*The Evolution Book,*Workman Publishing Co., inc.: New York. A hands-on, project-oriented survey of evolution and its mechanisms. Grades 4-8.

Troll, Ray, and Brad Matsen1996*Raptors Fossils Fins and Fangs:A Prehistoric Creature Feature,*Tricycle Press: Berkeley, CA. A light-hearted trip through time ("Good Gracious — Cretaceous!") with similes kids will like ("Pterosaurs — some as big as jet fighters."). Grades 4-6.

Origin of the Universe and the Earth

Dalrymple, G. Brent1991*The Age of the Earth,*Stanford University Press: Stanford, CA. A comprehensive discussion of the evidence for the ages of the Earth, moon, meteorites, solar system, Galaxy, and universe.

Longair, Malcolm S.1996*Our Evolving Universe,*Cambridge University Press: New York. A brief discussion of the origin and evolution of the universe.

Silk, Joseph1994*A Short History of the Universe,*Scientific American Library: New York. Popular treatment of the evolution of the universe.

Weinberg, Steven1993*The First Three Minutes: A Modern View of theOrigin on the Universe,*Basic Books: New York. An explanation of what happened during the Big Bang.

Evolution and Creationism Controversy

Godfrey, Laurie, ed. 1983*Scientists Confront Creationism,*W.W. Norton: New York. A collection of articles by scientists analyzing and refuting arguments of creation science.

Kitcher, Philip1982*Abusing Science: The Case Against Creationism,*MIT Press: Cambridge. A philosophical as well as scientific analysis of creation science.

Matsumura, Molleen1995*Voices for Evolution,*National Center for Science Education, Inc : Berkeley, CA. A collection of statements supporting the teaching of evolution from many different types of organizations: scientific, civil liberties, religious, and educational.

Numbers, Ronald1992*The Creationists: The Evolution of ScientificCreationism,*University of California Press: Berkeley, CA. A thorough history of the American creationist movement.

Pennock, Robert T.1999*Tower of Babel: The Evidence Against theNew Creationism,*MIT Press: Cambridge, MA. A philosopher of science analyzes the newer "intelligent design" theory and "theistic science" creationism.

Strahler, Arthur1987*Science and Earth History: The Evolution/CreationControversy,*Prometheus Press: Buffalo, NY. A comprehensive analysis of creationist scientific claims.

Toumey, Christopher P.1994*God's Own Scientists: Creationists ina Secular World,*Rutgers University Press: New Brunswick, NJ. An anthropologist's view of creationism as a belief system upholding the moral authority of both science and religion.

Skehan, James W.1986*Modern Science and the Book of Genesis,*National Science Teachers Association: Washington, DC. Written by a geologist (former Director of the Weston Seismological Observatory) and bible scholar, trained as a Jesuit priest.

Reviewers

This report has been reviewed by individuals chosen for their diverse perspectives and technical expertise, in accordance with procedures approved by the National Research Council's Report Review Committee. The purpose of the independent review is to provide candid and critical comments that will assist the authors and the National Academy of Sciences in making their published report as sound as possible and to ensure that the report meets institutional standards for objectivity, evidence, and responsiveness to the study charge. The contents of the review comments and draft manuscript remain confidential to protect the integrity of the deliberative process. We wish to thank the following individuals for their participation in the review of this report:

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