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Evolution in the 21st Century

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The theory of biological evolution is the central organizing principle of modern biology. In 1973, the eminent evolutionist Theodosius Dobzhansky famously asserted that “Nothing in biology makes sense except in the light of evolution.” Evolution provides a scientific explanation for why there are so many different kinds of organisms on Earth, and gives an account of their similarities and differences (morphological, physiological, and genetic). It accounts for the appearance of humans on Earth and reveals our species’ biological connections with other living things. It provides an understanding of the constantly evolving bacteria and viruses and other pathogenic organisms, and enables the development of effective new ways to protect ourselves against the diseases they cause. Knowledge of evolution has made possible improvements in agriculture and medicine, and has been applied in many fields outside biology; for example, software engineering, where genetic algorithms seek to mimic selective processes, and chemistry, where the principles of natural selection are used for developing new molecules with specific functions.

Charles Darwin (1809–1882) occupies an exalted place in the history of Western thought, deservedly receiving credit for the theory of evolution. In *The Origin of Species*, published in 1859, he laid out the evidence demonstrating the evolution of organisms. However, Darwin accomplished something much more important for intellectual history than demonstrating evolution. Indeed, accumulating evidence for

common descent with diversification may very well have been a subsidiary objective of Darwin's masterpiece. Darwin's *Origin of Species* is, first and foremost, a sustained effort to solve the problem of how to account scientifically for the adaptations or "design" of organisms. Darwin seeks to explain the design of organisms, their complexity, diversity, and marvelous contrivances as the result of natural processes.

In *The Origin of Species*, Darwin brings about the evidence for evolution mostly because evolution is a necessary consequence of his theory of design, and because the evolution of organisms displays the explanatory power of his theory of natural selection to account for the diversity of organisms, as well as their adaptations. The evolution of organisms was commonly accepted by naturalists in the middle decades of the 19th century. The intellectual challenge was to explain the origin of distinct species of organisms and how new ones come to be adapted to their environments. This Darwin accomplished with his theory of natural selection. Natural selection occurs because individuals having more useful traits, such as more acute vision or swifter legs, survive better, and produce more progeny than individuals with less favorable traits. The beneficial traits, thus, gradually increase in frequency over the generations, while the less beneficial or harmful ones eventually get eliminated. Diversification occurs because different organisms become adapted to different environments.

Darwin's evidence for the evolution of organisms went much further than what was generally known by his scientific contemporaries. Moreover, Darwin shows that the evidence is consistent with his theory of natural selection. For example, he showed that different parts of organisms evolve at different times and rates, rather than the gradual evolution of each individual as a whole, which was the generally accepted view and was postulated, for example, by Lamarck in his *Zoological Philosophy* of 1809, and by Robert Chambers in his *Vestiges of Natural Creation* of 1844. Darwin also affirms that some organisms may not evolve at all when they happen to be adapted to unchanging environments. Indeed, "Some of the most ancient Silurian animals, as the Nautilus, Lingula, etc., do not differ much from living species" (*Origin*, chap. IX, 306). The strength of the evidence accumulated by Darwin in *The Origin of Species* greatly contributed to extending the acceptance of evolution by Darwin's contemporaries.

Darwin and other 19th-century biologists found compelling evidence for biological evolution in the comparative study of living or-

ganisms, in their geographic distribution, and in the fossil remains of extinct organisms. Since Darwin's time, the evidence from these sources has become stronger and more comprehensive, while biological disciplines that have emerged recently—genetics, biochemistry, ecology, animal behavior (ethology), neurobiology, and especially molecular biology—have supplied powerful additional evidence and detailed confirmation. Accordingly, evolutionists are no longer concerned with obtaining evidence to support the fact of evolution, but rather are concerned with finding out additional information of the historical process in cases of particular interest. Moreover and most importantly, evolutionists nowadays are interested in understanding further and further how the process of evolution occurs.

The Fossil Record

Important discoveries continue, even in traditional disciplines such as paleontology. Skeptical contemporaries of Darwin asked about the “missing links,” particularly between apes and humans, but also between major groups of organisms, such as between fish and terrestrial tetrapods or between reptiles and birds. Evolutionists can now affirm that these missing links are no longer missing. Molecular biology has made it possible to reconstruct the “universal tree of life,” which summarizes the continuity of succession from the original forms of life, ancestral to all living organisms, to every species now living on Earth. The main branches of the tree of life have been reconstructed on the whole and in great detail. Further details about more and more branches of the universal tree of life are published in scores of scientific articles every month. The virtually unlimited evolutionary information encoded in the DNA sequence of living organisms allows evolutionists to reconstruct the ancestral relationships leading to present-day organisms, with as much detail as wanted, limited only by the willingness to invest the appropriate resources of human time and laboratory expenses.

In addition, the known fossil record has made great strides over the last century and a half. Many fossils intermediate between diverse organisms have been discovered over the years. Two examples that have received recent attention in the media are *Archaeopteryx*, an animal intermediate between reptiles and birds, and *Tiktaalik*, an intermediate between fishes and tetrapods.

The first *Archaeopteryx* was discovered in Bavaria in 1861, two years after the publication of Darwin's *The Origin*, a discovery that was noted by Darwin in the last two editions of *The Origin*. Other *Archaeopteryx* specimens have been discovered in the past hundred years. The most recent, the tenth specimen so far recovered, was described in December 2005. *Archaeopteryx* lived during the Late Jurassic period, about 60 million years ago, and exhibited a mixture of both avian and reptilian traits. All known specimens are small, about the size of a crow, and share many anatomical characteristics with some of the smaller bipedal dinosaurs. Its skeleton is reptile-like, but *Archaeopteryx* had feathers, clearly shown in the fossils, with a skull and a beak like those of a bird.

Paleontologists have known for more than a century that tetrapods (amphibians, reptiles, birds, and mammals) evolved from a particular group of fish called lobe-finned. Until recently, *Panderichthys* was the known fossil fish closest to the tetrapods. *Panderichthys* was somewhat crocodile-shaped and had a pectoral fin skeleton and shoulder girdle intermediate in shape between those of typical lobe-finned fish and those of tetrapods, which allowed it to "walk" in shallow waters but probably not on land. In most features, however, *Panderichthys* was more like a fish than like an amphibious tetrapod. *Panderichthys* is known from Latvia, where it lived some 385 million years ago (the mid-Devonian period).

Until very recently, the earliest tetrapod fossils that are more nearly fishlike were also from the Devonian, about 376 million years old. They have been found in Scotland and Latvia. *Ichthyostega* and *Acanthostega* from Greenland, which lived more recently, about 365 million years ago, are unambiguous walking tetrapods, with limbs that bear digits, although they retain from their fish ancestors such characteristics as true fish tails with fin rays. Thus, the time gap between the most tetrapodlike fish and the most fishlike tetrapods was nearly 10 million years, between 385 and 376 million years ago.

Recently, several specimens have been discovered of a fossil that has been named *Tiktaalik*, which goes a long way toward breaching this gap; it is the most nearly intermediate between fish and tetrapods yet known. Several specimens have been found in Late Devonian river sediments, dated about 380 million years ago, on Ellesmere Island in Nunavut, Arctic Canada. *Tiktaalik* displays an array of features that are just about as precisely intermediate between fish and tetrapods as

one could imagine, and exactly fits the time gap as well (see Daeschler, *et al.* 2006; Shubin, *et al.* 2006).

The missing link between apes and humans is not missing any longer either. The fossils that belong to the human lineage after its separation from the ape lineages are called hominids. Not one but hundreds of fossil remains from hundreds of individual hominids have been discovered since Darwin's time and continue to be discovered at an accelerating rate. The oldest known fossil hominids are 6 to 7 million years old, come from Africa, and are known as *Sahelanthropus* and *Orrorin*. These ancestors were predominantly bipedal when on the ground and had very small brains. *Ardipithecus* lived about 4.4 million years ago, also in Africa. Numerous fossil remains from diverse African origins are known of *Australopithecus*, a hominid that appeared between 3 and 4 million years ago. *Australopithecus* had an upright human stance but a cranial capacity of less than 500 cc, comparable to that of a gorilla or chimpanzee. The skull of *Australopithecus* displayed a mixture of ape and human characteristics. Other early hominids partly contemporaneous with *Australopithecus* include *Kenyanthropus* and *Paranthropus*; both had comparatively small brains. *Paranthropus* represents a side branch of the hominid lineage that became extinct.

Along with increased cranial capacity, other human characteristics have been found in *Homo habilis*, which lived between about 2 and 1.5 million years ago in Africa and had a cranial capacity of more than 600 cc, and in *Homo erectus*, which evolved in Africa sometime before 1.8 million years ago and had a cranial capacity of 800 to 1,100 cc. Shortly after its emergence in Africa, *H. erectus* spread to Europe and Asia, even as far as the Indonesian archipelago and northern China. *Homo erectus* fossils from Java have been dated at 1.81 and 1.66 million years ago, and from Georgia between 1.6 and 1.8 million years ago.

The transition from *H. erectus* to *H. sapiens* may have started around 400,000 years ago. Some fossils of that time appear to be "archaic" forms of *H. sapiens*. The species *Homo neanderthalensis* appeared in Europe more than 200,000 years ago and persisted until 30,000 years ago. The Neandertals have been thought to be ancestral to anatomically modern humans, but comparisons of DNA from Neandertal fossils with living humans indicate that *H. neanderthalensis* may have been a separate species that became extinct.

Molecular Evolution

Molecular biology, a discipline that emerged in the second half of the 20th century, nearly 100 years after the publication of *The Origin of Species*, has provided the strongest evidence yet of the evolution of organisms. Molecular biology proves the fact of evolution in two ways: first, by showing the unity of life in the nature of DNA and the workings of organisms at the level of enzymes and other protein molecules; second, and most important in practice for evolutionists, by making it possible to reconstruct evolutionary relationships that were previously unknown, and to confirm, refine, and time all evolutionary relationships from the universal common ancestor up to all living organisms. The precision with which these events can be reconstructed is one reason why the evidence from molecular biology is so useful to evolutionists and so compelling.

The molecular components of organisms are remarkably uniform—in the kinds of molecules that are present, as well as in the ways in which these molecules are assembled and used. In all microorganisms, plants, animals, and humans, the instructions that guide the development and functioning of organisms are encased in the same hereditary material, DNA, which provides the instructions for the synthesis of proteins. The thousands of enormously diverse proteins that exist in organisms are synthesized from different linear combinations, in sequences of variable length, of 20 amino acids, the same 20 in all proteins and in all organisms. Yet several hundred other amino acids exist, such as are found in a variety of plants, and a virtually infinite number of them could be synthesized. Moreover, the genetic code, by which the information contained in the DNA of the cell nucleus is passed on to proteins, is virtually the same in all organisms. Similar metabolic pathways—sequences of biochemical reactions—are used by the most diverse organisms to produce energy and to make up the cell components.

The unity of life reveals the genetic continuity and common ancestry of all organisms. There is no other rational way to account for their molecular uniformity, given that numerous alternative structures and fundamental processes are in principle equally likely.

DNA and proteins have been called “informational macromolecules” because they are long linear molecules made up of sequences of smaller units—nucleotides in the case of DNA, amino acids in the case of proteins—that embody evolutionary information in their

particular sequence, similarly as particular sequences of letters and words convey semantic information. Comparing the sequence of the components in two macromolecules establishes how many units are different. Because evolution usually occurs by changing one unit at a time, the sequence differences between two organisms are an indication of their recency of common ancestry. Thus, the inferences from paleontology, comparative anatomy, and other disciplines that study evolutionary history can be tested in molecular studies of DNA and proteins by examining the sequences of nucleotides and amino acids. The authority of this kind of test is overwhelming: each of the thousands of genes and thousands of proteins contained in an organism provides an independent test of that organism's evolutionary history.

Molecular evolutionary studies have three notable advantages over comparative anatomy and the other classical disciplines. One is that the information is readily quantifiable: the number of units that are different is easily established when the sequence of units is known for a given macromolecule in different organisms. It is simply a matter of aligning the units (nucleotides or amino acids) between two or more species and counting the differences. The second advantage is universality: comparisons can be made between very different sorts of organisms. There is very little that comparative anatomy can say when, for example, organisms as diverse as yeasts, pine trees, and human beings are compared, but there are numerous DNA and protein sequences that can be compared in all three. The third advantage is multiplicity: each organism possesses thousands of genes and proteins, every one of which reflects the same evolutionary history. If the investigation of one particular gene or protein does not satisfactorily resolve the evolutionary relationship of a set of species, additional genes and proteins can be investigated until the matter has been settled.

Evolution and the Public

Evolution, as stated earlier in this essay, is the organizing principle of modern biology. The fact of evolution is universally accepted by all experts, so that evolutionists are no longer concerned with obtaining evidence to support it. The theory of evolution seeks to account for the history of evolution and for the processes that explain it. It has advanced enormously over the last century and a half, since the time when *The Origin of Species* was published. The rate of advance of evolutionary knowledge is itself accelerating. Consider my personal

experience. When I came to the United States in 1961 as a student at Columbia University, no courses in evolution were offered there, nor were they offered in other universities. Now, many universities have departments of evolution, and a range of undergraduate and graduate courses are offered. Numerous textbooks in evolution are available as well. As far as my memory can tell, in 1961 there was only one scientific journal, *Evolution*, dedicated to the subject. It was published quarterly, with perhaps a dozen or so articles per issue. There are now scores of journals dedicated largely or exclusively to evolution, mostly published monthly, where thousands of scientific articles are published every year.

Yet, in the United States, many people reject the scientific knowledge concerning evolution (apparently for religious reasons in most cases). According to a Gallup Poll of 1,016 U.S. adults taken in November 2004, 45% of those surveyed favored the statement that “God created human beings in their present form within the last 10,000 years”; 38% favored that “Man developed over millions of years, but God guided the process”; and 13% that “Man developed over millions of years from less advanced life forms.” Teaching creationism rather than evolution in schools is favored by a large number of American citizens. In a CNN/USA *Today* Gallup Poll of 1,001 adults conducted in March 2005, 76% would not “be upset if public schools in [their] community taught creationism,” but only 63% would not “be upset if the schools taught evolution.” Only 22% would be upset if creationism were taught, while 34% would be upset if evolution were taught. Other polls yield similar statistics.

The U.S. National Academy of Sciences (NAS) has been concerned with this unfortunate state of affairs. In 1984, the NAS published *Science and Creationism: A View from the National Academy of Sciences*. A second edition was published in 1999. A third edition, sufficiently modified to deserve a new title, *Science, Evolution, and Creationism*, was published on January 4, 2008.

Science and Creationism was prepared by a committee of the NAS in response to statutes passed by the legislatures of, first, the state of Arkansas, and shortly thereafter, the state of Louisiana, that required “creation science” be taught in public schools together with evolution. The Louisiana “Creation Act” was appealed all the way to the U.S. Supreme Court, which in 1987 (*Edwards v. Aguillard*) concluded that the act’s “primary purpose was to change the public school science curriculum to provide persuasive advantage to a particular

religious doctrine that rejects the factual basis of evolution in its entirety. Thus, the act is designed either to promote the theory of creation science that embodies a particular religious tenet or to prohibit the teaching of a scientific theory disfavored by certain religious sects. In either case, the act violates the First Amendment.”

Science, Evolution, and Creationism consists of three main chapters. The first chapter briefly describes the process of evolution and the nature of science in contrast to other forms of knowledge. The second chapter surveys the scientific evidence that supports evolution from diverse disciplines that include paleontology, comparative anatomy, biogeography, molecular biology, genetics, and anthropology. The third chapter examines Intelligent Design and other creationist perspectives so as to point out the scientific and legal reasons for not teaching them in public school science classes.

Scientists and religious authors have written eloquently about their awe and wonder at the history of the universe and of life on this planet, explaining that they see no conflict between the evidence for evolution and their belief in God. Moreover, authorities of diverse religious denominations have issued statements affirming the compatibility between the tenets of their faith and the acceptance of biological evolution.

Science and religion concern different aspects of the human experience. Scientific explanations are based on evidence drawn from examining the natural world and rely exclusively on natural processes to account for natural phenomena. Scientific explanations are subject to empirical tests by means of observation and experimentation and are subject to the possibility of modification and rejection. Religious faith, in contrast, does not depend on empirical tests and is not subject to the possibility of rejection based on empirical evidence. The significance and purpose of the world and human life, as well as issues concerning moral and religious values, are of great importance to many people, perhaps a majority of humans, but these are matters that transcend science.

Many people have questions about biological evolution. They may have been told that scientific understanding of evolution is incorrect or at least doubtful. They may be skeptical that a natural process could account for the astonishing diversity of the living world and the marvelous adaptations of organisms to their ways of life. People of faith wonder whether accepting evolution is compatible with their religious beliefs.

Science, Evolution, and Creationism speaks to these questions. It is written to serve as a source of information and as a resource for people who find themselves embroiled in debates about evolution. It was designed to be helpful to “school board members, science teachers and other education leaders, policy makers, legal scholars, and others in the community who are committed to providing students with quality science education.” As stated in the preface, *Science, Evolution, and Creationism* “is also directed to the broader audience of high-school and college students as well as adults who wish to become more familiar with the many strands of evidence supporting evolution and to understand why evolution is both a fact and a process that accounts for the diversity of life on Earth.”

In addition to the NAS *Science, Evolution, and Creationism*, a large number of books are now available that seek to show that there is no necessary opposition between the theory of evolution and religious faith. Rather, science and religion can be mutually motivating and inspiring for people of faith. Science may inspire religious beliefs and religious behavior, as we respond with awe to the immensity of the universe and the wondrous diversity of organisms and their marvelous adaptations. Religion promotes reverence for creation, for humankind as well as the environment. Religion may be a motivating force and source of inspiration for scientific research and may move all to learn more about the world of creation.

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Suggested Readings

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