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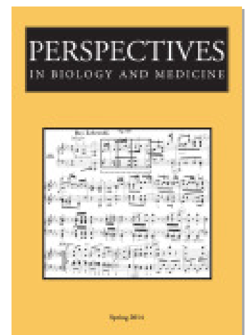

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DARWINIAN EVOLUTION AND THE PROBLEM OF EXTRATERRESTRIAL LIFE

*THEODOSIUS DOBZHANSKY**

The heretic Giordano Bruno was burned at the stake in Rome on February 19, 1600. Among his heresies was his belief in a plurality of worlds inhabited by rational beings. The inquisitors who condemned Bruno surely did not doubt that heavens are inhabited. They insisted, however, that God and saints and angels dwell not on another planet but somewhere above the clouds and the firmament. It was really Copernicus, and after him Galileo and Kepler, who showed that heavens are not a sphere enveloping a centrally located earth, and thus raised the question of the abode of extraterrestrial life.

The idea that man is the sole rational life in the universe seems incredible and even distasteful to many people. Popular imagination always fancied material or incorporeal beings residing in extraterrestrial habitats and craved to communicate with them. From 1877 on, some serious astronomers claimed to have seen "canals" appear and disappear on the surface of Mars, and this was freely interpreted as evidence of a technologically advanced civilization using irrigation for its agriculture. Less serious observers reported seeing flying saucers and other unidentified flying objects and expected Martians or other visitors from outer space to disembark from them.

Better observations, as well as space flights, brought disappointments to believers in extraterrestrial manlike beings. Neither the moon nor the planets (other than the earth) in our solar system can credibly be supposed to harbor manlike inhabitants. Some kind of primitive life is improbable but is not completely ruled out. Believers

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now look beyond the confines of the solar system. The survey of biological science edited by Philip Handler [1] contains the following statements: "Given manifestations of intelligent activity no greater than we ourselves produce in the form of radio transmission, existing terrestrial technology is capable of detecting such activities over distances as enormous as 1000 light years, within which range there are 10 million stars," and "a serious, well-funded search for extraterrestrial signals should be organized on a worldwide basis."[1]

Stating the Problems

The demonstration by Darwin in 1859 and 1871 that the living world, including man, is a product of evolutionary development placed the problem of extraterrestrial life in a new perspective [2, 3]. If such life exists at all, it must also have evolved from some simple beginnings. In our day, spectacular advances of molecular biology and biochemistry led to a revival of interest in the problem of the origin of life from nonliving matter. Plausible schemes of how life could have arisen on earth, and by extension on earthlike planets if such actually exist elsewhere in the universe, have been worked out.

It must, however, be stressed that the problem of the origin of life is quite distinct from that of its subsequent evolution. Assuming that life has in fact arisen, what inferences or predictions can one draw concerning its evolutionary development? Cosmologists and exobiologists (specialists on life outside the earth) who speculate on this topic assume lightly that the development would be on the whole like that of life on Earth. The climax predicted with astonishing confidence is the emergence of humanoids, manlike rational beings, and the eventual appearance of extraterrestrial civilizations and technologies as advanced as ours or more advanced. Hence the proposals to organize "a serious, well-funded search for extraterrestrial signals."

Evolutionary biologists have mostly steered clear of these issues, probably finding them too speculative. G. G. Simpson [4] is a conspicuous exception. His incisive analysis of "the nonprevalence of humanoids" led him to conclude: "The assumption, so freely made by astronomers, physicists, and some biochemists, that once life gets started anywhere, humanoids will eventually and inevitably appear is plainly false. The chance of duplicating man on any other planet is the same as the chance that the planet and its organisms have had

1 Although one of the 175 "contributors" to the survey, I have seen the whole of it only after its publication.

a history identical in all essentials with that of the earth through some billions of years. Let us grant the unsubstantiated claim of millions or billions of possible planetary abodes of life; the chances of such historical duplication are still vanishingly small." I have reached similar conclusions [5].

In the present article, an attempt is made to reexamine particularly those aspects of the modern Darwinian (or Neo-Darwinian, or synthetic) theory of evolution which bear on the problems of determinism versus chance, and repeatability versus uniqueness of the evolutionary development.

Necessity and Chance in Evolution

Two antipodal views of life have always had their adherents. One accepts whatever happens as having been necessary and predetermined to happen. The other sees the world as a playfield of chance: there is no intrinsic necessity for many events that we observe; quite different events could have happened instead. Scientists usually espouse a determinist point of view. The determinist creed was stated with perfect clarity in 1820 by Laplace. His famous dictum asserts that an intelligence sufficiently powerful to know the positions at a given instant of all the particles in the universe, and all the forces acting in nature, and furthermore able to subject these data to analysis, would be able to predict the future and to retrodict the past. To such an intelligence "nothing would be uncertain, the future as well as the past would be present to its eyes."

Laplace's claim appeared to be valid in 1820, but modern philosophy of science regards it as doubtful. Nagel [6] finds Laplace "guilty of a serious non sequitur," since "the determinism of classical mechanics is severely limited to a determinism with respect to mechanical states." Anyway, Laplacean determinism sheds no light on evolutionary history. Since life and mankind did in fact arise on Earth, we may fancy that they would do so again if there existed another planet identical with Earth in minutest details throughout its history. But this has nothing to do with reality; one can envisage at most two or several planets with environments roughly imitating each other.

The question that logically presents itself is, then, whether evolutionary changes are evoked by the environments in which the organisms live or are predestined by the structure of the living matter itself. Both possibilities had their adherent. Darwin's theory of natural selection maintained that the prime mover of evolutionary change is adaptation to the environment. The modern theory, upheld by most evolutionists, is a direct intellectual descendant from Darwin's theory. It affirms that life responds to the environment by evolutionary changes and that natural selection is the chief mechanism mediating these responses. It should, however, be stressed that according to this view the environment does not directly impose on the organism specific evolutionary changes, as was believed by the Neo-Lamarckians, although not by Lamarck himself.

The influence of environment on evolution is more subtle and more interesting. A living species is confronted by challenges presented by the environments in which it exists. It may or may not respond to these challenges by adaptive alterations of its genetic constitution. Whether it responds depends on many factors, the simplest and perhaps most important of which is the availability of suitable genetic variants arisen by mutation and sexual recombination. The complexity of the situation introduces an element of chance in the evolutionary events. The role of "chance" in evolution is all too frequently misunderstood. Chance does not mean acausality; a chance event is not due to "pure spontaneity." It occurs "at the intersection of two independent causal series," or "if in a given context of inquiry the statement asserting its occurrence is not derived from anything else" [6].

Non-Darwinian Theories of Evolution

If theories which consider natural selection to be the prime guiding agency of evolutionary change are dubbed "Darwinian," then there are several non-Darwinian theories. No critical review can be given here, but it is only fair that some of them be mentioned as possible alternatives which have been considered and rejected by most biologists. Traditional creationism proffers an uncomplicated solution of the problem of adaptedness. Each species was created by God as we find it now, with structures and functions it needs to live in certain environments. Another form of creationism acknowledges the fact of evolution but imagines it to have been propelled and guided by some inscrutable force. Finalist theories put the causation of evolution upside down—it is not caused by present and past states of the species or of its environment but is drawn toward some predestined goal or end. This goal is most often assumed to be the origination of man. Organisms, like human artifacts, are constructed by something outside and above them. In Polanyi's [7] terminology, they have "boundary conditions" imposed upon them.

Rensch [8] calls evolution "a determinate process" and writes "that all future evolution is also determined." This is true in the sense of Laplacean universal determinacy, but it is only a part of the story, and not the most interesting part. A hard predetermination of the course of evolution was posited by autogenetic theories, which Rensch and a majority of modern evolutionists reject. Such theories (orthogenesis, nomogenesis, etc.) attach little significance to natural selection except as a conservative principle (normalizing selection). Berg [9] believed that "there are intrinsic and constitutional agencies laid down in the chemical structure of the protoplasm, which compel the organism to vary in a determined direction," and that "evolution is in a great measure an unfolding of preexisting rudiments." Other partisans of autogenesis stated explicitly that man and all other organic forms were contained in the primordial life. Evolution was only peeling off one disguise after another, until man stood revealed. It took between 3 and 4 billion years to achieve this result! We are given no hint as to what "chemical structure of the protoplasm" brought such a miraculous outcome.

Lamarckism and neo-Lamarckism are two more non-Darwinian theories. Ironically, they are not only not similar but in some ways diametrically opposed. Lamarck, in 1807, postulated a "law of nature" that directs evolutionary changes toward increasing complexity and versatility. Lamarck's is really the oldest theory of autogenesis. Neo-Lamarckism appeals instead to influences of the external environment, which induces structural and other changes in bodies subjected to it. These changes are assumed, wrongly as we know at present, to be inherited. Neo-Lamarckism is related to the views of Geoffroy Saint-Hilaire, a younger contemporary of Lamarck, more than to those of Lamarck himself. Why the changes imposed by the environment should be adaptive remains a puzzle, unless purposive reactions are taken to be inherent in life. The alternative is, of course, to assume that the changes are winnowed by natural selection and that only the adaptive ones are preserved. Darwin came increasingly in his later years to rely upon such a compromise solution, but his views are not usually considered non-Darwinian on this account.

The most recent non-Darwinian theory, proposed by King and Jukes [10], also has a substantial Darwinian component. They acknowledge that "evolutionary change at the morphological, functional, and behavioral levels results from the process of natural selection, operating through adaptive changes in DNA." They argue, however, that many mutations are selectively neutral, and these "become passively fixed as evolutionary changes through the action of random genetic drift."

Life and Adaptedness

Autogenetic theories (including that of Lamarck) assume that evolution moves, regardless of the environment, in a fixed direction. The direction of the changes may be adverse to survival. If so, the species dies out. Autogenesis thus explains extinction, but it is in trouble explaining adaptedness. How the adaptedness of life is achieved, maintained, and advanced is a fundamental and distinctive biological problem. No theory of evolution which fails to provide a rational explanation of adaptedness can be acceptable.

There is evolution in the living as well as in the nonliving world. Everywhere, "the current state of a system is the result of a more or less continual change from its original state" [11]. We are cognizant of stellar evolution, evolution of continents and oceans, of rocks, soils, and living beings. On the human level, there are cultural, social, political, and economic evolutions. Biological evolution, however, has properties which evolutionary changes in inorganic nature do not have. Life is an utterly improbable state of matter; how can it persist amid hostile environments? Life endures because one of the essential attributes of the living world is its ability to evolve. Organic evolution serves a function which evolution of the inorganic world does not have. This function is to maintain or enhance the adaptedness of living species.

The concept of adaptedness is meaningless outside of biology. In Ayala's words [12], adaptedness of living things is internal teleology. It is an outcome of evolution of the living systems themselves. By contrast, man makes and uses tools to perform certain functions; their "adaptedness" for these functions is due to external teleology, imposed by man. In inorganic nature, except when sequestered in human artifacts, there is neither internal nor external teleology. Expressions which suggest otherwise are metaphors, which must be understood as such if they are not to be misleading.

For example, a famous book of Henderson [13] is entitled *The Fitness of the Environment.* It points out that life on Earth could not exist if it were not for the extraordinary physical and chemical properties of water and of carbon compounds, which are "adapted" to become constituents of living bodies. Yet the "adaptedness" or "fitness" of water and carbon surely do not mean the same thing as the adaptedness of pine and spruce trees to survive cold winters, or of predators to catch their prey. Unless one wishes to say that an external teleology is imposed upon water and carbon by the Creator in order to generate life, the only meaningful statement is that living things are adapted to build their bodies of some materials but not of others. Thus, some organisms have calcareous, others siliciferous, and a few strontium-containing skeletons.

Biology transcends chemistry and physics not because it deals with some special vital force but because it studies systems which operate in ways that do not occur in the nonliving world. Darwinian theories of evolution by natural selection, reformulated on the foundation of modern genetics, are taken by most biologists as guiding lights in studies of adaptation. Organic adaptedness exemplifies internal teleology. Its present state is the outcome of a more or less continuous process of gradual accretions. At no stage of the process have the genetic changes occurred with the present or any future state in view; they came to pass exclusively because they were adaptive when and where they happened. There is one thing that natural selection cannot do: since it has no foresight, it cannot build genotypes that will be favorable not in the present but in some future environments. It is for this reason that evolution controlled by natural selection may end in maladaptation and extinction. A genetic endowment that makes a species well adapted today may be faulty in the future. If a reconstruction of this endowment cannot be achieved rapidly enough, the species may perish. Man is the only species that can anticipate future needs and prepare for them, if he so chooses. But this belongs to the realms of artificial and cultural, not of natural, selection.

Mutations—Raw Materials of Evolution

It has been recognized, at least since Johannsen [14] if not earlier, that natural selection does not create the genetic variability upon which it operates. The raw materials of evolution are mutational changes. The selection perpetuates and multiplies mutants which increase the fitness of their carriers, and eliminates the deleterious ones. Because their origin is due to accidents, chiefly to errors in the replication of DNA molecules, mutations are adaptively ambiguous.

They arise regardless of whether they will be useful where and when they appear, or ever. It is generally agreed that many, perhaps most, mutations are adverse to adaptedness, and only a minority are useful. From here, it may seem to be only a small step to the conclusion that evolution is a chain of lucky accidents.

Miscomprehension of the role of so-called chance in evolution has warped many judgments. Auden [15], who is properly impressed by facts of organic adaptedness, says: "If you ask me only to believe that this is the result of random mutations—and as you probably know most random mutations that we observe are lethal—put through the sieve of natural selection, I think this is much crazier than believing in fairies." Auden is a poet rather than a biologist, but his statement packs neatly the whole collection of fallacies, which some biologists have also improvised. Mutations are "random" only in the sense that they do not arise exclusively when the species needs them and, as stated below, their origin is due mainly to replication errors. They are not random because a mutation, unless it destroys the gene altogether, can only make a slight variant of the structure of the gene, a structure which is a product of its long evolutionary history.

If a gene is a series of some hundreds of DNA nucleotide pairs, it can be changed by single nucleotide substitutions in some thousands of ways. There is a multitude but not an infinity of possible changes. The α chain of human hemoglobin differs in a single amino acid (out of 141) from gorilla hemoglobin. A single nucleotide substitution in the gene coding for this hemoglobin chain suffices to account for the difference. Human α chain differs, however, in eighteen amino acids from horse, twenty-five from rabbit, and seventy-one from carp hemoglobins. The α and β chains of human hemoglobin differ in eighty-four amino acid substitutions, additions, or losses. The genes coding for the α and β chains arose from a common ancestral gene, which became duplicated in our remote progenitor and subsequently diverged by accumulation of mutations. Could the gene coding for α be transformed by a single mutation into that coding for β chain of hemoglobin? This is utterly improbable because it would require a coincidence of the particular eighty-four substitutions.

A single mutation is, on the molecular level, an accident. It can be compared with a sound produced by striking a single piano key at random. What we observe on the organismic level is harmonious systems of components arisen by mutations. They have been orchestrated by a deaf and blind but highly resourceful composer—natural selection. Chlorophyll, hemoglobins and myoglobins, the human brain, and man as a whole are no more accidental than a Beethoven symphony.

To put it in another way, mutation and sexual recombination supply the raw materials from which natural selection constructs genotypes attuned to the demands of the environments. Evidently no construction can happen without raw materials, as no mosaic picture can be composed without a supply of stones of various colors. But if a stone of exactly the right color is unavailable, a slightly different shade may still permit a mosaic picture to be made. Ours is not the best of all thinkable worlds, perhaps only of possible worlds.

Natural Selection—Directing Agency of Evolutionary Changes

Natural selection has often been called another chance factor, on a par with mutation. This is a misapprehension; natural selection is an antichance agency. The origin of the misapprehension is that natural selection operates mostly with probabilities. To be promoted by selection, a variant gene or a gene combination need only to increase the likelihood that it will be transmitted to the next generation more often than some alternative genes or gene combinations. Vice versa—a gene need not be lethal to have its frequency in a population diminish from generation to generation. The crux of the matter is that natural selection involves a feedback between the gene pool of a species and its environment. The gene pool is continuously in flux; countless gene combinations that mutation and sexual recombination generate are being tried out for adaptedness to the environment.

The most insidious misconstruction is viewing natural selection as a sieve. The point involved is rather subtle. Most adaptive systems are far too complex to arise by single mutations. True enough, one mutation may confer on a microorganism a resistance to an antibiotic, or on an insect a resistance to an insecticide. But to believe that the "invention" of photosynthesis, or of constant body temperature, or of human mind came about by single mutations which passed through a "sieve" is nonsense. All these "inventions" are outcomes of long evolutionary developments. Assuming that life arose only once, every gene as well as every living species has had a history somewhere between 3 and 4 billion years long and numbers of generations difficult to estimate even as to the order of magnitude. Planets and solar systems had still longer histories, but these histories were not controlled by natural selection. The history of life was, and is, so controlled.

When environments, cultural or physical or ecological, undergo rapid alterations, the rates of genetic changes also accelerate. What is important is that the changes caused by directional natural selection are as a rule adaptive. They increase the Darwinian fitness in the environments in which they occur. Man did not arise by a lucky chance mutation which happened to pass through the "sieve" of natural selection. To say that he arose by a succession of chance mutations is misleading; his biological base has been constructed by natural selection, in a multitude of responses to environmental challenges. The responses were mediated by natural selection. It does not follow from this that man was bound or predetermined to arise.

Cladogenesis and Anagenesis

It is platitudinous to note that man faces the same biological necessities as other animals, and in fact all living beings. He needs food to replenish his energy store, must find a mate, and must nurture, protect, and train his progeny until they are old enough to fend for themselves. Every biological species has evolved its own distinctive answers to the problems posed by the universal biological needs. Life has deployed itself in some millions of species, instead of remaining a single one, because the diversity of environments on our planet can best be utilized by a multitude of diverse living beings.

Any species that is not on the brink of extinction manifestly has a valid set of solutions for the basic biological problems. This is what a biologist means by the statement that every species has an adaptedness to its environment. But if so, why has evolution not come to a halt? It is going on and on, bringing forth ever-new solutions of the same primordial problems. To a nonbiologist (or to an exclusively laboratory biologist), this looks like *plus ça change plus c'est la même chose*. What really happens is much more interesting than endless variations on the same theme. Life tends to spread and utilize every opportunity for living, no matter how narrow and constraining it may seem to us. Habitable caves have a total area which is a tiny fraction of the earth's surface, and food resources are scanty even in proportion to the area. Yet there evolved in subterranean habitats a diverse and highly specialized fauna of thousands of species. There are plants and animals specialized to live in hot springs, harsh deserts, and frigid arctic or antarctic regions.

Three kinds of evolutionary changes, which are not mutually exclusive and frequently occur together, can be distinguished. The first is adaptive radiation or cladogenesis. A group of animals or plants become diversified, so that the descendants of one ancestral form adopt different ways of living. They become morphologically, physiologically, and behaviorally adjusted to their diverse ways of gaining subsistence from their respective environments. The second is called by Simpson [4] "relay effect." This is best explained by examples. During the "age of reptiles," the Mesozoic, a variety of ecological niches were filled by herbivorous, carnivorous, land-, water-, and air-dwelling (flying) reptiles. With the advent of the Cenozoic era, the same ecological niches were settled by correspondingly specialized mammals, while most of the reptiles died out. During the Tertiary, there was always a variety of hoofed herbivorous mammals; however, there was a relay of different mammalian orders replacing each other in the various ecological niches. The former occupants of these niches became rare or extinct. What is the biological meaning of the relay effect? The successors were presumably more efficient than their predecessors in the exploitation of a set of environments and ways of living.

The least frequent but perhaps most important kind of evolution is anagenesis. This has also been called phyletic or progressive evolution; the last of these designations has so many ill-defined connotations that some evolutionists (e.g., Simpson) avoid it altogether. What is involved is discovery by a species or a group of species of previously unexploited ecological opportunities, and adoption of a novel way of living appropriate for these opportunities. Evidences of such evolutionary masterstrokes are found in the paleontological record.

For close to 3 billion years life existed only in water; every living body sitll contains water which is essential for its remaining alive. Land seemed unpropitious as a dwelling place, since any organism venturing on land faced the problem of obtaining water from somewhere. Nevertheless, some land plants appeared in the Silurian and became widespread in the Devonian period, closely followed by emergence of land animals. Insects became common by the end of the Paleozoic, and by the end of the Mesozoic some of them established mutualistic relationships with some plants. Flowering plants burst forth on the scene, enlisting the services of insects for transportation of their pollen, that is, the male generative elements. The invention of constant body temperature in mammals and birds made them less dependent than their ancestors were on vagaries of weather. And, finally, at the close of the Pliocene, or early in the Pleistocene, there appeared an extraordinary animal who began progressively to rely on learned rather than on genetically fixed behavior for securing his livelihood. Culture became man's paramount adaptive mechanism. While other living beings achieve adaptedness to their environments by changing their genes, man does so mainly, although not exclusively, by changing his environment to fit his genes.

Divergent and Convergent Evolution

As stated above, every living species faces basically the same biological necessities, and every species has its own distinctive solutions of the universal biological problems. The multiplicity of the solutions is clearly a result of adaptation to different challenges presented by different environments. And here we find a phenomenon which has fascinated biologists for several centuries. Sometimes quite diverse organisms facing similar environments have evolved analogous, or parallel, adaptive traits. Whales and dolphins are not fish, but they do resemble fish in having fins and body shapes convenient for movements in water. Whales and dolphins descended from mammals which lived on land and lacked fishlike traits; the present condition is a result of evolutionary convergence. Ants and termites belong to quite different insect orders, but they evolved numerous similarities in the structure of their societies. In Australia, marsupials evolved a series of ecological forms which are represented elsewhere by placental mammals; an analogous situation prevailed in South America during the Tertiary, when this continent was populated by marsupials and was devoid of placentals. Examples of this sort can be multiplied indefinitely. Rensch [8] lists 100 "rules of evolution" to show that "evolution is a largely lawful process, and with regard to the effect of continuous mutation and natural selection it is also a determinate process."

It is indeed remarkable that similar environments have often evoked similar evolutionary adaptive responses in not closely related forms of life. But it is equally significant that in many instances the responses were not similar. Adaptedness to a given environment can be secured by different means. For example, to survive winter cold, a species may evolve a mechanism of winter dormancy, or constant body temperature, or migration to warmer climates, or the use of fire. Predation of juveniles can be countered by high fecundity, or by concealment, or by parental care and protection. Desert plants resist aridity by transforming leaves into spines, or by shedding leaves during dry and developing them during wet seasons, or by compressing the life cycle of germination, growth, flowering, and maturing seeds into a short time span during which water is plentiful. There is nothing to indicate that any of these methods of adaptation is intrinsically superior to the others.

Some instances of nonutilization of available adaptive options are conspicuous and worthy of careful thought. The twenty-one now-living phyla of the animal kingdom all originated in the sea. Most of them also gave rise to creatures dwelling in fresh water, but some, including the ancient and widespread echinoderms and brachiopods, have not done so. Adaptations to life on land have been achieved independently by arthropods, chordates, molluscs, annelids, nematodes, and a few flatworms and nemertines, but not by other phyla. Land animals often evolved lineages which went back to live in fresh and in salt water. Insects have radiated into a number of species roughly equal to all other animals combined. They live in an enormous variety of environments, including some outlandish ones, but they are remarkably unsuccessful in readaptation to marine life. The fly genus *Pontomyia* is the only insect which passes its entire life cycle in the plankton near coral reefs [16]. Ants of the subfamily Attini are "agriculturists," building elaborate fungus plantations in their nests, and feeding on the fungi which they raise. This subfamily has many very successful species in the tropics of the Western Hemisphere, but nothing like them has evolved in the Old World tropics, where the environment would seem to be equally favorable. The existence of an adaptive opportunity clearly does not guarantee that this opportunity will be utilized.

Primordial Life and Progressive Evolution

The probability, or improbability, of independent origin of life in several places in the universe need not be considered in the present article. Astronomers have no conclusive evidence of earthlike planets outside the solar system, but hold that they may not only exist but be very numerous. For the sake of argument, let us assume that that life, based on proteins and nucleic acids, is present in extraterrestrial habitats. If so, what inferences can be drawn concerning its evolution?

Despite all the uncertainties inevitable in dealing with a topic so speculative as extraterrestrial life, two inferences can be made. First, the genetic materials will be subject to mutation. Accurate self-copying is the prime function of any genetic materials, but it is hardly conceivable that no copy erors will ever be made. If such errors do occur, the second inference can be drawn: the variants that arise will set the stage for natural selection. This much must be a common denominator of terrestrial and extraterrestrial life. Does this make progressive evolution inevitable? This is a possible, but by no means a necessary, outcome. Among various kinds of natural selection that we know [17], the most obvious is normalizing selection. This is a conservative, not an innovative, agent; it guards adaptive genotypes against degenerative changes. An innovative agent is directional selection which alters the genotype and makes its carriers better fit to survive, usually in environments different from those of their ancestors.

Life newly arisen must be a frail thing. It subsists in a single, very narrow ecological niche. According to current theories, life on Earth arose in a dilute "soup" of abiotically synthesized organic compounds in the primeval ocean, and was "feeding" on these compounds. All mutations might then be harmful and would be swept out of existence by normalizing natural selection. To escape this bind, life had to deploy itself over two, several, and eventually over numerous ecological niches, thus opening up a field for the action of directional selection. Life on Earth has managed to do so, but it should not be lightly assumed that any life would necessarily succeed also.

Capturing energy sources other than the aforementioned dilute "soup" must have been a crucial change in organic evolution. Utilization of solar energy by photosynthesis is the most successful solution of this problem achieved by life on earth. Here again, it should not be taken for granted that photosynthesis was guaranteed to arise. Photosynthesis did not arise by a lucky chance mutation. A workable mechanism could only be compounded over a long stretch of time by selection. It probably involved accretion of many mutational constituents, some of which may have been selected originally for physiological reasons unrelated to photosynthesis. Photosynthesis was neither a gift of chance nor vouchsafed by necessity. Chance and necessity are complementary aspects of the evolutionary process, somewhat like the wave and particle aspects in quantum theory of modern physics.

Life on Earth branched into plant and animal kingdoms. This was not a foregone conclusion. Earth could have remained inhabited only by photosynthesizing plants and saprophytic microbes. He is a brave zoologist who thinks that he knows why the animal kingdom must have differentiated into the twenty-one existing phyla, and not some quite dissimilar ones. Or, when the vertebrates appeared, should they necessarily have branched into fish, amphibians, reptiles, birds, and mammals? The origin of man was one of the many unforseeable outcomes of evolutionary development. The emergence of man is a matter of the relatively recent past, and it can be discussed somewhat more realistically than the events of remote and obscure antiquity.

The Evolutionary Uniqueness of Man

In man, biological evolution has transcended itself. It has done so by giving rise to the biological, genetic foundation of culture. Many definitions of culture have been proposed. One of them is: "patterns explicit and implicit of and for behavior, acquired and transmitted by symbols, constituting the distinctive achievement of human groups, including their embodiments in artifacts" [18]. Although there exist genetic differences among individuals in their propensities to learn various aspects of culture, the capacity to acquire and transmit culture is species-wide. There is no doubt that this capacity is a supremely important evolutionary attainment of the human species. It has conferred on mankind not only an adaptedness but also an unsurpassed adaptability to a great variety of environments, particularly those created or modified by cultures themselves. Man adapts not only *by* culture but also *to* culture.

The superiority of culture as a means of adaptation is due to its far greater versatility compared to biological evolutionary adaptive processes. Knowledge can, in principle, be transmitted to anybody, while genes can be passed solely to one's progeny. A new idea or an invention may be conveyed to any number of people at the same time; a genetic mutation or a recombination, no matter how favorable, needs many generations to spread through a species. Biological evolution is, accordingly, outdistanced by the cultural.

Man and higher primates differ in body structures only enough to warrant man's being considered a separate family—Hominidae. The main differences are those connected with upright walking. The gap between mental abilities of man and even his closest relatives, chimpanzee and gorilla, is far greater. Culture includes much more than using and making tools, and it demands cognitive skills which are far beyond the capabilities of man's cousins. Man has an aptitude for abstract and symbolic thought. This aptitude has been utilized for the purpose of communication by means of symbolic languages. Human social living is predicated upon the existence of language and manipulation of symbols. Man reflects upon himself and can see himself, as it were, from outside, as an object among a multitude of other objects. His most elusive property is self-awareness; it is elusive because every person directly experiences solely his own self-awareness and can only infer the existence of self-awareness in other persons because they act in ways analogous to his. Nevertheless, self-awareness is for every one of us the most indubitable of all realities; it is the basis of Descartes's "cogito ergo sum." Man contemplates his individual future and discovers that his destination is inevitably death. Man possesses not only self-awareness but also death-awareness.

Just how and why man's ancestors of 2,000,000–3,000,000 years ago embarked on so singular a method of adaptation is a matter of speculation. Some anthropologists have plausibly supposed that this may have been brought about by alterations of the diet and in the ways of securing food. Our ancestors changed from arboreal to terrestrial habitats, acquired erect posture, and shifted from a predominantly vegetarian to an at least partly meat diet. They became hunters who profited by cooperation with their fellows to track and overpower progressively larger and more powerful game. Hunting in groups, rather than singly, put a selective premium on the ability to act in concert and to communicate with conspecific individuals. Communication by symbolic language is by far the most versatile method, making feasible an infinite variety of messages. Prolonged helplessness of human infants compelled other changes. It necessitated a division of labor between females and males, and what has been given the sobriquet "domestication of fathers." Fathers not only became food providers but, instead of fighting each other for the possession of females, turned partly or exclusively to monogamy. Loss of estrus and continuous sexual receptivity of the human female, contrasting with the situation in other primates and in most mammals, facilitated the "domestication."

There are at least 2,000,000 species living on Earth. Among them, man is the only one having symbolic language, extragenically transmitted culture, self-awareness, and death-awareness. These unique abilities made mankind singularly successful in adapting to and controlling its environments. And yet no other species was impelled by natural selection to evolve in similar ways. This fact alone shows how naïve is the opinion that if life exists anywhere it must eventually give rise to rational beings. It is no less fatuous to think that if mankind were destroyed here on Earth, another intelligent species would evolve to replace it. As Simpson rightly wrote [4], "If human origins were indeed inevitable under the precise conditions of our actual history, that makes the more nearly impossible such an occurrence anywhere else."

Chance and Necessity in Evolution

In evolutionary biology, chance and necessity are not mutually exclusive. The dilemma is removed once the nature of the evolutionary process is understood. Mutations are accidental only with respect to the adaptive needs of their carriers. Otherwise, the mutations possible in a given gene are circumscribed by its historically evolved structure. By contrast, the adaptive needs impose constraints upon the action of natural selection. Natural selection is an antichance agency. It operates as a feedback servomechanism between a species and its environment. Its operation results as a rule in maintenance or enhancement of adaptedness. And yet no particular form of adaptedness is imposed by the environment or by selection. In this world one can become adapted to live in different ways and by different means.

Some purists regard "invention" as too anthropomorphic a word to be used in connection with biological evolution. I think it is most apposite. Was mankind predestined or was it "invented"? Imagine that there was a highly competent biologist living in Eocene times; could he have predicted that man would appear? Or else, suppose that by some utterly unlikely chance there is another planet somewhere, on which there arose animals and vertebrates and mammals like those which lived on earth during the Eocene period. Must manlike creatures develop also on this imaginary planet? I believe that the last two questions must be answered in the negative. Man has at least 100,000 genes, and perhaps half of them (or more) changed at least once since the Eocene. The probability is, to all intents and purposes, zero that the same 50,000 genes will change in the same ways and will be selected again in the same sequence as they were in man's evolutionary history.

Prodigious numbers of gene patterns arise, particularly in sexually reproducing species. Sewall Wright pointed out in 1932 [19] that

1,000 genes, each with only ten alleles (these are again overconservative estimates), could make $10^{1,000}$ combinations. Individuals of all species than ever lived, and presumably that will ever live, are very much fewer. A vast majority of potentially possible gene combinations remain unrealized. What evolutionary changes could have sprung from the potentially possible but unrealized gene combinations we shall probably never know.

What really matters is that some gene combinations among those that actually arose were selected because they were advantageous. They were advantageous not because they eventually added up to man, and in some remote future may become a genetic foundation of superman. They were beneficial at the times and places when and where they were selected, to our remote ancestors who were in some respects quite different from ourselves. The adaptive traits in man and in his ancestors are not and were not independent but functionally and ecologically interdependent. Versatile hands made possible extensive tool use and tool making, and reliance on tools increased the selection pressure for further improvements in the human kind of locomotion and in manual dexterity, which in turn led to even more complete dependence on tools. Division of labor between the sexes and cooperation in hunting rendered effective communication indispensable, and emergence of symbolic language made societal arrangements more complex and eventually vital. The ability to govern one's behavior in the light of experience increased the adaptedness of behavioral plasticity and stimulated information storage and transmission, first by oral tradition and subsequently by writing and printing.

Some 2,000,000 years ago, East Africa was inhabited by at least two species of australopithecines, at least one of which manufactured chipped stone tools. One of these probably was our ancestor. We do not know why the other, or others, died out. Perhaps the unsuccessful ones were too slow in developing human qualities, but it is also possible that they turned in some different adaptive directions which proved to be blind alleys. Evolution is a synthesis of determinism and chance, and this synthesis makes it a creative process. Any creative process involves, however, a risk of failure, which in biological evolution means extinction. On the other hand, creativity makes possible striking successes and discoveries. Man is the greatest success on Earth of biological evolution to date. Natural scientists have been loath, for at least a century, to asume that there is anything radically unique or special about the planet Earth or about the human species. This is an understandable reaction against the traditional view that Earth, and indeed the whole universe, was created specifically for man. The reaction may have gone too far. It is possible that there is, after all, something unique about man and the planet he inhabits.

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EXTRACURRICULAR INSTRUCTION

I sure had stern instruction
When I began maturing;
I think I can recall it all,
Its memory is enduring.

I kept my eye upon the ball,
My ear upon the ground;
My nose was to the grindstone,
Until it got quite round.

I kept my shoulder to the wheel,
My foot upon the brake;
I kept my voice box silent
Lest I make a big mistake.

I put my hand upon the plow,
My elbow on the table;
I knelt upon my knees at night,
And prayed that I'd stay able.

I kept my privates in my pants
Except when making water;
That's something everyone agreed,
As being what one ought ter.

All parts of my anatomy
Had things to do it seems,
Including that which fabricates
Thoughts, and plans, and dreams.

CARL A. DRAGSTEDT