Theodosius Dobzhansky

CREATIVE EVOLUTION[1]

We have hesitated in choosing this title because it is identical with that of Bergson's masterly work. Bergson was perhaps the most eminent philosopher to build his philosophical views in part on the basis of biological evolutionism. The biological knowledge which was available in Bergson's time is however now out of date. Our present understanding of evolution is rather different from his. This is as it should be. Science is cumulative knowledge. A scientist works to make the knowledge whith which he started obsolete. In a very real sense he works to make his own work obsolete as well. In so far as a philosophy has science as one of its components, or supports, philosophy must be rethought, reconstructed, and reformulated from the vantage point of each generation. If all conclusions based on scientific knowledge of a half century ago were still valid, this could only mean that the study of the evolution of life is no longer profitable. Such however is not the case.

Biological evolution is creative because it produces novelties.

[1] This article will appear, together with others, in a volume entitled *Essais sur l'évolution,* to be published by Masson et Cie as part of the series, "Les Grands Problèmes de la Biologie," edited by Professor Grassé.

An artist creates when he produces something new. His painting, his poem, his symphony are unlike anyone else's. To copy a painting, to recite a poem, or to play a symphony are creative acts only in so far as they give some new emphases to, or introduce novel variations of the original creations. Different forms of animal and plant life are different because they carry different constellations of genes. But here we must be on our guard not to oversimplify the actual situation. The biological (neo-Darwinist) theory of evolution is sometimes presented as a mere mechanical sorting of good and bad genes. This is however too narrow a view. In addition to being a mechanism, evolution is a creative adventure. It is creative in the same sense as the work of an artist is creative. It brings about absolute novelties, constellations of genes which did not exist anywhere before. Not all new gene constellations become established in nature, but only those internally harmonious, so that they enable their possessors to survive. And finally, evolutionary creativity, as artistic creativity, involves a risk of failure, miscreation, which in the biological world means death, extinction.

Sexual reproduction is a method of creation of novelty. Mendel demonstrated that an individual heterozygote for *n* genes can produce two to the *n*th power of different gametes. Consider a diploid species. If both parents are heterozygous for the same *n* genes, they are potentially able to produce three to the *n*th power of different genotypes in the offspring. If the two parents are each heterozygous for *n* different genes, then four to the *n*th power genotypes are potentially possible.

It is unfortunately unknown for how many genes a given individual, or an average individual, is heterozygous in human populations, or in those of mice, or of Drosophilae, or of pine trees. Some geneticists would estimate the average number in hundreds or even thousands. Although we are inclined to the view that the higher estimates are probably correct, let us take for the sake of argument a rather low figure, say 50. Now, two to the fiftieth, not to speak of three of four to the fiftieth, power are colossal figures. What they really mean biologically is that the sexual process is potentially capable of producing far more gene combinations than can be realized. This is because no species, at least among higher organisms, is represented by numbers of individuals great enough to embody all the potentially possible gene combinations.

Or to put it in another way, the potentially possible genetic variety is so great that the chances of any genotype being formed more than once are negligible. To put it still differently, except for identical twins, the genotype of every person, or every Drosophila, or every pine tree has never existed before, and presumably never will be formed in the future. It is often said that science can deal only with what is repeatable. Individuality, uniqueness, is the province of art rather than of science. This is true in a sense, but we claim for genetics the distinction of being the science that is concerned in part with understanding the production of what is individual and non-repeatable.

Is there much novelty in combining the same *n* genes in no matter how many different ways? *Plus ça change, plus c'est la même chose?* Here is a point which geneticists do not always make clear in their writings, and the lack of clarity is perhaps responsible in part for the opposition of many biologists to the so-called neo-Darwinist theory of evolution. (Neo-Darwinism is really the name applied to the theories of Weismann and his followers at the beginning of the present century. The current theory is the "synthetic" or the "biological" theory. We prefer the term "biological" because it implies that the theory is based on data of all biological disciplines rather than a single one or a few).

It may be that, on the molecular level, each gene is responsible for the production of only one polypeptide chain which is a constituent of a protein. But the development of an individual is something more than the production of so many polypeptide chains. It is a highly complex system of interactions, feedbacks, regulating processes. The development cannot be understood as a sum of actions of the genes, each operating independently of the others. On the contrary, the genes, or more precisely their effects, interact. Suppose that every change in the gene changes only a single enzyme, or a single protein. The consequences of such a single change may however be innumerable and may affect the whole body. Gene effects ramify in the development, and manifest themselves in most diverse body parts and body functions. In classical genetics this is termed pleiotropism of gene action. Examples of pleiotropism abound in human genetics. Hereditary variants are usually "syndromes." A syndrome means that not a single character but a whole constellation of characters is changed.

Thus, each individual genotype gives something new, something different, unprecedented and non-recurrent. A living individual is nature's creative experiment, trying out a new mode of living. Of course, not all experiments of living are successful. This we know very well in human affairs. Every person has a life different from all others, and by whatever criteria you choose to judge, some lives succeed better than others. In man the success or failure are determined not by the genes alone, although the genes cannot be left out of account. On the organic level below man, the role of the genes is greater. Biological success is life, survival, as contrasted with death, extinction.

Novelty is a necessary but not a sufficient condition of creativity. If you throw a handful of sand on a sheet of paper, the grains of sand will always mark a novel distribution. Some modern painters "paint" by pelting a canvas with colors. As biologists we may be ignorant in art, but we hope that not every painting so obtained is regarded as a *chef-d'œuvre.* Artistic creation must produce something not merely new but something of esthetic or other value. Biological value is, as stated above, survival of the individual, and, most of all, of the species.

Assume that there exist in the world only 10,000 different genes, and that each gene can change in only 10 different ways. These are doubtless underestimates. A minimal number of possible gene combinations is, then, 10 to the 10,000th power. The number of subatomic particles in the universe is a mere 10 to the power of about 80. It is, therefore, safe to say that only a vanishingly minute fraction of the potentially possible gene combinations can ever be realized in living individuals.

The question that logically presents itself is whether it is simply a matter of chance which gene combinations are realized and which are not. This is certainly not a matter of chance. The anti-chance agency which operates in the biological world is natural selection. The gene combinations that can be formed are mostly, though not exclusively, those that make survival and reproduction possible. An almost infinitely greater number of gene combinations that would be disharmonious are not produced at all; a relatively very few that are produced are not perpetuated.

The evidence of this is that the living world is not a continuum of variants, but an array of clusters. These clusters are the species, genera, families, orders, etc. Each cluster is an array of gene combinations which enable their carriers to have a certain mode of life. The genotypes intermediate between, say, mammals and birds do not exist and never existed. Of course, in some remote past mammals and birds arose from some common ancestors. Perhaps all organisms arose from a single primordial life. This does not however mean that all possible combinations of the genes of the now living mammals and birds ever existed. Such combinations could only be absurdly disharmonious.

It is often alleged that the biological (so-called neo-Darwinist) theory of evolution regards the existing organisms as products of lucky combinations of genes. This is sheer misunderstanding. Natural selection is an anti-chance agency. It is a cybernetic process which keeps the population and the species in harmony with its environment. Natural selection transfers to the genotype, and stores in the genotype, information about the states of environments. Living organisms have been called time-binding machines. From the evolutionary standpoint it is more meaningful to say that they are information-binding machines. Some Lamarckists have compared heredity to memory. This analogy becomes admissible if it is understood to mean that the hereditary endowment of a species is a repository of information concerning its present and past environments, assembled by natural selection in the history of the species.

Evolution occurs because living species maintain their adaptedness to their environments, or develop adaptedness to new environments. Is it correct to say that evolution is induced by the environment? To be valid, this statement must be carefully qualified. The direct action of the environment on the genotype may induce mutations. Most mutations are not however evolutionarily meaningful. Natural selection intervenes between the organism and the environment. We prefer to describe the relations between the environment and evolutionary changes in terms which the great English historian Toynbee has used to describe the relations between human history and environments. His terms are "challenge and response."

Evolutionary changes occur not because the genotype has in itself a program of step-by-step alterations leading from the beginning of life on our planet to its eventual culmination or destruction. This idea, accepted by followers of autogenetic, orthogenetic, and finalist theories of evolution, finds no support at all in anything we know about heredity. This idea is also uninteresting philosophically. If it were true, evolution could produce nothing new. It would not be a creative process.

Evolution is a response to environmental challenge. Now, a challenge invites but does not impose a response. A response may or may not occur. If it does, the species changes; if it does not, the species becomes a relic or extinct. It is important that there may be several different responses to the same challenge. This introduces an element of freedom in the biological evolution. Consider, for example, the ways in which plants become adapted to desert habitats. The challenge is the same—aridity, the need to conserve water. Yet, how remarkably different are the responses. Some plants have their leaves reduced to spines; others have the leaves covered with protective secretions; still others grow leaves only during the rainy season, and are leafless the rest of the time; and finally, some germinate, grow, flower, and mature seed quickly when a rainy season occurs. There is no evidence that any one of these responses is better than the others. Yet different genera and families of plants have responded differently. Those that did not respond cannot live in deserts.

As an illustration of how the response occurs, natural selection has often been compared to a sieve. This is a most unfortunate analogy; it is probably responsible for much of the opposition which the biological theory of evolution encounters. Let us see where the analogy is applicable and where it is not. If you expose large numbers of bacteria to an antibiotic, or large numbers of insects to an insecticide, all sensitive individuals are destroyed, and only a few resistant mutants survive. The antibiotic, or the insecticide, has acted as a sieve, which has separated the sensitive from the resistant genotypes. Yet evolution is far from so simple an affair.

Remember that every individual has a unique genotype. Remember also that the Darwinian fitness is a property of the genotype as a whole. We do not inherit the genotypes of our parents, we inherit only some of their genes. What natural selection promotes or suppresses is usually not this or that gene but a whole genotype. The phenomena of coadaptation go even beyond an individual genotype. It is the gene pool of a population, rather than a genotype, still less a single gene, that is selected. The sieve analogy breaks down. One would have to imagine an extraordinary sieve, so constructed that it retains particles or lets them pass, depending on what other particles are in the sieve.

If an analogy is desired, evolution by natural selection is rather like writing or playing symphonic music. The genes are more often like members of an orchestra, rather than the players. A good symphony is a very special interaction of all its parts, or a joint effort of all the players. A misplaced note or a bad musician can spoil the symphony. But one excellent musician can rarely by himself make a symphony or even a concerto good.

Comparing natural selection, which is a blind, impersonal, purposeless process, with a human activity such as performing or composing music will doubtless seem a dubious procedure to many biologists. We certainly do not intend to personify natural selection, but otherwise we must insist that this analogy is valid, as analogies go. It is certainly more valid than the sieve analogy. Much harm has been done by misrepresenting natural selection as a mere play of chance. This has given birth to a host of problems, pseudo-problems, and misunderstandings with which modern evolutionism must still contend.

Perhaps the most important of these problems is not new, since it was already discussed by Darwin. This is the evolutionary origin of complex organs, such as the vertebrate eye. It is, indeed, beyond belief that all the numerous and mutually well adjusted parts of the eye could have arisen by mutation, and have come together by chance. Suppose that some 100 genes must be in the proper allelic states to produce an eye, and suppose further that the mutation rate of these genes is on the average ten to the minus five power (1 : 100,000). The probability of all these mutations arising simultaneously in one individual is ten to the minus five hundredth power, or practically zero. And yet, it is pointed out, the absence of just one essential part of the eye makes it non-functional, and hence selectively useless.

Were this reasoning goes wrong is that it ignores history. Most surely, the human eye did not arise all at once in full perfection in the descendants of animals who had no organs of vision. Comparative anatomy discloses in the animal and even the plant world a great variety of photo-receptors, beginning with single photosensitive cells. Granted that these organs did not approach the functional efficiency of the human eye. Just the same, the possessors of these primitive organs derived some part of their adaptedness from their use. The dating is uncertain, but it is probable that human ancestors had some sort of eyes for half a billion years at least, probably much more. Now, our ancestors had photo-receptors not in order to provide ourselves, their remote descendants, with eyes. They had them because they used them. We are inclined to believe that it is not a collection of special "eye genes," but the whole human genotype that is needed to produce eyes. Eyes arise as an integral part of the embryogenesis. But the human genotype, as the genotype of any other organism, high or low, goes back to primordial life, some two billion years ago.

Evolutionary development, phylogeny, is often compared with individual development, ontogeny. Now, in the individual development there occur a series of most complex manoeuvres. Body structures and functions arise as if planned by some foresight. This foresight seems to aim at producing a body which can live in certain environments. Ontogeny seems to be attracted by its end rather than to be impelled by its beginning. This, again, seems a situation that natural selection cannot possibly achieve. On the contrary, it is tempting to suppose that the evolutionary development proceeds in the same way as the individual development. Why not suppose that primordial life was destined to produce man, and merely required two billion years to do so?

On a philosophical level, such an arrangement seems the height of futility. If God had planned all evolution only to produce man, the planning was remarkably inefficient. Why waste two billion years? Why all the suffering, tribulations, extinctions? On the biological level, ontogeny is understood better as a part of phylogeny, not the other way round. The ontogeny follows the course it does because it is a part of the cyclic, or better, spiral sequence of the ontogenesis of our ancestors. Organs in a developing individual are formed for future uses, because in evolution they were formed for contemporaneous utility. The development of an individual may be said to end in death; it makes biologically better sense to say that the development continues in the progeny.

Evolution is utilitarian. It does not, however, follow that every single trait or character found in the organism must be per se utilitarian. Consider the characteristics that distinguish species

https://doi.org/10.1177/039219216701505804 Published online by Cambridge University Press

of insects, or of plants, or of mammals. Many of them seem trivial and utterly without adaptive significance. Why, for example, do some species of Drosophilae have the anterior scutellar bristles convergent and other species divergent? Species with convergent and with divergent bristles seem to be equally well off in nature. Why do related species of birds differ in details of their coloration and of their songs? Would this or that bird survive less well if it sang a little differently?

First of all, two things must be made clear. The "utility" must be understood broadly. The colorations, songs, and modes of behavior act in many animals as species recognition marks. The bird songs are also connected with their territoriality. The nightingale sings as he does because his mate should be able to recognize him as a nightingale. Some species of birds have song "dialects" in different localities. To secure a mate in a given locality, it may conceivably be advantageous to sing in the local dialect.

The second argument is more general. Natural selection deals not with traits but with organisms. It is not a trait, it is a living individual or a Mendelian population that survives or dies, reproduces or remains sterile. A "trait" is really an abstraction which a human observer isolates for the purposes of describing the object of his studies. The positions of the bristles on a fly's body are external manifestations of the developmental pattern of a given fly species. It is the whole development pattern, not the convergence or the divergence of a part of bristles, that is adaptive.

Consider the rudimentary organs which abound in the bodies of many species. Why, for example, has the vermiform appendix been preserved in man? It gives only trouble to many people. One may, indeed, think that if there existed a special gene that formed the appendix and nothing else, this gene probably would have been lost in the human species. The genes do not however act that way. There is no special gene for the vermiform appendix, another for the small intestine, still another for the colon, etc. All these organs are integral parts of the development pattern of the digestive system. Evolutionary changes would have to alter the whole pattern in order to suppress the appendix. Now, this may, of course, happen—there are mammals without the vermiform appendix. But a change of this magnitude will be useful or harmful as a whole, and its component parts will contribute to the

https://doi.org/10.1177/039219216701505804 Published online by Cambridge University Press

adaptedness of the organism as a whole. It would be a daring biologist who would imagine that he knows which changes would be favorable and which unfavorable.

Is evolution, then, due to chance or to design? Was the origin of man in evolution a lucky accident, or was man preformed in primordial life? So far as we can judge from what is known at present, neither of these alternatives is true. Evolution proceeds by trial and error. Teilhard de Chardin, who invented this remarkably apt formula, was at the same time a believer in orthogenesis. We need not discuss here whether this belief was consistent with the idea of evolution by trial and error. What is clear is that trial and error describes perfectly, although of course metaphorically, evolution by natural selection. Curiously enough, Teilhard de Chardin was sceptical about natural selection.

Natural selection makes the species respond, usually adaptively, to the challenges of the environment. Yet natural selection has no foresight, it is opportunistic. It is opportunistic because it adapts the species always to the environments which exist here and now. It cannot adapt the species to environments which will exist in the future. The natural selection that acted on our australopithecine ancestors benefited the australopithecines, not homo sapiens. True enough, *homo sapiens* is what he is because the evolution of his ancestors proceeded as it did. To repeat, evolution is a cybernetic process; it is a series of feedbacks between the organism and the environment; in evolution, every change is conditioned by what changes preceded it, and it conditions the changes that will follow it. This is the meaning of the phenomenon called pre-adaptation. We conclude that something was a pre-adaptation only *ex post facto*. The development of the erect posture in human ancestors was a pre-adaptation which permitted the development of human hands, capable of making and using the complex machines of the modern age. But the erect posture must have been useful to our ancestors who did not operate modern machines. Erect posture developed in several groups of animals which did not subsequently invent machines.

Opportunism is however a dangerous course. It benefits the opportunist in the short run, but it often harms him in the long run. Adaptation to a present environment may make difficult adaptations to future environments. This is the danger of specialization. An organism narrowly specialized for some mode of life may happen to be perfectly adapted to an environment which does not endure. Such an organism lacks adaptability, it does not respond to novel environmental challenges. This often leads to extinction.

Here, then, we have a third characteristic of biological evolution which resembles artistic creation. Creation in art always involves a risk of failure. Even among Beethoven's compositions some are much inferior to others. Probably no artist regards all of his works as uniformly successful. Neither is all evolution uniformly successful. Paleontology gives ample evidence that most evolutionary lines end in extinction. Extinction is biological failure. Extinction is understandable because evolution proceeds by trial and error. It would not be understandable if evolution proceeded by orthogenesis. To explain extinction, the followers of orthogenesis had to invent a theory of evolutionary senility, analogous to an individual's old age. Biological theory of evolution has no need of the assumption of evolutionary senility. This is because, if we do not oversimplify things for the purpose of popular presentation, we must envisage evolution as a creative adventure. So understood, the biological theory may be acceptable to biologists who oppose its oversimplified version.

If the method of evolution is trial and error, the question that logically presents itself is to what degree is evolution deterministic or indeterministic. This question is discussed today most often in connection with the speculations concerning the existence of extra-terrestrial life. Are there rational beings, humanoids, on planets other than the earth in our own and in other solar systems? A symposium was recently held in the United States to discuss the promising methods of communication with these humanoids. We surely do not pretend to solve this question here, but as biologists we are entitled to formulate some prolegomena to its solution.

We believe that evolution is deterministic, but only in the sense of Laplace. That is to say, if a planet existed exactly like the earth in every smallest detail, then everything would develop there as it has on earth. This statement is meaningless however in practice. Though some astronomers estimate that there may be billions of planets with conditions approximately similar to those on earth, no one to our knowledge has claimed that there are identical twins among planets. The question must therefore be stated differently. Given environments that are more or less similar, will evolution follow more or less similar courses? Or else, suppose that the higher organisms on earth are destroyed, would evolution eventually reproduce them starting with the lower ones?

Let us assume, for the purpose of argument, that living matter based on nucleic acids and proteins does exist on other planets. At least some molecular biologists believe this to be probable enough. Let us also assume that the physical conditions—temperature, humidity, the chemistry of the atmosphere and of the rocks—are not radically unlike the terrestrial ones. And finally, let us assume that mutations occur in the extra-terrestrial genes, and hence that natural selection operates.

The crux of the matter is that there are many, perhaps an infinite number, of adaptive responses to the same environmental challenge. We have discussed above the diversity of forms of adaptedness of higher plants to desert conditions. Any organismic biologist can give other examples of the quite different solutions to the same adaptive problem by different organisms. And hardly any biologist would dare to say that still other solutions could not possibly have been invented. It may very well be that some of these solutions are more successful than others. It does not follow from anything that genetics has discovered that the most successful solution will surely be found given enough time. Even if only a single solution is possible, it does not follow that it will be arrived at.

Biologists have quite properly been impressed by the phenomena of evolutionary convergence. Among desert plants, *Cactaceae* and *Euphorbiaceae* have evolved strikingly similar forms in the deserts of America and Africa respectively. Ants and termites, insects not at all closely related, evolved forms of social life which are certainly not identical and yet similar in many ways. Flight has evolved independently in several classes of vertebrates, not to speak of the invertebrates. It is however useful to be reminded that while convergence and parallelism are often found, they do not invariably occur. Unlike snakes and spiders, mammals and birds have not evolved poisonous fangs, although one can imagine that fangs might have been useful to some of them for defense or offence. There are more species of insects than of all other animals counted together, yet truly marine insects are conspi-

https://doi.org/10.1177/039219216701505804 Published online by Cambridge University Press

cuously few. Horse-like forms appeared in different orders of mammals on the northern continents and in South America, but they have not evolved in Australia.

In evolution every change is conditioned by the preceding changes, and conditions the succeeding changes. Because of its cybernetic character evolution is, as human history, unrepeatable. The evolutionary inventions made the earliest had the greatest influence on the subsequent changes. Consider such things as photosynthesis by means of chlorophyll; transmission of impulse by means of nerve fibers; sexual reproduction and meiosis. The fact that both ants and termites have invented social life is surely remarkable. But after all, they were both terrestrial animals, arthropodes, insects. In other words, they did have some basic similarities on which to build similar further improvements. Can we however he sure that the basic inventions, as those mentioned above, are bound to occur where there are DNA and proteins? We see no reasons sufficient for such assurance.

Before Copernicus and Galileo man believed himself to be the center of the universe. This illusion has received so many setbacks that we are now suspicious of any theory that would suggest that man is central or unique in anything. The non-centrality and non-uniqueness of man should not however be dogmatic. After all, man may well be the only rational being in the universe. And if he is the only rational being, then he may well be the center of the universe, not in the geometric sense of course, but in the spiritual sense.