Evolution and Tinkering

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François Jacob

Some of the 16th-century books devoted to zoology and botany are illustrated by superb drawings of the various animals that populate the earth. Certain contain detailed descriptions of such creatures as dogs with fish heads, men with chicken legs, or even women without heads. The notion of monsters that blend the characteristics of different species is not itself surprising: everyone has imagined or sketched such hybrids. What is disconcerting today is that in the 16th century these creatures belonged, not to the world of fantasies, but to the real world. Many people had seen them and described them in detail. The monsters walked alongside the familiar animals of everyday life. They were within the limits of the possible.

When looking at present-day science fiction books, one is struck by the same phenomenon: the abominable animals that hunt the poor astronaut lost on a distant planet are products of recombinations between the organisms living on the earth. The creatures coming from outer space to explore the earth are depicted in the likeness of man. You can watch them emerging from their unidentified flying objects (UFO's); they are vertebrates, mammals without any doubt, walking erect. The only variations concern body size and the number of eyes. Generally these creatures have larger skulls than humans, to suggest bigger brains, and sometimes one or two radioantennae on the head, to suggest very sophisticated sense organs. The surprising point here again is what is considered possible. It is the idea, more than a hundred years after Darwin, that, if life occurs anywhere, it is bound to produce animals not too different from the terrestrial ones; and above all to evolve something like man.

The interest in these monsters is that they show how a culture handles the possible and marks its limits. It is a requirement of the human brain to put order in the universe. It seems fair to say that all cultures have more or less succeeded in providing their members with a unified and coherent view of the world and of the forces that run it. One may disagree with the explanatory systems offered by myths or magic, but one cannot deny them unity and coherence. In fact, they are often charged with too much unity and coherence because of their capacity to explain anything by the same simple argument. Actually, despite their differences, whether mythic, magic, or scientific, all explanatory systems operate on a common principle. In the words of the physicist Jean Perrin, the heart of the problem is always "to explain the complicated visible by some simple invisible" (*1*). A thunderstorm can be viewed as a consequence of Zeus' anger or of a difference of potential between the clouds and the earth. A disease can be seen as the result of a spell cast on the patient or of an infection by a virus. In all cases, however, one watches the visible effect of some hidden cause related to the whole set of invisible forces that are supposed to run the world.

The World View of Science

Whether mythic or scientific, the view of the world that man constructs is always largely a product of imagination. For the scientific process does not consist simply in observing, in collecting data, and in deducing from them a theory. One can watch an object for years and never produce any observation of scientific interest. To produce a valuable observation, one has first to have an idea of what to observe, a preconception of what is possible. Scientific advances often come from uncovering a hitherto unseen aspect of things as a result, not so much of using some new instrument, but rather of looking at objects from a different angle. This look is necessarily guided by a certain idea of what the so-called reality might be. It always involves a certain conception about the unknown, that is, about what lies beyond that which one has logical or experimental reasons to believe. In the words of Peter Medawar, scientific investigation begins by the "invention of a possible world or of a tiny fraction of that world" (*2*). So also begins mythical thought. But it stops there. Having constructed what it considers as the only possible world, it easily fits reality into its scheme. For scientific thought, instead, imagination is only a part of the game. At every step, it has to meet with experimentation and criticism. The best world is the one that exists and has proven to work already for a long time. Science attempts to confront the possible with the actual.

The price to be paid for this outlook, however, turned out to be high. It was, and is perhaps more than ever, renouncing a unified world view. This results from the very way science proceeds. Most other systems of explanation—mythic, magic, or religious—generally encompass everything. They apply to every domain. They answer any possible question. They account for the origin, the present, and the end of the universe. Science proceeds differently. It operates by detailed experimentation with nature and thus appears less ambitious, at least at first glance. It does not aim at reaching at once a complete and definitive explanation of the whole universe, its beginning, and its present form. Instead, it looks for partial and provisional answers about those phenomena that can be isolated and well defined. Actually, the beginning of modern science can be dated from the time when such general questions as, "How was the universe created?

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What is matter made of? What is the essence of life?" were replaced by such limited questions as "How does a stone fall? How does water flow in a tube? How does blood circulate in vessels?" This substitution had an amazing result. While asking general questions led to limited answers, asking limited questions turned out to provide more and more general answers.

At the same time, however, this scientific method could hardly avoid a parceling out of the world view. Each branch of science investigates a particular domain that is not necessarily connected with the neighboring ones. Scientific knowledge thus appears to consist of isolated islands. In the history of sciences, important advances often come from bridging the gaps. They result from the recognition that two hitherto separate observations can be viewed from a new angle and seen to represent nothing but different facets of one phenomenon. Thus, terrestrial and celestial mechanisms became a single science with Newton's laws. Thermodynamics and mechanics were unified through statistical mechanics, as were optics and electromagnetism through Maxwell's theory of magnetic field, or chemistry and atomic physics through quantum mechanics. Similarly different combinations of the same atoms, obeying the same laws, were shown by biochemists to compose both the inanimate and the living worlds.

The Hierarchy of Objects

Despite such generalizations, however, large gaps remain, some of which probably will not be bridged for a long time, if ever. Today, there exists a series of sciences that differ, not only by the nature of the objects that are studied, but also by the concepts and the language that are used. These sciences can be arranged in a certain order—physics, chemistry, biology, psychosociology—an order that corresponds to the hierarchy of complexity found in the objects of these sciences. Following the line from physics to sociology, one goes from the simpler to the more complex objects and also, for obvious reasons, from the older to the younger science, from the poorer to the richer empirical content, as well as from the harder to the softer system of hypotheses and experimentation. In order to obtain a unified world view through science, the question has repeatedly been raised as to the possibility of making bridges between adjacent disciplines. Because of the hierarchy of objects, the problem is always to explain the more complex in terms and concepts applying to the simpler. This is the old problem of reduction, emergence, whole and parts, and so forth. Is it possible to reduce chemistry to physics, biology to physics plus chemistry, and so forth? Clearly an understanding of the simple is necessary to understand the more complex, but whether it is sufficient is questionable.

This type of question has resulted in endless arguments. Obviously, the two critical events of evolution—first the appearance of life and later that of thought and language—led to phenomena that previously did not exist on the earth. To describe and to interpret these phenomena, new concepts, meaningless at the previous level, are required. What can the notions of sexuality, of predator, or of pain represent in physics or chemistry? Or the ideas of justice, of increase in value or of democratic power in biology? At the limit, total reductionism results in absurdity. For the pretention that every level can be completely reduced to a simpler one would result, for example, in explaining democracy in terms of the structure and properties of elementary particles; and this is clearly nonsense.

This problem can be considered in a different way. One can look at the series of objects, moving from the simpler to the more complex. Molecules are made of atoms. They therefore obey the laws that determine the behavior of atoms. But, in addition, two statements can be made about molecules. First, they can exhibit new properties, such as isomerization, racemization, and so forth. Second, the subject matter of chemistry, the molecules found in nature or produced in the laboratory, represents only a small fraction of all the possible interactions between atoms. Chemistry constitutes, therefore, a special case of physics. This is even more so with biology that deals with a complex hierarchy of objects ranging from cells to populations and ecosystems. The objects which exist at each level constitute a limitation of the total possibilities offered by the simpler level. For instance, the set of molecules found in living organisms represents a very restricted range of chemical objects. At the next level, the number of animal species amounts to several millions; however, this is small relative to the number that could exist. All vertebrates are composed of a very limited number of cellular types, at most 200, such as muscle cells, skin cells, and nerve cells. The great diversity of vertebrates results from differences in the arrangement, in the number, and in the proportion of these 200 types. Similarly, the human societies with which ethnology and sociology deal represent only a restricted group of all possible interactions between human beings.

Constraints and History

Nature functions by integration. Whatever the level, the objects analyzed by natural sciences are always organizations, or systems. Each system at a given level uses as ingredients some systems of the simpler level, but some only. The hierarchy in the complexity of objects is thus accompanied by a series of restrictions and limitations. At each level, new properties may appear which impose new constraints on the system. But these are merely additional constraints. Those that operate at any given level are still valid at all more complex levels. Every proposition that is true for physics is also true for chemistry, biology, or sociology. Similarly every proposition that is valid for biology holds true in sociology. But as a general rule, the statements of greatest importance at one level are of no interest at the more complex ones. The law of perfect gases is no less true for the objects of biology or sociology than for those of physics. It is simply irrelevant in the context of the problems with which biologists, and even more so sociologists, are concerned.

This hierarchy of successive integrations, characterized by restrictions and by the appearance of new properties at each level, has several consequences. The first is the necessity of analyzing complex objects at all levels. If molecular biology, which presents a strong reductionist attitude, yielded such a successful analysis of heredity, it was mainly because, at every step, the analysis was carried out simultaneously at the level of the molecules and at the level of the black box, the bacterial cell. This applies also to recent developments in immunology. And it seems likely that such a convergence of analysis will play an important role in the study of human beings and their societies.

The second point concerns predictability. Is it possible to make predictions at one level on the basis of what is known at a simpler one? Only to a very limited extent. The properties of a system can be explained by the properties of its components. They cannot be deduced from them. Starting from fundamental laws of physics, there is no way of reconstructing the universe. This means that a particular system, say a cell, has only a certain probability of appearing. All predictions about its existence can only be statistical. Molecular biology has shown that ultimately the characteristics of a cell rest on the structure of its molecular components. But the appearance of life on the earth was not the necessary consequence of the presence of certain molecular structures in prebiotic times. In fact, there is absolutely no way of estimating what was the probability for life appearing on earth. It may very well have appeared only once.

The third point concerns the nature of the restrictions and limitations found at every step of increasing complexity. Can one explain why, among all the possible interactions at one level, only certain are actually observed at the more complex one? How is it that only some types of molecular structures are present, for instance, in living organisms? Or only some interactions in human societies? There is no general answer to such questions, and it seems doubtful that there will ever be a specific answer for any one particular level of complexity. Complex objects are produced by evolutionary processes in which two factors are paramount: the constraints that at every level control the systems involved, and the historical circumstances that control the actual interactions between the systems. The combination of constraints and history exists at every level, although in different proportions. Simpler objects are more dependent on constraints than on history. As complexity increases, history plays a greater part. But history has always to be introduced into the picture, even in physics. According to present theories, heavier nuclei are composed of lighter ones and ultimately of hydrogen nuclei and neutrons. The transformation of heavy hydrogen into helium occurs during the fusion process, which is the main source of energy in the sun as well as in hydrogen bombs. Helium and all the heavier elements are thus the result of a cosmological evolution. According to present views, the heavier elements are considered as products of supernovae explosions. They seem to be very rare and not to exceed 1 or 2 percent by mass of all matter, while helium represents one-fifth and hydrogen four-fifths of all matter. The earth and the other planets of the solar system have thus been made of very rare material under conditions that seem to be rarely encountered in the cosmos. The source of hydrogen itself is left to theories and speculations concerning the origin of the universe.

Natural Selection

The constraints to which systems are subjected vary with the level of complexity. There are always some constraints imposed by stability and thermodynamics. But as complexity increases, additional constraints appear—such as reproduction for living systems, or economic requirements for social systems. Consequently, there cannot be any general law of evolution, any recipe that accounts for increasing complexity at all levels. Since Darwin, biologists have progressively elaborated a reasonable, although still incomplete, picture of the mechanism that operates in the evolution of the living world, namely, natural selection. For many, it has been tempting to invoke a similar mechanism of selection to describe any possible evolution, whether cosmological, chemical, cultural, ideological, or social. But this seems condemned to fail from the outset. The rules of the game differ at each level. New principles have, therefore, to be worked out at each level.

Natural selection is the result of two constraints imposed on every living organism: (i) the requirement for reproduction, which is fulfilled through genetic mechanisms carefully adjusted by special devices such as mutation, recombination, and sex to produce organisms similar, but not identical, to their parents; and (ii) the requirement for a permanent interaction with the environment because living beings are what thermodynamicists call open systems and persist only by a constant flux of matter, energy, and information. The first of these factors generates random variations and produces populations in which all individuals are different. The interplay of the two factors results in differential reproduction and consequently in populations that evolve progressively as a function of environmental circumstances, of behavior, and of new ecological niches. But natural selection does not act merely as a sieve eliminating detrimental mutations and favoring reproductions of beneficial ones as is often suggested. In the long run, it integrates mutations, and it orders them into adaptatively coherent patterns adjusted over millions of years, and over millions of generations as a response to environmental challenges. It is natural selection that gives direction to changes, orients chance, and slowly, progressively produces more complex structures, new organs, and new species. Novelties come from previously unseen association of old material. To create is to recombine.

Engineer and Tinkerer

The action of natural selection has often been compared to that of an engineer. This, however, does not seem to be a suitable comparison. First, because in contrast to what occurs in evolution, the engineer works according to a preconceived plan in that he foresees the product of his efforts. Second, because of the way the engineer works: to make a new product, he has at his disposal both material specially prepared to that end and machines designed solely for that task. Finally, because the objects produced by the engineer, at least by the good engineer, approach the level of perfection made possible by the technology of the time. In contrast, evolution is far from perfection. This is a point which was repeatedly stressed by Darwin who had to fight against the argument of perfect creation. In the *Origin of Species*, Darwin emphasizes over and over again the structural or functional imperfections of the living world. For instance, when he discusses natural selection (*3*, p. 472):

> Nor ought we to marvel if all the contrivances in nature be not, as far as we can judge, absolutely perfect. We need not marvel at the sting of the bee causing the bee's own death; at drones being produced in such vast numbers for one single act, and being then slaughtered by their sterile sisters; at the astonishing waste of pollen by our firtrees; at the instinctive hatred of the queen bee for her own fertile daughters; at ichneumonidae feeding within the live bodies of caterpillars; and at other such cases. The wonder indeed is, on the theory of natural selection, that more cases of the want of absolute perfection have not been observed.

There are innumerable statements of this type in the *Origin of Species*. In fact, one of the best arguments against perfection comes from extinct species. While the number of living species in the animal kingdom can be estimated to be around a few million, the number of extinct ones since life existed on earth has been estimated by Simpson (*4*) at around five hundred million.

Natural selection has no analogy with any aspect of human behavior. However, if one wanted to play with a comparison, one would have to say that natural selection does not work as an engineer works. It works like a tinkerer—a tinkerer who does not know exactly what he is going to produce but uses whatever he finds around him whether it be pieces of string, fragments of wood, or old cardboards; in short it works like a tinkerer who uses everything at his disposal to produce some kind of workable object. For the engineer, the realization of his task depends on his having the raw materials and the tools that exactly fit his project. The tinkerer, in contrast, always manages with odds and ends. What he ultimately produces is generally related to no special project, and it results from a series of contingent events, of all the opportunities he had to enrich his stock with leftovers. As was discussed by Levi-Strauss (*5*), none of the materials at the tinkerer's disposal has a precise and definite function. Each can be used in a number of different ways. In contrast with the engineer's tools, those of the tinkerer cannot be defined by a project. What these objects have in common is "it might well be of some use." For what? That depends on the opportunities.

Evolution as Tinkering

This mode of operation has several aspects in common with the process of evolution. Often, without any well-defined long-term project, the tinkerer gives his materials unexpected functions to produce a new object. From an old bicycle wheel, he makes a roulette; from a broken chair the cabinet of a radio. Similarly evolution makes a wing from a leg or a part of an ear from a piece of jaw. Naturally, this takes a long time. Evolution behaves like a tinkerer who, during eons upon eons, would slowly modify his work, unceasingly retouching it, cutting here, lengthening there, seizing the opportunities to adapt it progressively to its new use. For instance, the lung of terrestrial vertebrates was, according to Mayr (*6*), formed in the following way. Its development started in certain freshwater fishes living in stagnant pools with insufficient oxygen. They adopted the habit of swallowing air and absorbing oxygen through the walls of the esophagus. Under these conditions, enlargement of the surface area of the esophagus provided a selective advantage. Diverticula of the esophagus appeared and, under continuous selective pressure, enlarged into lungs. Further evolution of the lung was merely an elaboration of this theme—enlarging the surface for oxygen uptake and vascularization. To make a lung with a piece of esophagus sounds very much like tinkering.

Unlike engineers, tinkerers who tackle the same problem are likely to end up with different solutions. This also applies to evolution, as exemplified by the variety of eyes found in the living world [see (*7*)]. It is obviously a great advantage under many conditions to possess light receptors, and the variety of photoreceptors in the living world is amazing. The most sophisticated are the image-forming eyes that provide information, not only on the intensity of incoming light, but also on the objects light comes from, on their shape, color, position, motion, speed, distance, and the like. Such sophisticated structures are necessarily complex. They can develop only in organisms already complex themselves. One might suppose, therefore, that there is just one way of producing such a structure. This is not the case. Eyes appeared a great many times in the course of evolution, based on at least three principles—pinhole, lens, and multiple tubes. Lens eyes, like ours, appeared both in mollusks and vertebrates. Nothing looks so much like our eye as the octopus eye. Both work in almost exactly the same way. Yet they did not evolve in the same way. Whereas in vertebrates photoreceptor cells of the retina point away from light, in mollusks they point toward light. Among all solutions found to the problem of photoreceptors, these two are similar but not identical. In each case, natural selection did what it could with the materials at its disposal.

Evolution does not produce novelties from scratch. It works on what already exists, either transforming a system to give it new functions or combining several systems to produce a more elaborate one. This happened, for instance, during one of the main events of cellular evolution: namely, the passage from unicellular to multicellular forms. This was a particularly important transition because it carried an enormous potential for a specialization of the parts. Such a transition, which probably occurred several times, did not require the creation of new chemical species, for there are no major differences between molecular types of uni- and multicellular organisms. It was mainly a reorganization of what already existed.

Molecular Tinkering

It is at the molecular level that the tinkering aspect of natural selection is perhaps most apparent. What characterizes the living world is both its diversity and its underlying unity. The living world contains bacteria and whales, viruses and elephants, organisms living at −20°C in polar areas and others at 70°C in hot springs. All these objects, however, exhibit a remarkable unity of chemical structures and functions. Similar polymers, nucleic acids or proteins, always made of the same basic elements, the four bases and the 20 amino acids, play similar roles. The genetic code is the same and the translating machineries are very nearly so. The same coenzymes mediate similar reactions. Many metabolic steps remain essentially the same, from bacteria to man. Obviously, for life to emerge, a number of new molecular types had first to be formed. During chemical evolution in prebiotic times and at the beginning of biological evolution, all those molecules of which every living being is built had to appear. But once life had started in the form of some primitive self-reproducing organism, further evolution had to proceed mainly through alterations of already existing compounds. New functions developed as new proteins appeared. But these were merely variations on previous themes. A sequence of a thousand nucleotides codes for a medium-sized protein. The probability that a functional protein would appear de novo by random association of amino acids is practically zero. In organisms as complex and integrated as those that were already living a long time ago, creation of entirely new nucleotide sequences could not be of any importance in the production of new information.

The appearance of new molecular structures during much of biological evolution must, therefore, have rested on alteration of preexisting ones. This is exemplified by the finding that large segments of genetic information, that is, of DNA, turn out to be homologous, not only in the same organism, but also among different organisms, even among those that are phylogenetically distant. Similarly, as more is known about amino acid sequences in proteins, it appears not only that proteins fulfilling similar functions in different organisms have frequently similar sequences, but also that proteins with different functions often exhibit rather large segments in common. The hypothesis most generally envisaged to account for these similarities was proposed by Horowitz (*8*), by Ingram (*9*), and by Ohno (*10*). A segment of DNA, corresponding to one or several genes, is assumed to be duplicated by some genetic mechanism. When a gene exists in more than one copy in a cell or a gamete, it is released from the contraints imposed on functions by natural selection. Mutations can then accumulate more or less freely and result in modified protein structures, some of which can eventually fulfill new functions. Since natural selection exerts a continual pressure on organisms, an alteration in a protein can be further improved by other, later changes. It can also lead to a perturbation in the interactions with other proteins and eventually favor modifications of these proteins. A large fraction of the genome of complex organisms might actually derive from a few ancestral genes.

Biochemical changes do not seem, therefore, to be a main driving force in the diversification of living organisms. The really creative part in biochemistry must have occurred very early. For the biochemical unity that underlies the living world makes sense only if most of the important molecular types found in organisms, that is, most of the metabolic pathways involved in the production of energy and in biosynthesis or degradation of the essential building blocks already existed in very primitive organisms such as bacteria. Once this stage passed, biochemical evolution continued as more complex organisms appeared. But it is not biochemical novelties that generated diversification of organisms. In all likelihood, it worked the other way around. It is the selective pressure resulting from changes in behavior or in ecological niches that led to biochemical adjustments and changes in molecular types. What distinguishes a butterfly from a lion, a hen from a fly, or a worm from a whale is much less a difference in chemical constituents than in the organization and the distribution of these constituents. The few big steps of evolution required acquisition of new information. But specialization and diversification occurred by using differently the same structural information. Among neighboring groups, vertebrates for instance, chemistry is the same. What makes one vertebrate different from another is a change in the time of expression and in the relative amounts of gene products rather than the small differences observed in the structure of these products. It is a matter of regulation rather than of structure [see (*11*)].

After egg fertilization, embryonic development occurs in a fixed order and according to a precise schedule set by the genetic program contained in the chromosomes. This program determines when and where lines of differentiated cells will emerge, when and where different proteins will be made and in what amounts. Both the quality and quantity of the different proteins vary in time and space during development. Thus in the adult, the various types of cells or tissues contain different repertoires of molecular types in agreement with their functions. The genetic program is executed through complex regulatory circuits that switch the different biochemical activities of the organism on or off. Very little is known as yet about the regulatory circuits that operate in the development of complex organisms. It is known, however, that, among related organisms such as mammals, the first steps of embryonic development are remarkably similar, with divergences showing up only progressively as development proceeds. These divergences concern much less the actual structure of cellular or molecular types than their number and position. It seems likely that divergence and specialization of mammals, for instance, resulted from mutations altering regulatory circuits rather than chemical structures. Small changes modifying the distribution in time and space of the same structures are sufficient to affect deeply the form, the functioning, and the behavior of the final product—the adult animal. It is always a matter of using the same elements, of adjusting them, of altering here or there, of arranging various combinations to produce new objects of increasing complexity. It is always a matter of tinkering.

Consequences of Tinkering

Marks of this tinkering are thus found at every level thoughout the living world. Of course, they can be found in human beings as shown by the following few examples. In humans, as in many mammals, there exist very complex processes responsible for such functions as blood coagulation, inflammatory reactions against foreign bodies, and the immunological defenses mediated by the so-called complement system. These three processes have been independently analyzed in some detail during recent years. Each one exhibits an unexpected complexity. Each involves about ten proteins, none of which initially has enzymatic activity. Conversion of the first protein into a catalytically active form triggers a cascade of reactions. The first protein cleaves the second one at a specific point; a product of this reaction cleaves the third protein, and so on. In this series of reactions, the individual proteins are thus split in sequence and the released fragments serve as activators, or inhibitors, in other reactions of the chain. Furthermore, these three chains of reactions are not wholly independent. A product of cleavage in one chain can suddenly become an active element in another chain or even play a role in a completely different process. These products may serve as signals to connect chemically unrelated, but physiologically dependent, systems. It is as though some protein molecules, which happened to be formed, were used here or there as a source of smaller but active peptides as new functions were taking shape. Recently, a number of peptides of different sizes have been found to participate in a variety of physiological processes. Some of them, such as hormone peptides or brain peptides, are known not to be chemically transformed in the reaction they activate or inhibit. They appear just to bind to some protein to favor an allosteric transition, thus acting as simple chemical signals. For the biologist, it is thus generally impossible to make a prediction, or even an inspired guess, about the nature of such molecules and their structural relations with other constituents. All he can do is to detect them, purify them, and analyze them. Later, as the structures of more proteins become known, there will perhaps be a chance to define the functional interrelations and evolutionary relationship among such molecules.

Another example of tinkering can be found in early human embryonic development. Embryonic development is a tremendously complicated process of which little is known at present. Studies of the past 10 or 20 years have revealed an amazing phenomenon. In various human populations, 50 percent of all conceptions are estimated to result in spontaneous abortion [see (*12*)]. A large fraction of these abortions occur during the first 3 weeks of pregnancy and generally pass unnoticed. Thus, in half of the total conceptions, something is wrong to begin with. Many of these spontaneous abortions appear to be due to an odd number of chromosomes; instead of having one set of chromosomes derived from its mother and one from its father, the embryo lacks a chromosome, or has an extra one, or even has three sets instead of two. As a result, some functions necessary to embryonic development are not performed correctly. The fetus dies and is expelled. Thus many potentially malformed fetuses disappear; not all, unfortunately, since some of them still come to term. This reveals the imperfections of a mechanism that is at the very core of any living system and that has been refined over millions of years.

A third example of tinkering which is very intriguing when one thinks about it is the association between reproduction and what is generally called pleasure. Sex is one of the most efficient inventions of evolution. In lower organisms which apparently reproduce asexually by fission, the genetic program is scrupulously recopied at every generation. Within a population, it always remains the same, except for rare mutations. Division of the organism is an automatic process resulting from growth. When something resembling sexuality exists, as in bacteria, it is a luxury. In such populations, adaptation necessarily involves the selection of rare mutants under environmental conditions. In contrast, sexual reproduction, which probably occurred early in evolution, compels reassortment of genetic programs in interbreeding populations. As a result, every genetic program (that is, every individual) is different from the others. This permanent reshuffling of genetic elements provides tremendous potentialities of adaptation. But once sexuality had become a necessary condition for reproduction, it required special mechanisms: one, allowing individuals of opposite sexes to recognize and meet each other and a second, driving them to unite. The first of these requirements has been fulfilled by a variety of specific signaling systems—visual, auditory, or olfactory—of amazing precision and efficiency. The second has been met through the development of genetically determined and very rigid programs of behavior. For instance, in birds, at the proper season, the view of an individual of the opposite sex initiates a whole process of rituals, courtship, and parade leading almost automatically to copulation, nidation, and progeny care. The course of evolution, however, is characterized by a trend to greater flexibility in the execution of the genetic program. As this program became more open, so to speak, the behavior became less rigidly determined by the genes. Reactions to sexual signals were no longer completely automatic. In order to drive the individuals toward reproduction, sexuality had therefore to be associated with some other devices. Among these was pleasure. In the Oxford dictionary, pleasure is defined as "the opposite of pain," obviously, but also as "the condition of consciousness induced by the enjoyment of what is felt or viewed as good or desirable." It seems likely that feelings of discomfort and pleasure must already have existed for a long time in complex animals. An animal is more likely to have progeny if a feeling of discomfort dissuades it from entering harmful situations. It is clear that the existence of nervous centers, connected with sense organs and able to correlate what is felt as pleasant or unpleasant with what is actually good or bad for survival, is of great selective value. In fact, such centers are now known to exist. Some 20 years ago, neurobiologists detected in the brain, first in the rat and later in many vertebrates, the presence of two remarkable centers—one called the center of aversion and the other called the center of autostimulation. Fitted with correctly implanted electrodes and given the means of activating at will the latter center, a rat gives himself pleasure until it collapses from sheer exhaustion. Experiments performed during brain surgery and descriptions of feelings by the patients leave very little doubt as to the existence of such centers in man and to its association with sexual activity. Thus pleasure appears as a mere expedient to push individuals to indulge in sex and therefore to reproduce. A rather successful expedient indeed, as judged by the state of the world population.

A Final Example of Tinkering: The Human Brain

Although our brain represents the main adaptive feature of our species, what it is adapted to is not clear at all. What is clear, however, is that, like the rest of our body, our brain is a product of natural selection, that is, of differential reproductions accumulated over millions of years under the pressure of various environmental conditions. Our brain has therefore evolved at our gonad's service, as already emphasized by Freud many years ago. But curiously enough, brain development in mammals was not as integrated a process as, for instance, the transformation of a leg into a wing. The human brain was formed by superposition of new structures on old ones. To the old rhinencephalon of lower mammals a neocortex was added that rapidly, perhaps too rapidly, took a most important role in the evolutionary sequence leading to man. For some neurobiologists, especially McLean (*13*), these two types of structures correspond to two types of functions but have not been completely coordinated or hierarchized. The recent one, the neocortex, controls intellectual, cognitive activity. The old one, derived from the rhinencephalon, controls emotional and visceral activities. In contrast to the former, the latter does not seem to possess any power of specific discrimination, or any capacity for symbolization, language, or self-consciousness. The old structure which, in lower mammals, was in total command has been relegated to the department of emotions. In man, it constitutes what McLean calls "the visceral brain." Perhaps because development is so prolonged and maturity so delayed in man, these centers maintain strong connections with lower autonomic centers and continue to coordinate such fundamental drives as obtaining food, hunting for a sexual partner, or reacting to an enemy. This evolutionary procedure—the formation of a dominating neocortex coupled with the persistence of a nervous and hormonal system partially, but not totally under the rule of the neocortex—strongly resembles the tinkerer's procedure. It is somewhat like adding a jet engine to an old horse cart. It is not surprising, in either case, that accidents, difficulties, and conflicts can occur.

It is hard to realize that the living world as we know it is just one among many possibilities; that its actual structure results from the history of the earth. Yet living organisms are historical structures: literally creations of history. They represent, not a perfect product of engineering, but a patchwork of odd sets pieced together when and where opportunities arose. For the opportunism of natural selection is not simply a matter of indifference to the structure and operation of its products. It reflects the very nature of a historical process full of contingency.

As Simpson (*4*) pointed out, the interplay of local opportunities—physical, ecological, and constitutional—produces a net historical opportunity which in turn determines how genetic opportunities will be exploited. It is this net historical opportunity that mainly controls the direction and pace of adaptive evolution. This is why the probability is practically zero that living systems, which might well exist elsewhere in the cosmos, would have evolved into something looking like human beings. Even if life in outer space uses the same material as on the earth, even if the environment is not too different from ours, even if the nature of life and of its chemistry strongly limits the way to fulfill certain functions, the sequence of historical opportunities there could not be the same as here. A different play had to be performed by different actors. Despite science fiction, Martians cannot look like us. And we might as well have looked like one of those 16th-century monsters.

References and Notes

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