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I

Of Strange Objects

THE DIFFERENCE between artificial and natural objects seems immediately and unambiguously apparent to all of us. A rock, a mountain, a river, or a cloud—these are natural objects; a knife, a handkerchief, a car—so many artificial objects, artifacts.* Analyze these judgments, however, and it will be seen that they are neither immediate nor strictly objective. We know that the knife was man-made for a use its maker visualized beforehand. The object renders in material form the preexistent intention that gave birth to it, and its form is accounted for by the performance expected of it even before it takes shape. It is another story altogether with the river or the rock which we know, or believe, to have been molded by the free play of physical forces to which we cannot attribute any design, any "project" or purpose. Not, that is, if we accept the basic premise of the scientific method, to wit, that nature is *objective* and not *projective*.

the natural and the artificial

Hence it is through reference to our own activity, conscious and projective, intentional and purposive—it is as

* In the literal sense: products of human art or workmanship.

makers of artifacts—that we judge of a given object's "naturalness" or "artificialness." Might there be objective and general standards for defining the characteristics of artificial objects, products of a conscious purposive activity, as against natural objects, resulting from the gratuitous play of physical forces? To make sure of the complete objectivity of the criteria chosen, it would doubtless be best to ask oneself whether, in putting them to use, a program could be drawn up enabling a computer to distinguish an artifact from a natural object.

Such a program could be applied in the most interesting connections. Let us suppose that a spacecraft is soon to be landed upon Venus or Mars; what more fascinating question than to find out whether our neighboring planets are, or at some earlier period have been, inhabited by intelligent beings capable of projective activity? In order to detect such present or past activity we would have to search for and be able to recognize its *products*, however radically unlike the fruit of human industry they might be. Wholly ignorant of the nature of such beings and of the projects they might have conceived, our program would have to utilize only very general criteria, solely based upon the examined objects' structure and form and without any reference to their eventual function.

The suitable criteria, we see, would be two in number: (a) regularity, and (b) repetition. By means of the first one would seek to make use of the fact that natural objects, wrought by the play of physical forces, almost never present geometrically simple and straightforward structures: flat surfaces, for instance, or rectilinear edges, right angles, exact symmetries; whereas artifacts will ordinarily show such features, if only in an approximate or rudimentary manner.

Of the two criteria, repetition would probably be the more decisive. Materializing a reiterated intent, homologous artifacts meant for the same use reflect, faithfully in the main, the constant purpose of their creator. In that respect the discovery of numerous specimens of closely similar objects would be of high significance.

These, briefly defined, are the general criteria that might serve. The objects selected for examination, it must be added, would be of *macroscopic* dimensions, but not *microscopic*. By macroscopic is meant dimensions measurable, say, in centimeters; by microscopic, dimensions normally expressed in angstroms (a hundred million of which equal one centimeter). This proviso is crucial, for on the microscopic scale one would be dealing with atomic and molecular structures whose simple and repetitive geometries, obviously, would attest not to a conscious and rational intention but to the laws of chemistry.

Now let us suppose the program drawn up and the machine built. To check its performance, the best possible test would be to put it to work upon terrestrial objects.

difficulties of a space program

Let us invert our hypotheses and imagine that the machine has been put together by the experts of a Martian NASA aiming at detecting evidence of organized, artifact-producing activity on Earth. And let us suppose that the first Martian craft comes down in the Forest of Fontainebleau, not far, let's say, from the village of Barbizon. The machine looks at and compares the two series of objects most prominent in the area: on the one hand the houses in Barbizon, on the other hand the rock formations of Apremont. Utilizing the criteria of regularity, of geometric simplicity, and of repetition, it will have no trouble deciding that the rocks are natural objects and the houses artifacts.

Focusing now upon lesser objects, the machine examines some pebbles, near which it discovers some crystals—quartz crystals, let us say. According to the same criteria it should of course decide that while the pebbles are natural, the quartz crystals are artificial objects. A decision which appears to point to some "error" in the writing of the program. An "error" which, moreover, proceeds from an interesting source: if the crystals present perfectly defined geometrical shapes, that is because their macroscopic structure directly reflects the simple and repetitive microscopic structure of the atoms or molecules constituting them. A crystal, in other words, is the macroscopic expression of a microscopic structure. An "error" which, by the by, should be easy enough to eliminate, since all *possible* crystalline structures are known to us.

But let us suppose that the machine is now studying another kind of object: a hive built by wild bees, for example. There it would obviously find all the signs indicating artificial origin: the simple and repeated geometrical structures of the honeycombs and the cells composing them, thanks to which the hive would earn classification in the same category of objects as the Barbizon dwellings. What are we to make of this conclusion? We know the hive is "artificial" insofar as it represents the product of the activity of bees. But we have good reasons for thinking that this activity is strictly automatic—immediate, but not consciously projective. At the same time, as good naturalists we view bees as "natural" beings. Is there not a flagrant contradiction in considering "artificial" the

product of a "natural" being's automatic activity?

Carrying the investigation a little further, it would soon be seen that if there is contradiction, it results not from faulty programming but from the ambiguity of our judgments. For if the machine now inspects, not the hive, but the bees themselves, it cannot take them for anything but artificial, highly elaborated objects. The most superficial examination will reveal in the bee elements of simple symmetry: bilateral and translational. Moreover and above all, examining bee after bee the computer will note that the extreme complexity of their structure (the number and position of abdominal hairs, for example, or the ribbing of the wings) is reproduced with extraordinary fidelity from one individual bee to the next. Powerful evidence, is it not, that these creatures are the products of a deliberate, constructive, and highly sophisticated order of activity? Upon the basis of such conclusive documentation, the machine would be bound to signal to the officials of the Martian NASA its discovery, upon Earth, of an industry compared with which their own would probably seem primitive.

In this little excursion into the not-so-very-farfetched, our aim was only to illustrate the difficulty of defining the distinction—elusive, for all its obviousness to our intuitions—between "natural" and "artificial" objects. In fact, on the basis of structural criteria, macroscopic ones, it is probably impossible to arrive at a definition of the artificial which, while including all "veritable" artifacts, such as the products of human workmanship, would exclude objects so clearly natural as crystalline structures, and indeed, the living beings themselves which we would also like to classify among natural systems.

Looking for the cause of the confusion—or in any case, seeming confusion—the program is leading to, we may perhaps wonder whether it does not arise from our having wished to limit it to considerations only of form, of structure, of geometry, and so divesting our notion of an artificial object of its essential content. This being that any such object is defined or explained primarily by the function it is intended to fulfill, the performance its inventor expects of it. However, we shall soon find that by programming the machine so that henceforth it studies not only the structure but the eventual performance of the examined objects, we end up with still more disappointing results.

For let us suppose that this new program does enable the machine to analyze correctly the structure and the performance of two series of objects—horses running in a field and automobiles moving on a highway, for example. The analysis would tend to the conclusion that these objects are closely comparable, those making up each series having a built-in capacity for swift movement, although over different surfaces, which accounts for their differences of structure. And if, to take another example, we were to ask the machine to compare the structure and performance of the eye of a vertebrate with that of a camera, the program would have to acknowledge their profound similarities: lenses, diaphragm, shutter, light-sensitive pigments: surely, the same components could not have been introduced into both objects except with a view to getting similar performances from them.

objects endowed with a purpose

The last of these examples is a classic one of functional

adaptation in living beings, and I have cited it only to emphasize how arbitrary and pointless it would be to deny that the natural organ, the eye, represents the materialization of a "purpose"—that of picking up images—while this is indisputably also the origin of the camera. It would be the more absurd to deny it since, in the last analysis, the purpose which "explains" the camera can only be the same as the one to which the eye owes its structure. Every artifact is a product made by a living being which through it expresses, in a particularly conspicuous manner, one of the fundamental characteristics common to all living beings without exception: that of being *objects endowed with a purpose or project*, which at the same time they exhibit in their structure and carry out through their performances (such as, for instance, the making of artifacts).

Rather than reject this idea (as certain biologists have tried to do) it is indispensable to recognize that it is essential to the very definition of living beings. We shall maintain that the latter are distinct from all other structures or systems present in the universe through this characteristic property, which we shall call *teleonomy*.

But it must be borne in mind that, while necessary to the definition of living beings, this condition is not sufficient, since it does not propose any objective criteria for distinguishing between living beings themselves and the artifacts issuing from their activity.

It is not enough to point out that the project which gives rise to an artifact belongs to the animal that created it, and not to the artificial object itself. This obvious notion is also too subjective, as the difficulty of utilizing it in the computer program would prove: for upon what basis would the machine be able to decide that the project of picking up images—the project represented by the camera—belongs to some object other than the camera itself? By examining nothing beyond the finished structure and by simply analyzing its performance it is possible to identify the project, but not its author or source.

To achieve this we must have a program which studies not only the actual object but its origin, its history, and, for a start, how it has been put together. Nothing, in principle at least, stands in the way of formulating such a program. Even if it were rather crudely compiled, we would be able with it to discern a radical difference between any artifact, however highly perfected, and a living being. The machine could not fail to note that the macroscopic structure of an artifact (whether a honeycomb, a dam built by beavers, a paleolithic hatchet, or a spacecraft) results from the application to the materials constituting it of forces *exterior* to the object itself. Once complete, this macroscopic structure attests, not to inner forces of cohesion between atoms or molecules constituting its material (and conferring upon it only its general properties of density, hardness, ductility, etc.), but to the *external* forces that have shaped it.

On the other hand, the program will have to register the fact that a living being's structure results from a totally different process, in that it owes almost nothing to the action of outside forces, but everything, from its overall shape down to its tiniest detail, to "morphogenetic" interactions within the object itself. It is thus a structure giving proof of an autonomous determinism: precise, rigorous, implying a

self-constructing machines

virtually total "freedom" with respect to outside agents or conditions—which are capable, to be sure, of impeding this development, but not of governing or guiding it, not of prescribing its organizational scheme to the living object. Through the autonomous and spontaneous character of the morphogenetic processes that build the macroscopic structure of living beings, the latter are absolutely distinct from artifacts, as they are, furthermore, from the majority of natural objects whose macroscopic morphology largely results from the influence of external agents. To this there is a single exception: that, once again, of crystals, whose characteristic geometry reflects microscopic interactions occurring within the object itself. Hence, utilizing this criterion alone, crystals would have to be classified together with living beings, while artifacts and natural objects, alike fashioned by outside agents, would comprise another class.

That this last criterion, after those of regularity and repetition, should point to a similarity between crystalline structures and the structures of living beings might well set our programmer to thinking. Though unversed in modern biology, he would be obliged to wonder whether the internal forces which confer their macroscopic structure upon living beings might be of the same nature as the microscopic interactions responsible for crystalline morphologies. That this is indeed the case constitutes one of the main themes to be developed in the ensuing chapters of this essay. But for the moment we are looking for the most general criteria to define the macroscopic properties that set living beings apart from all other objects in the universe.

Having "discovered" that an internal, autonomous determinism guarantees the formation of the extremely complex structures of living beings, our programmer (with no training in biology, but an information specialist by profession) must necessarily see that such structures represent a considerable quantity of information whose source has still to be identified: for all expressed–and hence received–information presupposes a source.

Let us assume that, continuing his investigation, our programmer at last makes his final discovery: that the source of the information expressed in the structure of a living being is *always* another, structurally identical object. He has now identified the source and detected a third remarkable property in these objects: their ability to reproduce and to transmit *ne varietur* the information corresponding to their own structure. A very rich body of information, since it describes an organizational scheme which, along with being exceedingly complex, is preserved intact from one generation to the next. The term we shall use to designate this property is *invariant reproduction*, or simply *invariance*.

self-reproducing machines

With their invariant reproduction we find living beings and crystalline structures once again sharing a property that renders them unlike all other known objects in the universe. Certain chemicals in supersaturated solution do not crystallize unless the solution has been inoculated with crystal seeds. We know as well that in cases of a chemical capable of crystallizing into two different systems, the structure of the crystals appearing in the solution will be determined by that of the seed employed. Crystalline structures, however, represent a quantity of

information by several orders of magnitude inferior to that transmitted from one generation to another in the simplest living beings we are acquainted with. By this criterion–purely quantitative, be it noted–living beings may be distinguished from all other objects, crystals included.

Let us now forget our Martian programmer and leave him to mull things over undisturbed. This imaginary experiment has had no other aim than to compel us to "rediscover" the more general properties that characterize living beings and distinguish them from the rest of the universe. Let us now admit to a familiarity with modern biology, so as to go on to analyze more closely and to try to define more precisely, if possible quantitatively, the properties in question. We have found three: teleonomy, autonomous morphogenesis, and reproductive invariance.

Of them all, reproductive invariance is the least difficult to define quantitatively. Since this is the capacity to reproduce highly ordered structure, and since a structure's degree of order can be defined in units of information, we shall say that the "invariance content" of a given species is equal to the amount of information which, transmitted from one generation to the next, assures the preservation of the specific structural standard. As we shall see later on, with the help of a few assumptions it will be possible to arrive at an estimate of this amount.

strange properties: invariance and teleonomy

That in turn will enable us to bring into better focus the notion most immediately and plainly inspired by the examination of the structures and performances of living beings, that of teleonomy. Analysis nevertheless reveals it to be a profoundly ambiguous concept, since it implies the subjective idea of "project." We remember the example of the camera: if we agree that this object's existence and structure realize the "project" of capturing images, we must also agree, obviously enough, that a similar project is accomplished with the emergence of the eye of a vertebrate.

But it is only as a part of a more comprehensive project that each individual project, whatever it may be, has any meaning. All the functional adaptations in living beings, like all the artifacts they produce, fulfill particular projects which may be seen as so many aspects or fragments of a unique primary project, which is the preservation and multiplication of the species.

To be more precise, we shall arbitrarily choose to define the essential teleonomic project as consisting in the transmission from generation to generation of the invariance content characteristic of the species. All the structures, all the performances, all the activities contributing to the success of the essential project will hence be called "teleonomic."

This allows us to put forward at least the *principle* of a definition of a species' "teleonomic level." All teleonomic structures and performances can be regarded as corresponding to a certain quantity of information which must be transmitted for these structures to be realized and these performances accomplished. Let us call this quantity "teleonomic information." A given species' "teleonomic level" may then be said to correspond to the quantity of information which, on the average and per individual, must be transferred to assure the generation-to-generation transmission of the specific content of reproductive invariance.

It will be readily seen that, in this or that species situated higher or lower on the animal scale, the achievement of the fundamental teleonomic project (i.e., invariant reproduction) calls assorted, more or less elaborate and complex structures and performances into play. The fact must be stressed that concerned here are not only the activities directly bound up with reproduction itself, but all those that contribute–be it very indirectly–to the species' survival and multiplication. For example, in higher mammals the play of the young is an important element of psychic development and social integration. Therefore this activity has teleonomic value, inasmuch as it furthers the cohesion of the group, a condition for its survival and for the expansion of the species. It is the degree of complexity of all these performances or structures, conceived as having the function of serving the teleonomic purpose, that we would like to estimate.

This magnitude, while theoretically definable, is not measurable in practice. Still, it may serve as a rule of thumb for ranking different species or groups upon a "teleonomic scale." To take an extreme example, imagine a bashful poet who, prevented by shyness from declaring his passion to the woman he loves, can only express it symbolically, in the poems he dedicates to her. Suppose that at last, conquered by these refined compliments, the lady surrenders to the poet's desire. His verses will have contributed to the success of his essential project, and the information they contain must therefore be tallied in the sum of the teleonomic performances assuring transmission of genetic invariance.

Indisputably, no analogous performance figures in the successful accomplishment of the project in other animal species, the mouse for instance. But—and this is the important point—the genetic invariance content is about the same in the mouse and the human being (and in all mammals, for that matter). *The two magnitudes we have been trying to define are therefore quite distinct.*

Which leads us to consider a most important question concerning the relationship among the three properties we singled out as characteristic of living beings. The fact that the computer program identified them successively and independently does not prove that they are not simply three manifestations of a single, more basic, more secret property, inaccessible to any direct observation. Were this so, the drawing of distinctions among the properties, the seeking of different definitions for them, might be nothing but delusion and arbitrariness. Far from shedding light on the real problem, far from tracking down "the secret of life" and truly dissecting it, we would be engaged merely in exorcizing it.

It is perfectly true that these three properties—teleonomy, autonomous morphogenesis, and reproductive invariance—are closely interconnected in all living beings. Genetic invariance expresses and reveals itself only through, and thanks to, the autonomous morphogenesis of the structure that constitutes the teleonomic apparatus.

There is this to be observed right away: not all of these three concepts have the same standing. Whereas invariance and teleonomy are indeed characteristic "proper-

ties" of living beings, spontaneous structuration ought rather to be considered a mechanism. Further on we shall see that this mechanism intervenes both in the elaboration of teleonomic structures and in the reproduction of invariant information as well. That it finally accounts for the latter two properties does not, however, imply that they should be regarded as one. It remains possible—it is in fact methodologically indispensable—to maintain a distinction between them, and this for several reasons:

1. One can at least *imagine* objects capable of invariant reproduction but devoid of any teleonomic apparatus. Crystalline structures offer one example of this, at a level of complexity admittedly very much lower than that of all known living organisms.

2. The distinction between teleonomy and invariance is more than a mere logical abstraction. It is warranted on grounds of chemistry. Of the two basic classes of biological macromolecules, one, that of proteins, is responsible for almost all teleonomic structures and performances; while genetic invariance is linked exclusively to the other class, that of nucleic acids.

3. Finally, as will be seen in the next chapter, this distinction is assumed, explicitly or otherwise, in all the theories, all the ideological constructions (religious, scientific, or philosophical) pertaining to the biosphere and to its relationship to the rest of the universe.

Living creatures are strange objects. At all times in the past, men must have been more or less confusedly aware of this. The development of the natural sciences beginning in the seventeenth century, their flowering in the nineteenth, instead of effacing this impression rather rendered it more acute. Over against the physical laws governing macroscopic systems, the very existence of living organisms seemed to constitute a paradox, violating certain of the fundamental principles modern science rests upon. Just which ones? That is not immediately clear. Hence the question is, precisely, to analyze the nature of this—or these—"paradoxes." This will give us occasion to specify the relative position, vis-à-vis physical laws, of the two essential properties that characterize living organisms: reproductive invariance and structural teleonomy.

Indeed at first glance invariance appears to constitute a profoundly paradoxical property, since the maintaining, the reproducing, the multiplying of highly ordered structures seems in conflict with the second law of thermodynamics. This law enjoins that no macroscopic system evolve otherwise than in a downward direction, toward degradation of the order that characterizes it.

the "paradox" of invariance

However, this prediction of the second law is valid, and verifiable, only if we are considering the overall evolution of an *energetically isolated* system. Within such a system, in one of its phases, we may see ordered structures take shape and grow without that system's overall evolution ceasing to comply with the second law. The best example of this is afforded by the crystallization of a saturated solution. The thermodynamics of such a system are well understood. The local enhancement of order represented by the assembling of initially unordered molecules into a perfectly defined crystalline network is "paid for" by a transfer of thermal energy from the crystalline phase to the solution: the entropy—or disorder—of the

system as a whole augments to the extent stipulated by the second law.

This example shows that, within an isolated system, a local heightening of order is compatible with the second law. We have pointed out, however, that the degree of order represented by even the simplest organism is incomparably higher than that which a crystal defines. We must now ask whether the conservation and invariant multiplication of such structures is also compatible with the second law. This can be verified through an experiment closely comparable with that of crystallization.

We take a milliliter of water having in it a few milligrams of a simple sugar, such as glucose, as well as some mineral salts containing the essential elements that enter into the chemical constituents of living organisms (nitrogen, phosphorus, sulfur, etc.). In this medium we grow a bacterium, for example *Escherichia coli* (length, 2 microns; weight, approximately 5×10^{-13} grams). Inside thirty-six hours the solution will contain several billion bacteria. We shall find that about 40 per cent of the sugar has been converted into cellular constituents, while the remainder has been oxidized into carbon dioxide and water. By carrying out the entire experiment in a calorimeter, one can draw up the thermodynamic balance sheet for the operation and determine that, as in the case of crystallization, the entropy of the system as a whole (bacteria plus medium) has increased a little more than the minimum prescribed by the second law. Thus, while the extremely complex system represented by the bacterial cell has not only been conserved but has multiplied several billion times, the thermodynamic debt corresponding to the operation has been duly settled.

No definable or measurable violation of the second law has occurred. Nonetheless, something unfailingly upsets our physical intuition as we watch this phenomenon, whose strangeness is even more appreciable than before the experiment. Why? Because we see very clearly that this process is bent or oriented in one exclusive direction: the multiplication of cells. These to be sure do not violate the laws of thermodynamics, quite the contrary. They not only obey them; they utilize them as a good engineer would, with maximum efficiency, to carry out the project and bring about the "dream" (as François Jacob has put it) of every cell: to become two cells.

Later we shall try to give an idea of the complexity, the subtlety, and the efficiency of the chemical machinery necessary to the accomplishment of a project demanding the synthesis of several hundred different organic constituents; their assembly into several thousand macromolecular species; and the mobilization and utilization, where necessary, of the chemical potential liberated by the oxidation of sugar: i.e., in the construction of cellular organelles. There is, however, no physical paradox in the invariant reproduction of these structures: invariance is bought at not one penny above its thermodynamic price, thanks to the perfection of the teleonomic apparatus which, grudging of calories, in its infinitely complex task attains a level of efficiency rarely approached by man-made machines. This apparatus is entirely logical, wonderfully rational, and perfectly adapted to its purpose: to preserve and reproduce the structural norm. And it achieves this, not by departing from physical laws, but by exploiting them to the exclusive advantage of its per-

teleonomy and the principle of objectivity

sonal idiosyncrasy. It is the very existence of this purpose, at once both pursued and fulfilled by the teleonomic apparatus, that constitutes the "miracle." Miracle? No, the real difficulty is not in the physics of the phenomenon; it lies elsewhere, and deeper, involving our own understanding, our intuition of it. There is, really, no paradox or miracle; but a flagrant *epistemological contradiction.*

The cornerstone of the scientific method is the postulate that nature is objective. In other words, the *systematic* denial that "true" knowledge can be got at by interpreting phenomena in terms of final causes—that is to say, of "purpose." An exact date may be given for the discovery of this canon. The formulation by Galileo and Descartes of the principle of inertia laid the groundwork not only for mechanics but for the epistemology of modern science, by abolishing Aristotelian physics and cosmology. To be sure, neither reason, nor logic, nor observation, nor even the idea of their systematic confrontation had been ignored by Descartes' predecessors. But science as we understand it today could not have been developed upon those foundations alone. It required the unbending stricture implicit in the postulate of objectivity—ironclad, pure, forever undemonstrable. For it is obviously impossible to imagine an experiment which could prove the *nonexistence* anywhere in nature of a purpose, of a pursued end.

But the postulate of objectivity is consubstantial with science; it has guided the whole of its prodigious development for three centuries. There is no way to be rid of it, even tentatively or in a limited area, without departing from the domain of science itself.

Objectivity nevertheless obliges us to recognize the teleonomic character of living organisms, to admit that in their structure and performance they act projectively—realize and pursue a purpose. Here therefore, at least in appearance, lies a profound epistemological contradiction. In fact the central problem of biology lies with this very contradiction, which, if it is only apparent, must be resolved; or else proven to be utterly insoluble, if that should turn out indeed to be the case.

II Vitalisms and Animisms

SINCE THE TELEONOMIC properties of living beings appear to challenge one of the basic postulates of the modern theory of knowledge, any philosophical, religious, or scientific view of the world must, *ipso facto*, offer an implicit if not an explicit solution to this problem. Every solution in its turn, whatever the motivation behind it, just as inevitably implies a hypothesis as to the causal and temporal precedence, in relation to each other, of the two properties characteristic of living beings: invariance and teleonomy.

the priority relationship between invariance and teleonomy: a fundamental dilemma

We shall defer until Chapter VI an exposition of, and justifications for, the single hypothesis that modern science here deems acceptable: namely, that invariance necessarily precedes teleonomy. Or, to be more explicit, the Darwinian idea that the initial appearance, evolution, and steady refinement of ever more intensely teleonomic structures are due to perturbations occurring in a structure *which already possesses the property of invariance*—hence is capable of preserving the effects of chance and