# NEW CONCEPTS IN THE EVOLUTION OF COMPLEXITY: STRATIFIED STABILITY AND UNBOUNDED PLANS

*by J. Bronowski*

Vitalism is a traditional and persistent belief that the laws of physics that hold in the inanimate world will not suffice to explain the phenomena of life. Of course it is not suggested, either by those who share the belief or by those like me who reject it, that we know all the laws of physics now, or will know them soon. Rather what is silently supposed by both sides is that we know what kind of laws physics is made up of and will continue to discover in inanimate matter; and although that is a vague description to serve as a premise, it is what inspires vitalists to claim (and their opponents to deny) that some phenomena of life cannot be explained by laws of this kind.

The phenomena that are said to be inaccessible to physics are of two different kinds. One school of vitalists stresses the *complexity of the individual* organism. The other school of vitalists asserts that physical laws are insufficient to explain the direction of evolution in time: that is, the *increase in complexity in new species,* such as man, when compared with old species from which they derive, such as the tree-shrews. The two grounds for finding physics to fall short are therefore quite distinct, and I shall discuss them separately. I begin with a summary sketch of each.

The first ground, then, is that the *individual* organism (even a single cell) functions in a way which transcends what physics can explain, and implies the existence of laws of another kind—what Walter M. Elsasser[1] calls biotonic laws. Elsasser argues that the development of an organism is too complex to be coded in the genes, and that there must be larger laws of biological organization that guide it overall. Eugene P. Wigner[2] argues that development and reproduction are subject to so many sta-

J. Bronowski is resident fellow, The Salk Institute for Biological Studies, La Jolla, Calif., and director, Council for Biology in Human Affairs, sponsored by The Salk Institute. This paper was presented at the meetings of the American Association for the Advancement of Science, Boston, Mass., December 27, 1969. It will appear also in *Boston Studies in the Philosophy of Science* (New York: Humanities Press, 1970), vol. 8, and *Synthese* 21, no. 2 (1970), and is printed with permission from the other publishers: Humanities Press, New York, and D. Reidel Publishing Co., Dordrecht, Holland.

tistical variations that there can be no certainty that the organism will survive them unless it is controlled by higher laws.

These arguments do not differ in principle from the classical argument, put forward (for example) by Bolingbroke[3] early in the eighteenth century, that an organism is at least as complicated as a clock, and that we cannot imagine a clock to have come into being by accident. True, neither Elsasser nor Wigner speaks of origins, but both imply that the configuration of parts and the sequence of functions in the cell require a higher coordination than is provided by the laws of physics—by what one might call the simple engineering rules between the parts of the clock. Bolingbroke ascribes this higher coordination to God, and Elsasser and Wigner to biotonic laws, but this is only a difference in nomenclature.

The second school of vitalists finds another ground for claiming that the laws of physics are biologically incomplete, namely, in questions about the *evolution* of organisms. Michael Polanyi[4] asks questions of this kind, though he lumps all levels together—origins, functioning of individuals, and the sequence of species. He claims, as vitalists have always done, that there must be an overall plan which directs them all, and I shall criticize the confusion of meanings in his idea of plan or purpose. I shall distinguish between two concepts, the usual concept of a closed or bounded plan (that is, a tactic or solution for a defined problem), and a new concept of an *open or unbounded plan* (that is, a general strategy).

But beyond these concepts, there remains the crucial question raised by Polanyi—and others before him, of course, in earlier forms. Evolution has the direction, speaking roughly, from simple to more and more complex: more and more complex functions of higher organisms, mediated by more and more complex structures, which are themselves made of more and more complex molecules. How has this come about? How can it be explained if there is no overall plan to create more complex creatures—which means, at least, if there is no overall law (other than evolution as a mechanism) to generate complexity? In particular, how do we square this direction with the Second Law of Thermodynamics, which (as a general description subsuming ordinary physical laws) predicts the breakdown of complex structures into simple ones? This is the constellation of questions to which I shall give most attention.

The course of my argument will incidentally reveal what additional physical laws we expect to discover as we continue to unfold the chemistry of life. In essence, they can be expected to be laws of specific relations between a few kinds of atoms which govern the *stability* of the structures that can be assembled from them. These are indeed laws of cooperative phenomena or ensembles, but they are highly particular and empirical, being simply accounts of the stability to be found in different conjunctions of matter under the conditions we know on earth.

## MACHINERY OF THE CELL

I shall assume that we are all familiar with the way in which heredity is mediated by genes, which are molecules made up from four fairly small chemical bases that are strung out on two paired strands of DNA. Since there are many varieties of living creatures, and many genes in each, there are many different forms of DNA, in each of which the sequence of bases is different and is characteristic for directing some chemical process in that creature. The sequence of bases in a molecule of DNA spells out the twenty amino acids which in their turn make the proteins. We have a simple hierarchy: the four bases are the four letters of the alphabet, each set of three letters makes up a word which is a fundamental amino acid, and the twenty words in their turn are assembled into different sentences which are the different proteins.

The book of heredity is not the whole book of life. It records only those instructions which make a species breed true, so that the child is revealed as a copy of the parents. Yet this is far-reaching, because the living child, the living cell, is not a static copy but is a dynamic process in which one action follows another in a characteristic pattern. We only dimly understand how the process of maturation unfolds this inborn ability. Nevertheless, we have made a beginning by seeing how the processes of making one protein after another are programmed from the vocabulary of life so that they develop a stepwise, coordinated sequence.

Elsasser has argued that the development of living creatures (some of which consist of only a single cell) is too complex and too closely integrated to be directed by the genetic machinery. To this fundamental and, so to speak, primitive claim, a biologist can only reply that there is absolutely no evidence to support it. No counting of constants, no calculation of the content of information in a set of chromosomes, can give any ground for it, because we simply do not know what the inner relations and restrictions between the parts of a complex molecule are. We do not even understand yet why a long protein molecule folds into the specific geometrical configuration which is its own, and not into any other. But we expect to find these laws, and we expect them to be no more esoteric or biotonic than, say, the laws which inform us that some assemblies of fundamental particles in physics make up stable atomic nuclei, and others do not.

In the same way, there is no evidence at all that the interaction of genes, either on the same or on different chromosomes, requires any kind of master law. In general it is mediated by local relations in the organ that is being shaped, just as the growth of a set of normal cells on a microscope slide is controlled in a regular array by chemical contact between the walls of neighboring cells. It may be that there are some places on the chromosomes where master controls reside, but if so, they can be expected simply to have the character of special genes. We already know that there are some master genes which control groups of other genes, for example by making them all more mutable or more stable.

A single-cell bacterium goes through its life cycle on an exact schedule, and every step in the sequence is a rearrangement of and within the molecules which compose it. So the machinery of the cell, the clockwork that drives and demonstrates its life, is a constant shaping and reshaping of its molecular material. It is suggested by vitalists that these cycles are so matched to its environment that they have the manifest plan or purpose, they are patently *designed,* to preserve the life of the bacterium. Of course this cannot be simply on the ground that the processes of life are cyclic: for there are plenty of physical actions, say in gravitation, which are cyclic—from the tides to the seasons. Nor can it be on the ground that there is something mysterious about the resistance of a cycle against disturbing forces, for that is displayed by any cycle—for example, a spinning top. The fact that a living cell is geared to go on living in the face of a disturbance is no more supernatural than the fact that a falling stone is geared to go on falling, and a stone in free space is geared to go on moving in a straight line. This *is* its nature, and does not require explanation any more (or in any other sense) than does the behavior of a ray of light or the complex structure of an atom of uranium.

Therefore the vitalist must have some more sophisticated idea of a plan than the mere persistence of a cycle, or even of a linked group of cycles. Usually what he does is to propose a distinction between different levels of explanation (and, by implication, of action). He says that we may well explain the mechanics of each cycle, but that this still misses the point of what they achieve as a totality; and that this achievement, namely the perpetuation of life in general, cannot be understood except as an overall plan or purpose.

I shall return to the discussion of the concept of plans later. Here I will content myself with repeating again that though there is much about life that we do not understand, there is no evidence at all that this is because there is a mystery in its basic processes. Living matter is different from nonliving, but not because it follows different rules. The rules of organization by which the parts of a cell work together, the sequence of procedures which make it live, are understandable in the same terms as any other molecular process. The basic structures and sequences of life follow from those of dead nature without the intervention of any special powers or acts. There is no evidence for vitalism in the analysis of the cell, or of any simple assembly of cells that we know: a microorganism, a limb, or a cancer.

## THE ROLE OF ERRORS

A different and deeper question has been raised by Eugene Wigner. He remarks that living cells go through their life cycles by taking nourishment from the environment, and incorporating it either into their own structure or into that of daughter cells. During this transformation, he argues, quantum effects make it impossible to ensure with certainty that the cell will make an accurate copy of itself (or of some specified modification of itself); and therefore the laws of physics cannot suffice to explain how living matter perpetuates itself. Wigner calculates in detail how the manufacture in the cell of exact or similar, specified copies can be shown to be (in his phrase) "infinitely unlikely." Even if we treat the calculation as only indicative (as Wigner himself does at the end of his paper), the indication is that copying of any specific molecule (a strand of DNA, for instance) must produce an unacceptable error, as a result of unpredictable quantum events. And this, Wigner implies, flies in the face of our daily observation of the process of reproduction.

The argument is strange because it uses the same quantum effects that Max Delbrück[5] and Erwin Schrödinger[6] used long ago to arrive at exactly the opposite conclusion. Schrödinger reasoned that quantum effects are essential to explain the uniqueness of a living form. Wigner turns this reasoning upside down, and concludes that no living form can maintain its identity in the face of quantum disturbances.

When we examine the argument which leads Wigner to his conclusion, its limitations are evident (and are acknowledged by him). Wigner's procedure is to transform the quantum state vectors of the cell and its nourishment taken together into the state vectors of the two similar cells that are to result (and of the rejected part of the nourishment). It appears that the number of equations to be satisfied is far larger than the number of unknowns at our disposal, if it is assumed (as in the absence of any more specific knowledge Wigner has to assume) that the Hamiltonian matrix which represents the transformation consists, apart from its symmetry, of *random* elements. But of course this begs the whole question because it necessarily disregards all relations within the matrix of transformation—that is, the organized inner structure of the process of ingestion and cell division. So long as we do not know the relations between the elements of the matrix, the counting of unknowns and variables at our disposal is quite inconclusive, and can be wholly misleading.[7]

But in fact Wigner's procedure is (as he admits) even less realistic than this first criticism implies. For it is the nature of any argument that proposes a count of unknowns and variables that it can only assert or deny the existence of a solution that makes the outcome of the process *certain.* Even if we were to accept Wigner's assumptions, therefore, we could only conclude that the process of cell division as he idealizes it cannot be guaranteed to yield a second similar cell with *certainty.* But nothing is asserted, or could be concluded, about any process of cell division which has only a *probability* of producing viable offspring—even if the probability is as high as .99. The reasoning[8] is not applicable to probable outcomes, however high or low.

However, experience shows that no biological process works with certainty, and that few organisms produce similar and viable offspring with as high a probability as .99. We must therefore recognize that Wigner's argument misses the essence of biological processes, namely, that they do *not* function with certainty. Indeed, the evolution of more highly organized forms of life than the cell would not have been possible if they had done so.

A cell in its task of simply living makes proteins over and over again from the same blueprint, and now and again it also replicates the blueprint when it divides in two. No conceivable machinery, within the known laws of nature or any that we might think of, can carry on this endless work of copying with zero tolerance—which means, without making individual mistakes from time to time. We put these mistakes down to quantum effects, and that is right; yet in a sense quantum physics is simply a formalization of our well-founded and much wider conviction that no natural process can work with zero tolerance and so be immune from error. Just as we know that perpetual motion is impossible, and can derive a great part of classical mechanics from this Law of the Impossible, so we know that perpetual accuracy of reproduction is inconceivable, and we can regard quantum physics as a specification of that knowledge: the specification of a nonzero tolerance, namely Planck's quantum constant, below which we cannot press.

The discrepancy arises because life has two separate components, and Wigner ignores just that creative component which is characteristic of life and is absent in dead matter. Life is not only a process of accurate copying: that is carried out quite as neatly in the geometrical scaffolding of a dead crystal. Life is also and essentially an evolutionary process, which moves forward only because there are errors in the copy, and every so often one of these errors is successful enough to be incorporated as another step or threshold in its progression. It is important to understand that the living creature combines both procedures, and to see how it does so.

The accumulation of individual errors is certainly a handicap to a cell, but we have to distinguish between two kinds, or better between two places, of error. Errors made now and again in producing a molecule of a protein which is merely a momentary step in the metabolism of the cell are not likely to be important, for the next molecule of the protein can be expected to be normal again. But there are some proteins which play a basic part in the productive machinery of the cell, and act as jigs or machine-tools to help make copies of other proteins. When such a master molecule is wrongly made, it will in its turn cause errors in the making of other copies, and as a result the error will be cumulative. Leslie Orgel[9] has suggested that errors in such master molecules may be the cause for cells breaking down, and the suggestion is supported by recent experiments.[10] Moreover, if Orgel's picture is right, every cell must break down sooner or later when it accumulates errors in some master molecule. There can be no immortal cells. Indeed, Leonard Hayflick[11] has found in careful experiments that by the time a cell has divided about fifty times the clone of cells formed from it all fail to divide. *The machinery of life ensures the death of individuals.*

But exactly this machinery also ensures the evolution of new forms. *The errors which destroy the individual are also the origin of species.* Without these errors, there would be no evolution, because there would be no raw material of genetic mutants for natural selection to work on. There would only be one universal form of life, and however well adapted that might have been to the environment in which it was formed, it would have perished long ago in the first sharp change of climate. When Wigner and Walter Elsasser say that there must be some biological law different from the laws of physics in order that copying in the organism shall be free from error, and the storage of the instructions which govern its exact form and development from the cell shall be perfectly accurate, they are asking for the immortality of the individual but ensuring the destruction of species. We have only to look about us to see that the evidence is against them on both counts.

## EVOLUTION IS CRUCIAL

Evolution is crucial to any discussion of biology, because this and only this makes biology a different kind of subject from physics. A recent survey by John Desmond Bernal[12] of what is known about biological molecules begins with a chapter on "The Nature of Biology," and he opens it with a section whose title bluntly asks "Does Biology Exist?" The question is meant to remind us abruptly that biology is a different kind of study from other sciences, because it studies a very specialized and, as it were, accidental phenomenon. Bernal puts the distinction precisely:

> I believe there is a radical difference, fundamentally a philosophical difference, between biology and the so-called exact or inorganic sciences, particularly physics. In the latter we postulate elementary particles which are necessary to the structure of the universe and that the laws controlling their movements and transformations are intrinsically necessary and in general hold over the whole universe.
>
> Biology, however, deals with descriptions and ordering of very special parts of the universe which we call life—even more particularly in these days, terrestrial life. It is primarily a descriptive science, more like geography, dealing with the structure and working of a number of peculiarly organized entities, at a particular moment of time on a particular planet.[13]

Perhaps Bernal is too narrow when he compares biology with geography, which is mainly a description of space. The comparison that comes to my mind is rather with geology, which like biology deals with configurations in space and traces their behavior in time. But essentially the distinction that he makes is well grounded; life has a more accidental and local character than the other phenomena of the physical world.

I would go further, and say that life has a more *open and unbounded* character than the other phenomena of the physical world: it is incomplete and unfinished in a way that they are not. That is, biology has a different character from physics at every point in evolutionary time. The biological universe that we are discussing today is different from that which we could have discussed three million years ago—when indeed there was no *Homo sapiens* to discuss it. And we must expect that the biological universe of three million years hence may be quite as different again.

Let me make this distinction explicitly. The development of life from one form to another is unlike that of the rest of the physical world, because it is triggered by accidents, and they give each new form its unique character. Life is not an orderly continuum like the growing of a crystal; it creates new expressions, and remains constantly open to them, as a succession of errors which can only occur *because life is accident-prone.* The nature of life is only expressed in its perpetual evolution, which is another name for the succession (and the success) of its errors.

The molecules that make up a cell or an individual form a physical system with many states. If we map all possible states (disorderly as well as orderly) by the points of an abstract space, there is a narrow sequence of points which maps the sequence of steps in the life cycle of the cell, or the sequence of states of the individual before he returns to (approximately) the same state—say, waking in the morning. Since the cycle of states returns on itself, the sequence of points forms (virtually) a closed loop. Thus on the scale of the cell and of the individual, life is a process which is topologically closed. It runs over more or less the same loop again and again, and in time it runs down.

Yet life does not run down in the way in which natural processes run down, by the general leveling of energy peaks which is called the Second Law of Thermodynamics. The death of a cell or of an individual is not a leveling out, a falling apart of the architecture, as decay after death is. Instead, death is a failure of the metabolism to continue its cycles, and it begins in a failure to repeat the cycles accurately. It seems likely that the cell or individual is clogged by errors which are inevitable and become cumulative: whatever the underlying cause proves to be, the topological loop wavers and comes to a stop.

But life as an evolutionary sequence is not a closed loop. On the contrary, life as evolution is topologically open, for it has no cycle in time. Yet it derives this openness from just such accidents or errors, at least in kind, as kill the individual. The mechanism of survival for a species is its evolution, and evolution is that quantum resonator or multiplier, the exploitation of an accident to create a new and unique form, for which Max Delbrück was looking when he came into biology.

In summary, the closed loop of an individual life and the open path of evolution are dual aspects of life. The common mainspring of quantum accidents (that is, of errors in the copying of biological molecules) may be responsible for individual death, and is certainly responsible for evolution. Both are only properly understood when they are put side by side as complementary parts or processes of life.

## BOUNDED AND UNBOUNDED PLANS

I will make this distinction in another form by examining the different arguments for vitalism which have been advanced by Michael Polanyi, first at the level of the cell, and then at the level of evolution. At the first or lower level, Polanyi simply says that to explain the *machinery* of a cell is like explaining the machinery of a watch while missing the most important thing about it, which is that a watch is planned *for a purpose*—to tell the time.

The design of a watch is the classical illustration for God's design in man that deists introduced in the eighteenth century. Henry Saint-John, Viscount Bolingbroke, and William Paley in *A View of the Evidences of Christianity*[14] used it to claim that man is a more ingenious machine than is a watch, and must therefore be supposed to have been designed by a more ingenious creator. Polanyi now gives this argument a new look by saying that just as the design of the watch points to and is understood only in its purpose, so the design of the machinery of life points to and is understood only at a higher level of explanation by purpose. He calls this the boundary conditions for any mechanism, but these words only restate the requirement which he proposes, namely, that it must fit into and serve some overall plan outside itself. In essence, the argument remains in the eighteenth century: we *know* that the watch is ingenious because we know the purpose for which it is planned.

Perhaps it is easiest to see what is wrong with this argument by deriving a paradox from it, as follows. The argument is intended to show that man (and any other living form) is not simply a machine. In order to show this, he is compared with a typical machine, namely, a watch; and it is concluded that he is more sophisticated, that is, more purposeful, than the mechanism that drives the watch. How is this concluded? By showing that the watch itself, as a machine, is more sophisticated, that is, more purposeful, than the mechanism that drives it. In short, even a machine is not merely a mechanism, or what we usually call a machine. Man therefore is not a machine because he is a machine, and it has already been shown that a machine is not a machine.

How does this pardox come about? Evidently, by confusing the *external function* for which the machine has been made (by the watchmaker, for example) with the *inner plan* which the living creature follows as its natural and species-specific sequence of operations. To claim that this inner plan means anything more can be justified only by appealing to a quite abstract, classical tenet of philosophy, that the reduction of a sequence to its parts is not a sufficient explanation of their totality. But the implication is out of place here, where it merely restates the analogy of the watch which is designed to tell the time. There are indeed contexts in philosophy in which reductionism is not enough. But reductionism is valid and sufficient when it is an *historical* explanation, so that it presents a temporal and logical sequence of steps by which the result has been reached. (Indeed, all causal explanations are of this kind, and can only be challenged if we challenge the first cause.) To reduce a whole to its parts is a valid exposition of its plan if in fact the parts have come together in time, step by step, in building up a sequence of lesser wholes. So it is valid to regard an organism as an historical creation whose plan is explained by its evolution. But the plan of life in this sense is *unbounded*. Only unbounded plans can be creative; and evolution is such a plan, which has created what is radically new in life, the dynamic of time.

So it is timely now to consider *evolution as an open and unbounded plan,* and to ask what additional principles are needed to make it capable of creating the new living forms that we know. For it is essential that we recognize these forms as genuine creations, which have not been formed on a bounded plan like that which runs its rigid course from the seed to the full-grown plant.

The distinction here is between a sequence of actions which is fixed in advance by the end state that it must reach, and a train of events which is open and unbounded to the future because its specific outcome is not foreseen. *Any bounded plan is in essence the solution to a problem,* and life as a mechanism has this character. By contrast, the sequence of events that constitutes an unbounded plan is invented moment by moment from what has gone before, and the outcome is not solved but created. Life as an evolution is a creation of this kind.

In this analysis, the vitalist's question becomes directed to a different issue: the relation between the direction of evolution and the direction of time. In a history of three thousand million years, evolution has not run backward—at least, by and large, and in a definable statistical sense, it has not run backward. (The existence of some lines of regression, such as those which have produced the viruses, does not change this general characterization.) Why is this? Why does evolution not run at random hither and thither in time? What is the screw that moves it forward, or, at least, what is the ratchet that keeps it from slipping back? Is it possible to have such a mechanism which is not planned? What is the relation that ties evolution to the arrow of time, and makes it a barbed arrow?

The paradox to be resolved here is classical in science: how can disorder on the small scale be consonant with order on the large scale, in time or in space? If this question is asked of the molecules in a stream of gas, the answer is easy—the motion imposed on the stream swamps the random motions of the individual molecules. But this picture will not help to explain evolution because there is no imposed motion there. On the contrary, if we were to assume an imposed motion, we would be accepting the postulate of vitalism. Evolution must have a different statistical form, in which there is *an inherent potential for large-scale order to act as a sieve* or selector on the individual chance events. There are such cooperative phenomena in physics: for example, in the structure of crystals, which we understand, and perhaps in the structure of liquids, which we do not. The existence of a potential of order in the selection of chance events is clear, but what is never clear in advance is how it will express itself. It is here that we need two additional principles in evolution to give it a natural order in time.

### STRATIFIED STABILITY

There are five distinct principles which make up the concept of evolution, as I interpret it. They are: (*a*) family descent, (*b*) natural selection, (*c*) Mendelian inheritance, (*d*) fitness for change, and (*e*) stratified stability. The first three are familiar, and I need not elaborate them; they make up the standard account of the mechanism of evolution that has been accepted since Ronald A. Fisher first formalized it in *The Genetical Theory of Natural Selection.*[15]

But in my view it is now necessary to add the two further principles which I propose, namely, (*d*) fitness for change and (*e*) stratified stability. They are concerned, the one with the *variability* of living forms, and the other with their *stability;* and between them they explain how it comes about that biological evolution has a direction in time—and has a direction in the same sense as time. The direction of evolution is an important and indeed crucial phenomenon, which singles it out among statistical processes. For insofar as statistical processes have a direction at all, it is usually a movement toward the average—and that is exactly what evolution is *not.*

Of the two new principles that I propose, the first is only peripheral to my theme here, and I shall deal with it quite briefly. In order that a species shall be capable of changing to fit its environment tomorrow, it must maintain its *fitness for change* today. The dormant genes that may be promoted tomorrow when they become useful must be preserved today when they are useless. And for this they must be held now in a setting of other genes which makes it possible to promote them rapidly. If this is to be done in the present, without some mysterious plan for the future, it must be by *natural selection* not for this or that variant but *for variability itself.*

It is evident that there is natural selection in favor of genetic variability. The selection is made by the small changes, up and down and up again and down again, by which the environment flutters about its mean. A long-term trend in the environment which lasts a hundred generations or so will in that time select a new adaptation. But the short-term fluctuation which goes one way for a few generations and then the other way for a few generations will meanwhile select for adaptability. That is, the short-term fluctuation favors the establishment of an arrangement of genes that will help mutant genes to express themselves.

Indeed, we know now that there are single genes which function specifically to enhance variability. For example, there are single genes which increase the rate of mutation in several other genes at the same time. Their action could explain the tendency for genetic change in one part of an organism (particularly, and in the first place, a haploid organism) to keep pace with change in other parts. A master gene of this kind, which increases mutation, is a mechanism that opens up the future, not by foreseeing it but by promoting the capacity for change.

I turn now to the crucial part of my argument. It is evident that we cannot discuss the variability of organisms and species without also examining their stability. We have therefore also to trace a mechanism for stability, as the second of the two balanced mechanisms that are needed to complete our understanding of evolution. I call this, the fifth and last principle in my analysis of evolution, the concept of *stratified stability*.

Evolution is commonly presented, even now, as if it required nothing but natural selection to explain its action, one minute step after another, as it were gene by gene. But an organism is an integrated system, and that implies that its coordination is easily disturbed. This is true of every gene: normal or mutant, it has to be incorporated into the ordered totality of the gene complex like a piece in a jigsaw puzzle.

Yet the analogy of the jigsaw is too rigid: we need a geometrical model of stability in living processes (and in the structures that carry them out) which is not so landlocked against change. Moreover, the model must express the way in which the more complex forms of life arise from the simpler forms, and arise later in time. This is the model of stratified stability.

There are evolutionary processes in nature which do not demand the intervention of selective forces. Characteristic is the evolution of the chemical elements, which are built up in different stars step by step, first hydrogen to helium, then helium to carbon, and on to heavier elements. The encounter of hydrogen nuclei makes helium simply (though indirectly) because they hold together: arrangements are briefly formed which in time form the more complex configuration that is helium.[16] Each helium nucleus is a new unit which is stable, and can therefore be used as a new raw material to build up still higher elements.

The most telling example is the creation of carbon from helium. Two helium nuclei which collide do not make a stable element, and fly apart again in less than a millionth of a millionth of a second. But if in that splinter of time a third helium nucleus runs into the pair, it binds them together and makes a stable triad which is a nucleus of carbon. Every carbon atom in every organic molecule in every cell in every living creature has been formed by such a wildly improbable triple collision in a star.

Here then is a physical model which shows how simple units come together to make more complex configurations; how these configurations, if they are stable, serve as units to make higher configurations; and how these higher configurations again, provided they are stable, serve as units to build still more complex ones, and so on. Ultimately a heavy atom such as iron, and perhaps even a complex molecule containing iron (such as hemoglobin), simply fixes and expresses the potential of stability which lay hidden in the primitive building blocks of cosmic hydrogen.

The sequence of building up stratified stability is also clear in living forms. Atoms build the four base molecules, thymine and adenine, cytosine and guanine, which are very stable configurations. The bases are built into the nucleic acids, which are remarkably stable in their turn.[17] And the genes are stable structures formed from the nucleic acids, and so on to the subunits of a protein, to the proteins themselves, to the enzymes, and step by step to the complete cell. The cell is so stable as a topological structure in space and time that it can live as a self-contained unit. Still the cells in their turn build up the different organs which appear as stable structures in the higher organisms, arranged in different and more and more complex forms.

Two special conditions have assisted this mode of climbing from simple to complex. First, of course, there is the energy which comes to us from the sun, which increases the number of encounters between simple units and helps to lift them over the next energy barrier above them. (In the same way, simple atomic nuclei encounter one another reasonably often, and are lifted over the next energy barrier above them, by the energy in hot stars). And second, natural selection speeds up the establishment of each new stratum of stability in the forms of life.

The stratification of stability is fundamental in living systems, and it explains why evolution has a consistent direction in time. Single mutations are errors at random, and have no fixed direction in time, as we know from experiments. And natural selection does not carry or impose a direction in time either. But the building up of stable configurations does have a direction, the more complex stratum built on the next lower, which cannot be reversed in general (though there can be particular lines of regression, such as the viruses and other parasites which exploit the more complex biological machinery of their hosts). Here is the barb which evolution gives to time: it does not make it go forward, but it prevents it from running backward. The back mutations which occur cannot reverse it in general because they do not fit into the level of stability which the system has reached: even though they might offer an individual advantage to natural selection, they damage the organization of the system as a whole and make it unstable. Because stability is stratified, evolution is open, and necessarily creates more and more complex forms.[18]

There is therefore a peculiar irony in the vitalist claim that *the progress of evolution from simple to complex* cannot be the work of chance. On the contrary, as we see, exactly this *is how chance works, and is constrained to work by its nature.* The total potential of stability that is hidden in matter can only be evoked in steps, each higher layer resting on the layer below it. The stable units that compose one layer are the raw material for random encounters which will produce higher configurations, some of which will chance to be stable. So long as there remains a potential of stability which has not become actual, there is no other way for chance to go. It is as if nature were shuffling a sticky pack of cards, and it is not surprising that they hold together in longer and longer runs.

## THE SECOND LAW OF THERMODYNAMICS

It is often said that the progession from simple to complex runs counter to the normal statistics of chance that are formalized in the Second Law of Thermodynamics. Strictly speaking, we could avoid this criticism simply by insisting that the Second Law does not apply to living systems in the environment in which we find them. For the Second Law applies only when there is no overall flow of energy into or out of a system, whereas all living systems are sustained by a net inflow of energy.

But though this reply has a formal finality, in my view it evades the underlying question that is being asked. True, life could not have evolved in the absence of a steady stream of energy from the sun—a kind of energy wind on the earth. But if there were no more to the mechanism of molecular evolution than this, we should still be at a loss to understand how *more and more complex* molecules came to establish themselves. All that the energy wind can do, in itself, is to increase the range and frequency of variation around the average state: that is, to stimulate the *formation* of more complex molecular arrangements. But most of these variant arrangements fall back to the norm almost at once, by the usual thermodynamic processes of degradation; so that it remains to be explained why they do not all do so, and how instead some complex arrangements *establish* themselves, and become the base for further complexity in their turn.

It is therefore relevant to discuss the Second Law, which is usually interpreted to mean that all constituent parts of a system must fall progressively to their simplest states. But this interpretation quite misunderstands the character of statistical laws in general in nonequilibrium states. The Second Law describes the final equilibrium state of a system; if we are to apply it, as here, to stable states which are far from equilibrium, we must interpret and formulate it differently. *In these conditions, the Second Law of Thermodynamics becomes a physical law only if there is added to it the condition that there are no preferred states or configurations.* In itself, the Second Law merely enumerates all the configurations which a system could take up, and it remarks that the largest number in this count are average or featureless. Therefore, if there are no preferred configurations (that is, no hidden stabilities in the system on the way to equilibrium), we must expect that any special feature that we find is exceptional and temporary, and will revert to the average in the long run. This is *a true theorem in combinatorial arithmetic,* and (like other statistical laws) *a fair guess at the behavior of long runs.* But it tells us little about the natural world which, in the years since the Second Law seemed exciting, has turned out to be full of preferred configurations and hidden stabilities, even at the most basic and inanimate level of atomic structure.

The Second Law describes the statistics of a system around equilibrium whose configurations are all equal, and it makes the obvious remark that chance can only make such a system fluctuate around its average.[19] There are no stable states in such a system, and there is therefore no stratum that can establish itself; the system stays around its average only by a principle of indifference, because numerically the most configurations are bunched around the average.

But if there are hidden relations in the system on the way to equilibrium which cause some configurations to be stable, the statistics are changed. The preferred configurations may be unimaginably rare; nevertheless, they present another level around which the system can bunch, and there is now a countercurrent or tug-of-war within the system between this level and the average. Since the average has no inherent stability, the preferred stable configuration will capture members of the system often enough to change the distribution; and, in the end, the system will be established at this level as a new average. In this way, local systems of a fair size can climb up from one level of stability to the next, even though the configuration at the higher level is rare. When the higher level becomes the new average, the climb is repeated to the next higher level of stability; and so on up the ladder of strata.

So, contrary to what is usually said, the Second Law of Thermodynamics does not fix an arrow in time by its statistics alone. Some empirical condition must be added to it before it can describe time (or anything else) in the real world, where our view is finite.

When there are hidden strata of stability, one above another, as there are in our universe, it follows that the direction of time is given by the evolutionary process that climbs them one by one. Indeed, if this were not so, it would be impossible to conceive how the features that we remark could have arisen. We should have to posit a miraculous beginning to time at which the features (and we among them) were created ready-made, and left to fall apart ever since into a tohubohu of individual particles.

Time in the large, open time, takes its direction from the evolutionary processes which mark and scale it. So it is pointless to ask why evolution has a fixed direction in time, and to draw conclusions from the speculation. It is evolution, physical and biological, that gives time its direction; and no mystical explanation is required where there is nothing to explain. The progression from simple to complex, the building up of stratified stability, is the necessary character of evolution from which time takes its direction. And it is not a forward direction in the sense of a thrust toward the future, a headed arrow. What evolution does is to give the arrow of time a barb which stops it from running backward; and once it has this barb, the chance play of errors will take it forward of itself.

## NOTES

1. Walter M. Elsasser, *The Physical Foundation of Biology* (Elmsford, N.Y.: Pergamon Publishing Co., 1958).
2. Eugene P. Wigner, "The Probability of the Existence of a Self-reproducing Unit," in *The Logic of Personal Knowledge: Essays Presented to Michael Polanyi on His Seventieth Birthday* (London: Routledge & Kegan Paul, 1961).
3. Henry Saint-John, Viscount Bolingbroke, *Philosophical Works of the Late Right Honorable Henry St. John, Lord Bolingbroke* (London: David Mallett, 1754).
4. Michael Polanyi, "Life Transcending Physics and Chemistry," *Chemical and Engineering News* 45, no. 35 (1967):54–66; and "Life's Irreducible Structure," *Science* 160 (1968):1308–12.
5. Max Delbrück, "A Physicist Looks at Biology," *Transactions of the Connecticut Academy of Arts and Sciences* 38 (1949):173–90; and in *Phage and the Origins of Molecular Biology*, ed. John Cairns, Gunther S. Stent, and James D. Watson (Cold Spring Harbor, N.Y.: Cold Spring Harbor Laboratory of Quantitative Biology, 1966).

6. Erwin Schrödinger, *What Is Life?* (Cambridge: Cambridge University Press, 1944).

7. For example, it is a familiar paradox in projective algebraic geometry that an argument like Wigner's can be used to prove that every conic section is a pair of straight lines.

8. For example, if Wigner's reasoning here were applied to nuclear fission, it would persuade us that a chain reaction is impossible—because we can never stipulate that the entry of a neutron into a specified nucleus will *certainly* release two neutrons.

9. Leslie Orgel, "The Maintenance of the Accuracy of Protein Synthesis and Its Relevance to Ageing," *Proceedings of the National Academy of Science* 49 (1963):517–21.

10. See B. J. Harrison and Robin Holliday, "Senescence and the Fidelity of Protein Synthesis in *Drosophila*," *Nature* 213 (1967):990–92; and Robin Holliday, "Errors in Protein Synthesis and Clonal Senescence in Fungi," *Nature* 221 (1969):1224–28.

11. Leonard Hayflick, "Cell Culture and the Aging Phenomenon," in *Topics in the Biology of Aging*, ed. Peter L. Krohn (New York: Interscience Publications, 1966).

12. John Desmond Bernal, "Molecular Structure, Biochemical Function, and Evolution," in *Theoretical and Mathematical Biology*, ed. Talbot H. Waterman and Harold J. Morowitz (New York: Blaisdell Publishing Co., 1965).

13. Ibid., pp. 96–97.

14. William Paley, *A View of the Evidences of Christianity* (London: R. Faulder, 1794).

15. Ronald A. Fisher, *The Genetical Theory of Natural Selection* (Oxford: Clarendon Press, 1930).

16. See Hans A. Bethe, "Energy Production in Stars," *Physical Review* 55 (1939): 434–56.

17. See James D. Watson and Francis H. C. Crick, "Molecular Structure of Nucleic Acids: A Structure for Deoxyribose Nucleic Acid," *Nature* 171 (1953):737–38.

18. For a fuller account, see my Condon lectures for 1967 at the University of Oregon, published under the title *Nature and Knowledge* (Eugene: University of Oregon Press, 1969). Recently David Bohm has put forward a similar scheme for an inherent hierarchy of complexity, in which he calls *levels of order* what I call *strata of stability*. See his "Some Remarks on the Notion of Order," in *Towards a Theoretical Biology*, ed. C. H. Waddington (Chicago: Aldine Publishing Co., 1969), vol. 2.

19. It should be remarked that Johann von Neumann's quantum theoretical proof of the Second Law (see his *Mathematische Grundlagen der Quantenmechanik* [Berlin: Springer-Verlag, 1932]), like Wigner's argument above, assumes that the behavior of a system to which it is applied can be represented by a random symmetric Hamiltonian matrix—that is, contains no hidden inner relations.