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Causality and Anticipation

Analysis of the concept of anticipation can contribute to the philosophy of biology.

J. M. Burgers

The purpose of this article is to renew discussion of the problem whether the phenomena of life can be satisfactorily analyzed and explained on the basis of the laws discovered in the physical sciences, or whether more is needed. When mentioning the physical sciences, I have in mind the physical laws as they are formulated at present, with the trend of thinking that forms their present background. Otherwise the problem would become indefinite. I wish to consider the thesis that the features of life involve relations not covered by the present formulation of the physical laws, relations which, although not amenable to quantitative analysis, nevertheless play a decisive part in many reactions of living organisms. The problem is, on one hand, how to put this in appropriate terms, and on the other, to analyze some consequences of the thesis. It is useful to start with a brief recapitulation of what may be called the central doctrine of the laws of physics, namely the idea of causal relationship. This will be given in the next section. The principal argument concerning the need for extension to another form of relationship is presented in the third section of the article. It is taken from features of our human mental life (*1*).

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Causal Relationship

Our ideas concerning causal relationship are a central feature of the physical laws. It is not necessary to present an extensive description of these ideas and a summary statement will suffice.

We are convinced that all natural phenomena occurring in systems where there is no indication of life are related to the past of the systems in such a way that knowledge of any situation gives us information on which we can base more or less adequate predictions concerning subsequent situations.

"Knowledge of a situation" means the complex of data that we can obtain by making observations and measurements according to a scheme accepted and elaborated in the physical and related sciences. In making these observations we eliminate our personal involvement. We do not introduce such qualifications as "beautiful" or "ugly," "good" or "bad." Neither do we make reference to any purpose or intention; there is no reference to the future as a determining agent. In many cases we apply dissection of complicated phenomena into more simple events, in the conviction that the separate effects can be considered as self-contained. Recombination of features follows at a later stage, and although reciprocal influences are taken into account, it is assumed that these influences will not refer to a particular intention, involved in a "whole" and in some way transcending the partial effects.

It is in this way that the "past"—that is, those aspects of past phenomena which are amenable to measurement—has come to appear as the "cause" of the present. It is a concise statement summarizing the accumulated experience obtained by observing the behavior of nonliving bodies and systems, collected since the beginning of modern science.

In this century it has become evident that in the atomic and electronic domain the measurable data are not sufficient for a completely definite prediction of succeeding states; there is dispersion in the development and statistical predictions are the most that can be made. Thus, causal relationship is partly deterministic, partly statistical. In the investigation of these relations no evidence has been found for the effectiveness of "finalistic causes," that is, causes directed to the future. All predictions that can be made are still statements which relate the present to the past. It has also become clear that in the atomic and electronic domain every observation or measurement disturbs the system under observation.

There is no need to dwell on the power the scientific method of observation has given to mankind. However, it should not be overlooked that this enormous success has also depended on the type of problems studied. Many questions occupied the human mind during the Middle Ages, for example, the problem whether man's destiny was to adjust himself to a cosmic order, embracing both the moral and the material world. The new science of Leonardo, Galileo, and their followers was directed away from such problems and substituted a new set of questions. Pushed in this new direction, Western thought came more and more to rely on the assumption that everything in the Universe is determined by what has occurred in its past. It is here that a warning note is in order. There is no justification for enforcing this concept of causality on the entire Universe as the only possible form of relationship. In particular, while many phenomena exhibited by living beings can be foreseen on the basis

of causal relations with the past, we should be aware of the possibility of relations of another type. To obtain some understanding of such relations I will consider the way in which we experience life. Since we are a biological species, discussion of our experience is an appropriate topic for biology.

Anticipation

The point to discuss is that we have experience of our life and in particular that we experience our life as something that is continuing into the future. In our thoughts, in our feelings and actions there is not only a reminiscence of past events, but also a notion that we shall exist—that is, that we shall be open to experience and shall act—in the next instant and probably in the next after that, and so on. Even when one is aware of acute danger for one's life, this is an expectation concerning the future.

We find related feelings of expectation, although more primitive, in many domesticated animals (consider a dog and his master), and there is great probability that some forms are present in various other species. It is advisable not to tie the notion of expectation or anticipation to consciousness, but to assume that it is located (insofar as we may use this word) at a "deeper level." Evidently in humans it often reaches the level of consciousness, but probably even here this is not always the case. We do not know how it occurs in other living beings, but there is reason to suppose its effectiveness in many situations.

To come back to human experience: in our anticipatory feelings we do not consider ourselves completely bound by circumstances, although it is evident that we are bound in many ways. Notwithstanding the physical limitations to which we are subjected (they are an expression of the causal relations in which we are involved—for instance, we all have weight), we have the feeling that there is some leeway, that options are open, that there is some freedom of choice concerning our actions in the next moment. We have the feeling that we can make choices or decisions, and that our decisions have a real effect on our actions.

Even if one is of the opinion that this freedom is an illusion and that we are completely bound by states of atoms and molecules, the point remains that the feeling itself, the notion of being alive, is a real phenomenon. So far there is no way to translate descriptions of molecular situations into these feelings. Since the physical description eliminates all value judgments, present-day physics has no means to connect its equations with options such as we entertain in our mind. I presume therefore that we must give attention to the idea of freedom, as being an essential aspect of life, not included in the domain of physical relationship, and nevertheless effective. Thus "anticipation" and "feelings of freedom" should have a place in biological descriptions.

The term "choice" leads to the question: what directs a choice? A choice cannot be directed by a cause, for then it would not be a choice.

A choice refers to an anticipation of a future. The notion of a coming future involves an extrapolation from past experience to possible future events. This extrapolation is never fully determined. Experience is obtained in forms partly dependent on features of the experiencing subject, and data usually are insufficient; in certain cases there may also be quantum indeterminacy. Hence the fragmentary character of the extrapolation, which leaves options. We make our choice between these options.

In our human societies we are considered as responsible for many of our choices. Human society assumes that we can change our choices and that we can distinguish between "good" and "bad" choices. To cope with this feature at the biological level we cannot use the terms good and bad, and must look for a more basic notion. For this purpose we postulate that the feeling of having a certain freedom of choice carries with it a motivation of fundamental importance and we propose the statement: We try to make our choices in such a way that in the next instant we shall still have some freedom. We experience freedom as a feature of life, and we do our best not to be driven into a dead corner where choice is no longer possible. The basic principle of motivation is thus: conservation of some measure of freedom; to, which we may add: extension of potentialities for action, that is, extension of freedom.

Another way of expressing this is: Life—and now I go from human life to life in general—is a game against the environment, in which the player, the living organism, attempts to stay in the game by making appropriate choices or moves, so as to retain some measure of freedom. The comparison with a game does not assert that there are quantitative rules or definite algorithms by which moves can be determined. For each move guesses must be made, based on prior (and usually insufficient) experience.

Life is thus considered as the exertion of freedom and the struggle for preservation and extension of freedom. This is presented as more fundamental than any attempt at a physicochemical definition of life. The chemistry somehow is a result of the struggle (at least for the types of living beings with which we are acquainted). It is also proposed to consider the reproduction of living beings as a later step, not as a starting point.

The term freedom still needs discussion. One must ask: freedom for doing what? Observation of ourselves, as well as the study of the multitudinous species of living organisms, suggests the answer: freedom to make or promote arrangements, patterns in space or time, structures, in which some satisfaction is found, a satisfaction which most conveniently can be called esthetic. The term sounds vague, but it refers to something that I consider fundamental. It carries a notion related to the idea of play, to caring for a pleasing arrangement of objects or events. There is no appeal here to some standard canon; esthetics, as used here, refers to feelings playing a role in an individual choice. I assume that such esthetic values also carry germs of moral and ethical values such as are entertained by man. However, this must be left aside here.

As we do not find an evident discontinuity in the chain of life, I am induced to suppose that forms of anticipation are effective in all living organisms, even in plants. To extend it so far, anticipation should primarily reside in the cells, and probably also in parts of cells. We may presume that there exist forms of effectiveness at various levels, standing in a kind of hierarchy one above the other [see (*6*) for an author who supports this idea].

The argument developed here can be summarized in the statement: Life is a struggle against randomness. It strives to replace randomness by arrangements which give some esthetic satisfaction and which may have some meaning. For the processes involved here we shall use the term conceptual activity, to stress that they are active, not passive, and that they express themselves in judgments and concepts, directed in a limited way to the future.

Memory—Origin of Structures

The preceding discussion of concepts connected with the notion of anticipation has been given in order to develop some idea of what we are looking for. To reject this on the ground that it is anthropomorphism would be to miss the point. The concepts have been derived from observation of processes in the human mind, the existence and activity of which is a biological phenomenon. They have been presented in a form which may lead to the recognition of features effective in a wider

domain of life. The wider features refer to the place to be given to persistence and memory, in order to find an explanation for the evolution of living systems and living organisms. Assumptions concerning persistence and memory must be introduced to account for the fact that living organisms have become endowed with a complicated material apparatus.

The first assumption is that when a system in which choices are possible has found a chance to promote the occurrence of an arrangement guided by an esthetic preference, there will be a tendency to repeat this performance. Hence some form of memory must be effective, making possible repetition and involving awareness of this repetition (this contains more than merely mechanical repetition). This can lead to the birth of traditions.

The second assumption is that repetition of conceptual activity, that is, having repeated experiences and making repeated choices of a similar type, can lead to an extension of the domain of action and to choices effective within a wider terrain of possibilities. It is of particular interest to consider this at the level of atomic reactions, a point to which we also shall come back later on. When conceptual activity has repeatedly exerted influence on the course of certain atomic processes, an extended effect sometimes may be hit upon leading to an atomic arrangement that by purely physical relations will ensure a reaction which first could be obtained only as a result of the original narrower choices. If the wider choice can promote the occurrence of such an arrangement, it will relieve the system of the necessity of periodically repeating the original narrow choices. To make the wider choice is a step beyond the domain of choices performed before, and it can be seen as the building of an apparatus, or a structure which will "make life easier." Still wider possibilities may then open up. We must look here for the beginning of the evolution of living systems and living organisms. Roughly it may be compared with the invention of a piece of machinery or a tool to perform a function first accomplished by a worker who periodically has to make the same set of narrow decisions. In both cases an element of chance is involved: the opportunity can be seen and used, or it can be lost. I will come back to this idea in the last section of this article. I stress that in a living organism a structure is not built up by purely physical processes alone, as in the growth of a crystal: a living system requires conceptual activity taking advantage of a favorable opportunity.

If a physicist investigates the system he finds the structure and he will conclude that a certain reaction is caused by the structure, so that the occurrence of the reaction can be explained as the result of purely physical laws. This is true, but from our point of view the essence of life is to be found in the establishment of this structure, rather than in its functioning. It is this important phenomenon which makes it difficult to find out, through observation at the molecular level, what life is or what life does. Molecular biology shows us the structures present in living systems or living organisms, and it explains their mode of operation. The origin and the evolution of the structures, however, is not revealed. This is not a feature which occurs repeatedly in the same form. Perhaps something might be revealed in embryological development if we could make a distinction between development completely guided by genetic information and decisions to be made ad hoc in anticipatory choices. However, in the present state of research we do not have definite evidence for such choices. An enormous amount of information is stored in a material memory apparatus as DNA molecules and other structures, but we do not know whether this is sufficiently definite or whether it still needs interpretation by means of choices.

As mentioned earlier, choices made on the basis of anticipation of coming situations necessarily always refer to steps of limited extent. Accumulation of their effects must have led to the diversity of living forms which we know around us. Contingencies of all kinds have played a part in presenting new situations, with unexpected chances always coming up. There is no reason to accept predestination in admitting some amount of anticipation or foresight in the evolution of new forms. The course followed during the history of Earth might have come out differently. Choices in general are directed toward the attainment of more freedom and more possibilities for action. Thus they involve an ordering principle and consequently there is a ground for progression, although certain steps have led to parasitism and to what we, human beings, consider a loss of possibilities.

Reproduction, in the sense of preparing structures which can be detached to grow to new living systems or organisms, is part of the struggle for more possibilities. It must be considered as a secondary feature in the evolution of life. With its invention the problem of death will have arisen; this is also a later feature in the evolution of life. Natural selection could operate when birth and death had gained their ecological effects, not earlier. The idea of natural selection cannot be invoked for molecular reactions.

I hope that this discussion will make clear that an absolute polarization between causality and teleology, such as often is presented, needlessly obscures the problems of evolution and adaptation. There can be purposiveness in numerous small steps, reacting on an unlimited diversity of occasions presented by chance, with cumulative results that could not be foreseen nor have been intended from the beginning. The evolution of forms of life is dependent on an interplay of traditions and initiatives as is the evolution of human societies.

Effect on Matter

So far we have collected features involved in anticipation and in the conceptual activity connected with it, but we have avoided the problem of how this activity can affect the behavior of matter. Nevertheless this is what we need if we believe that anticipation is really active. What form of cosmology can be set up that will give a reasonable place to the physical effectiveness of choices?

I will attempt to give an answer to this question in two steps, one with very broad implications, the other concerned with a more narrow domain. The wider one, to be discussed in the next section, is to suppose that forms of conceptual activity are not limited to the living world, but are effective throughout the entire Universe. This idea was presented by the philosopher Alfred North Whitehead (1861–1947) in several of his books (*2*). The existence of Whitehead's philosophy relieves us of the problem of searching for a special carrier of effects reaching beyond those described in present-day physics, while furnishing the possibility of discussing such effects.

The more narrow step based on concepts taken from Whitehead's philosophy bears on a feature of the statistical aspects of quantum theory. We never have full information about the physical state of an atomic system at a given instant, and a reaction occurring in such a system can lead to a variety of results. In order to predict the probability of these results, physical theory has introduced the concept that we must find sets of configurations of equal statistical weight. Such sets form a basis on which a calculation of probabilities can be built. Evidently the assignment of equal weights is a hypothesis. It is supported by its elegance and by the success of its applications in the investigation of the behavior of nonliving matter. But actually it is merely a statement that physical theory thus far has not found need to give attention to the specific features of the individual configurations of the set as a reason for assigning unequal weights to them (*3*).

Still, the various configurations are different. They may belong to the same en-

ergy level, but their esthetic features (to use again a term introduced earlier) distinguish them from one another. We postulate that the choices connected with anticipation manifest themselves as unequal weights and thereby influence the probability distribution of the results.

This may be considered as a dangerous hypothesis, but we need something to make anticipation effective, once we have admitted its importance within ourselves. It is much less attractive to suppose that conceptual activity should have the effect of a force and contribute directly to energy or momentum. A preferential weight can promote certain arrangements of atoms in the synthesis of complicated molecules. It also can combat the danger of a gradually increasing dispersion which quantum theory predicts for physical systems that are not guided by anticipatory choices. It can make ineffective the principle of molecular reversibility.

The following remarks may be useful in this connection.

1) Statistical weights themselves cannot be measured or observed in any direct way, and it is only resulting distributions which can lead to observable features.

2) It would not be appropriate to believe that statistical weights are equal a priori, and that they are "willfully" altered by conceptual activity. The primary feature is unequal weights, perhaps even variable in time, assigned under the influence of esthetic relations. Equality of weights results when esthetic appreciations dwindle to noneffectiveness. The equality holding in nonliving systems must be considered as a secondary feature. It is related to an important thesis of Whitehead's philosophy, according to which the existence of matter is a secondary feature of the Universe (see the next section).

3) The assumption of an effect of conceptual activity on weights evidently remains a concept referring to results. Nothing can be said about a mechanism bringing forward these results. Physics operates with abstract concepts similarly devoid of a mechanical picture, for example, when a pattern produced by the interference of wave systems is assumed to guide the flux of particles. Another instance is the expression for the Lorentz force on an electric charge moving in a magnetic field, where no picture is given of a structure in space making this force perpendicular both to the direction of the motion and to that of the magnetic field.

Quantum theory can be seen as an expression of structures in space-time, different from what had been accepted in Newtonian mechanics. The picture sketched here, with its stress upon anticipation, requires ideas concerning space-time of a type assumed in Whitehead's cosmology. Thus there is in existence a world picture to which we can refer, and which supports our sketch.

Features of Whitehead's Cosmology

Whitehead has enunciated the doctrine that every event, every step or process in the Universe involves both effects from past situations and anticipation of future possibilities (*4*). Basic for this doctrine is the assumption that the course of the Universe results from a multiple and never-ending complex of steps developing out of one another. Each step is a "process," a mode of functioning, arising from an experience of existing facts through which it has causal relations with the past. The form of the experience is influenced by the conceptual activity which is initiated in the process. Conceptual activity involves anticipation concerning what may be coming and includes the recognition of certain forms of relationship in the experience. Driven by anticipation, the process moves forward and matures into the expression of a relationship that is considered as being of importance. In this expression the process reaches a result, a new fact, by which it extends the complex of facts already existing. Then a new process can arise, following a similar course. This goes on without end, with ramifications and convergences (*5*).

The picture of unending chains and complexes of processes, each with its own instance of conceptual activity, becomes more definite and stable through the assumption that evaluations and choices in successive processes are influenced by traditions, which in many cases can be very strong. A chain of processes, rhythmically repeating the same fact or a set of closely related facts, takes the form of a persistent material entity, subjected to a definite set of physical relations. Matter (and this includes physical fields) thus is considered as the outcome of chains or societies of processes in which a definite set of traditions holds. In this picture the notion of matter no longer is a primary feature of the Universe. It is relegated to the second plane, as the outcome of a form of functioning in which conceptual activity plays a primary role.

In Whitehead's picture the Universe is not just matter and motion, but is a complex of processes which unceasingly are evaluating forms of relationship and which express the results of these evaluations in facts and in structures. Tradition evidently is a strong rule in the majority of cases, as we perceive when we think of the enormous amount of nonliving matter in the Universe. Nevertheless, traditions are not absolute. Exceptions to the rigidity of traditions are possible, and new initiatives may spring up, giving room for changes and new traditions. This is where life is supposed to have emerged.

An Imaginative Example

An immediate application of the preceding ideas to real living organisms is still too difficult. The main way of thinking in biological research is directed away from it, although the zoologist W. E. Agar has developed a theory of the living organism based upon Whitehead's philosophy (*6*). Also various scientists have pointed out the insufficiency of a purely physical picture (*7*). But there is as yet no evident point of attachment between the ideas sketched in this article and modern biological research. The presentation of these ideas is therefore meant as an inducement for a fresh look, in the hope that it will open a new vista and lead to some rethinking.

It may be helpful to consider an imaginary example, by means of which some of the ideas can be illustrated. It is generally assumed that organic radicals and molecules formed spontaneously under the action of ultraviolet light or electric discharges in the primitive atmosphere of the Earth. We may suppose that certain of these radicals become attached to the basal plane of crystal flakes of micalike material (*8*). The absorbed material will probably arrange itself in more or less regular patterns, and this arrangement may facilitate reactions between various groups of atoms. Some of the reactions will be near-equilibrium fluctuations in the distribution of energy between the numerous degrees of freedom in the absorbed crystalline matter and its environment. There may also be migrations of electrons or protons. The material, moreover, can receive radiation from the Sun and can repeatedly absorb photons with much higher energy than the amounts involved in the near-equilibrium fluctuations at our present ambient temperature. For all these processes and their inverses physical theory gives probabilities based on a count of configurations to which equal weight is assigned. When the system exhibits only randomly occurring processes, with frequencies corresponding to the predicted probabilities, there is no evidence of life. For instance, if the physical description gives equal probability to electron transfer in any direction within a two-dimensional system, a "random walk" of the electron will appear, in which the mean square of the distance from a starting point increases indefinitely with the square root of the time.

Suppose, however, we find the electron

following a more or less cyclic path, at intervals returning to the neighborhood from which it originated and never moving far away from that neighborhood. If there are no physical forces which destroy the equal probability of all directions and drive the electron in a circle, we may conclude that there is effective an intention not described in physics, an intention to make the path into a cyclic one. This can then be taken as a primitive manifestation of life, a tendency toward order in an ambience of randomness.

The imposed condition of making a more or less closed path is a holistic condition. It refers to the result of a set of steps, seen, or experienced, or conceived as a unit. In order to be effective the intention must be concentrated on the set of steps, and it must be supported by integration of experience concerning past sets of similar steps. As mentioned earlier, the anticipation must involve a memorative faculty, although as yet there is no instrument or structure into which data can be inscribed.

This imaginative example gives us a first glimpse of the form in which life can manifest itself: it emerges as the introduction of a form of order in a field in which the physical relations do not provide a causal basis for that order.

After the establishment of such an ordered set of reactions, the system will still be subjected to many random processes. Among these may be found reactions produced by the incoming radiation and involving larger energy exchanges, leading to atomic arrangements on a more extensive scale. They may interfere with the original equal probability of electron movement in all directions in the plane and promote the chances for cyclic paths without a need for anticipation. In a purely physical field such an arrangement can alternate with arrangements promoting electron transfer in other directions. All such arrangements may have equal weight in the relevant physical description. We now propose that anticipation can widen its field of operation and (perhaps from a certain instant onward) can influence the frequency of physical reactions leading to atomic arrangements favorable for cyclic electron movement. This is again a case where intention interferes with randomness. The result of this can be that in the atomic system something comes forward which we may call a structure, and from now on this structure will ensure (partially or entirely, as the case may be) the cyclic movement of the electron through purely physical effects. Again the essential phenomenon of life must then be seen in the establishment of this structure (and in its maintenance and protection from dispersion). These considerations may throw light on what is called collection of information. Perhaps they may also throw light on the problem of the origin of life (*9*).

Current theory, referring to the fact that spontaneous reactions in certain nonliving physical systems can lead to the synthesis of highly complicated molecules, has suggested that chemistry may find molecules which will be able to duplicate themselves. Such molecules are then presented as a primitive form of life. I shall not deny the possibility of detecting such molecules, although I note that the most we have observed so far is indefinite growth of a structure so long as sufficient material is available, such as occurs in any process of crystallization. No case has been found where the growing mass divides itself into separate entities of a specific constitution, which, once having appeared, can grow again, and again divide in the same way, and so on. It is alleged that something of this nature can occur with template reproduction. Even if this were the case with certain chemical products, there remains the problem that in their description there is no indication of any form of life presenting choices or other aspects of conceptual activity. My conviction is that the customary stress on reproduction as the characteristic feature of life pushes us in a direction which does not give proper insight into the nature of life. To suggest that mentality will spontaneously come forward in a chemical structure from whose description every reference to mental aspects has been eliminated is wishful thinking. Something must be introduced to provide a germ from which anticipation can grow and gain influence, and this must be made explicit. What this may involve has been to some extent explored in the preceding pages. Perhaps other lines of exploration may be possible. The problem of the origin and nature of mentality, as well as that of its mode of operation, remains of fundamental importance. It should not be evaded.

Summary

I have discussed the problem whether an explanation of the phenomena of life can be deduced from an exclusive reliance on causal relationship as in the currently accepted physical description, or whether attention should be given to something more. For this more the concept of anticipation is taken. Starting from what we observe in our own minds various notions involved in the idea of anticipation have been brought forward. The picture is derived from the philosophy of A. N. Whitehead. It is admissible in this philosophy to postulate an influence of anticipation on the statistical weights which play a part in quantum physics. This influence could change the probability distribution of the results of atomic reactions and thus account for living beings having a way of behavior of their own.

I have also tried to show that an inquiry into the possibility that living organisms possess features not covered by present-day physics need not lead to a belief in supernatural phenomena. The idea of purpose should not be condemned. It does not mean being directed toward a definite goal for some billions of years. Although no quantitative relations have come forward the role of anticipation can be discussed on a rational basis and finds support in an important philosophical system. It introduces some attractive features into the definition of life and it can help to probe the depth of problems which the reductionist principle leaves unanswered. It might be considered as a picture complementary to the physical picture.

References and Notes

1. Part of the ideas developed in this article have been presented in earlier publications by the author: *Reflections on the Concept of Life* (No. P-4127, Rand Corporation, Santa Monica, Calif., 1969); "Causality and anticipation and their meaning for biology," *Proc. R. Neth. Acad. Sci. (Amst.) Sect. B Phys. Sci.* **75**, 375 (1972). Some of the ideas have also been touched on in a n ➡ "Curiosity and play: Basic factors in the development of life," *Science* **154**, 1680 (1966).
2. Whitehead's philosophy is presented in *Process and Reality, an Essay in Cosmology* (Cambridge Univ. Press, Cambridge, 1929). A helpful summary of the main ideas is given in part 3 of a later book, *Adventures of Ideas* (Cambridge Univ. Press, Cambridge, 1933). An introductory discussion occurs in *Science and the Modern World* (Macmillan, New York, 1925). See also *Modes of Thought* (Cambridge Univ. Press, Cambridge, 1938) for several important statements.
3. The reader is referred to the discussion of the postulate of equal statistical weights given in R. C. Tolman, *The Principles of Statistical Mechanics* (Oxford Univ. Press, London, 1938), pp. 59–62, as applied in the statistical mechanics of classical systems, and pp. 349–356 for the form in which it is used in quantum statistics.
4. A concise formulation of Whitehead's philosophy with a view to its meaning for physics and for the understanding of life is given in J. M. Burgers, *Experience and Conceptual Activity* (MIT Press, Cambridge, Mass., 1965).
5. The progress of large-scale time in Whitehead's cosmology goes in a definite direction, as the result of the succession of processes arising from experience of past events. Thus there is an essential irreversibility in the arrow of time. Biological time necessarily goes in the same direction. For further details see (*4*, pp. 42–45).
6. W. E. Agar, *A Contribution to the Theory of the Living Organism* (Melbourne Univ. Press, Carlton, Victoria, and Cambridge Univ. Press, Cambridge, ed. 1, 1943, and ed. 2, 1951). There is some difference in exposition between the two editions; in my view the first edition comes closer to what I consider to be Whitehead's ideas.
7. See for insta ➡ E. P. Wigner, "Are we machines?" *Proc. Am. Philos. Soc.* **113**, 95 (1969). Among other authors who have struggled with this problem we mention M. Polanyi, H. H. Pattee, and C. H. Waddington.
8. See the diagram on p. 1081 in C. Reid, "Quantum phenomena in biology," *Science* **131**, 1078 (1960).
9. If life has originated from the induction of periodic returns in a random system, this need not have been a rare event but could have occurred on a multitude of occasions. The assumption that the origin of life is a unique event, which sometimes is made, would then not be necessary. Life could have started in flashes of conceptual activity, appearing discontinuously and only later leading to continuous chains. Concerning the problem of the first appearance of life on Earth, see some observations in (*4*, pp. 144–149).