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Phenomenological Theory of Life

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Summary

A number of characteristics of the life phenomena are analysed on the physical basis so that life may be understood from the principles of physical science. This analysis includes the exponentially multiplying system, the concomitant linearly multiplying system, the self-controlled system, the self-maintained system, the motor system, the sensory system, and the sensory-motor coordination system. Combinations of these characteristics may be used to define a variety of lives. The definition may be generalized to include sub-life, primordial life, exo-life, super-life and pseudo-life which are special cases of the generalized life defined by one or several of the above discussed characteristics. Applications of the principles of pseudo-lives to social (economic system) and humanistic (civilization) studies are indicated.

A general theory of life based on the physical principles is developed in two parts. The first part is a phenomenological study concerning the question what is life. The phenomena of life that are seemingly different from physical systems are analysed in a number of aspects separately; each is studied on the basis of physical laws systematically and exhaustively, so that the various characteristics of life may be understood on the physical basis. The second part is an attempt to deduce biology from physical science by showing that the appearance of the various characteristics of life in the evolutional history follows the dictation of the physical principles. It also tries to establish the general dynamical principles in biology. The ultimate purpose is to learn the origin and evolution of life from the first principles of physics. This paper concerns the first part; the second part will be contained in another paper (1) referred to as Paper II.

The characteristics of life phenomena are listed and analysed below. The definition of life will be discussed afterward.

1. Exponentially multiplying system

One of the characteristics of life is the capability of living systems to multiply themselves identically (or nearly identically) so that the number of individuals increases exponentially (or nearly so) in the course of time in an infinite nutrient medium. This characteristic corresponds to the phenomenon of reproduction on the macroscopic level and to the function of replication of DNA on the molecular level.

In the physical universe such a system may occur under proper conditions. One example in nuclear astrophysics is the synthesis of elements by the rapid neutron absorption process (2) terminated by fission and repeated again and again. An exhaustive study will discover more of such systems. We shall limit ourselves to the field of catalytic synthetic chemical reactions on the molecular level, to which the presently known living systems belong.

Suppose in an infinite nutrient medium there are substrate molecules B_1, B_2,... ready to be synthesized into macromolecules. Suppose there exists a catalytic molecule A_1 which catalyses the synthesis of another molecule A_2 out of the B's. The number of A_1 molecules remains the same, catalyst being used over and over again without change. The number of A_2 molecules will increase linearly in time, but not exponentially. However, an exponentially multiplying system may be constructed if A_2 itself is a catalyst which catalyses the synthesis of another molecule A_3 out of the B's, and A_3 in turn catalyses the synthesis of A_4, and so on, ad infinitum, assuming the reaction rates are the same (or nearly so). The number of A's then increases exponentially. Such a system involving infinitely many catalysts is rare in occurrence, the probability being η^∞, where η is the average probability of one molecule's being a catalyst. On the other hand, if one of the A's, say A_{n+1}, happens to be identical with A_1, then an exponentially multiplying system may be formed with n catalysts, the probability of finding n catalysts being η^n, now much greater than η^∞. The probability is greatest when n=1, corresponding to auto-catalytic reactions. However, there are quantum mechanical reasons to believe that auto-catalytic synthetic reactions are extremely improbable and the most significant exponentially multiplying system is the n=2 system (3). This may be looked upon in a naive way: The catalyst and the product are the same, and one cannot expect the catalytic action to be carried out by the complementary relation of molecular configuration, which seems to be the major mechanism in biochemistry. The n=2 system is called the allowed system;

n=3 system is called the first forbidden system, etc.

Let us consider the allowed system which consists of two components A_1 and A_2. In the multiplying process the first, third, fifth, etc. generations are in the form of A_1, different from the second, fourth, sixth, etc. generations in the form of A_2. The system is thus inhomogeneous. On the other hand, one may easily construct a homogeneous system by a slight variation: Let the first generation be a composite of A_1 and A_2. The second generation is thus a composite of A_2 and A_1 which is identical with the first. We may now recognize that this is just the way DNA operates. The two strands of DNA are the two components A_1 and A_2; in the replication process A_1 catalyses the formation of A_2 and A_2 catalyses the formation of A_1. Each generation is a composite of A_1 and A_2.

It is gratifying to know that DNA belongs to the allowed system. If it were forbidden then there is always the danger that some day an allowed system will emerge and take over the world from the forbidden system.

Let us now consider the first forbidden system which consists of three components A_1, A_2 and A_3. A_1 catalyses the synthesis of A_2 which in turn catalyses the synthesis of A_3 which in turn catalyses the synthesis of A_1, thus forming a cycle. The homogeneous system may take the form of a three-stranded macromolecule with three-way pairing among the side chains of the three strands, analogous to the pairing of DNA. One interesting point on the error rate of replication may be mentioned here with regard to this kind of hypothetical informational molecule. The error rate in single strand recognition is at most 10^{-3} (4). Thus the error rate in replication with a single-stranded nucleic acid as the template is probably in the neighborhood of 10^{-4}. On the other hand, the error rate with a double-stranded DNA as the template is nearly the same as the rate of spontaneous mutation in reproduction which is about 10^{-8}. The large difference may be explained by the theory of replication previously developed by the author (5). The error rate of double-stranded DNA replication, because of the double check of the hydrogen-bonded-base-pairs, is the square of that of single-stranded DNA $(10^{-4})^2$, agreeing with the observed value of 10^{-8}. The three-stranded molecule, because of the three-way check, will have the replication error reduced further to 10^{-12}. The low error rate of double-stranded DNA over single-stranded nucleic acids probably is responsible to the fact that organisms based on double-stranded DNA is capable of developing into very complex forms while those based on single-stranded nucleic acids do not develop beyond the stage of virus. The degree of complexity from virus to man is increased by a factor of 10^4, judged by the increase of the length of DNA. One may surmise that the changing of the information molecule from double-stranded to triple-stranded would also increase the limit of complexity by another factor of 10^4 because of the even lower rate of replication error. If the somatic mutation theory of aging (6) is right, the lower rate of error in replication and in other form of mutation of the triple-stranded molecule will enable the organism to live a much longer life. Thus the hypothetical triple-stranded information molecule would give rise to the possibility of an organism much more long-living and much more complex and thus presumably much more intelligent than us (superman!). It is true that the lower rate of mutation leads to lower rate of evolution and the question may be raised whether the age of the physical universe is long enough for the superman to evolve. In this respect it may be mentioned that mutation in replication is not the major mechanism of evolution (see Paper II) and the other mechanisms of evolution will operate without hindrance. Though the first forbidden system has a lower rate of occurrence than the allowed system, the number of planetary systems in the stellar universe is sufficiently large to make the occurrence of the first forbidden system not impossible.

2. Concomitant linearly-multiplying system

In addition to being an exponentially multiplying system, known living systems are at the same time a linearly multiplying system corresponding to the growth of the individual on the macroscopic level. On the molecular level this corresponds to the function of transcription of DNA. The significant point here is that both systems are served by one and the same entity--the DNA molecule.

In the physical world it is easy to understand and construct linearly multiplying systems. Any one-stage or multi-state (not cyclic) catalytic reaction is a linearly multiplying system. But one entity serving two functions is unusual and has far reaching consequences in biology.

The significance of the double function is that it reduces the burden of reproducing the individual organism. Without such a system the replication process will have to reproduce the whole individual which involves a large number of molecules and a complex structure. With such a system it is only necessary to reproduce the genetic molecule; the development of the individual from the genetic molecule is left to the linearly multiplying system (principle of two-stage rocket). The task of replication is greatly simplified and this is made possible only when the two functions are carried out by the same molecule. The simplification of the machinery of life makes the development of complex forms of life possible.

Is it possible in the physical world to construct one entity which serves a double function? In engineering we can always design a machine to serve a specific function. One-purpose machines can always be expected. On the other hand, in special circumstances and by good luck, it is possible to design a machine to serve two independent functions. For example, the wheels of a bicycle serve two independent functions: one is that of a wheel, the other is that of a gyroscope. It is the special circumstances involved (both involve rotation) and the ingenuity of the inventor that make the combination possible; this simplifies the machinery of a bicycle as a vehicle to a great extent. Machines that serve two independent functions concomitantly are defined as supermachines of the first order; those that serve three independent functions are defined as supermachines of the second order, etc. Supermachines cannot be expected. On the other hand, by probability, out of a large number of machines there is always a small fraction for which the special circumstances may make them possible to become supermachines. A supermachine involves ingenuity but is by no means mysterious and can be understood in terms of physical and statistical considerations. On the other hand, it does involve an element of chance; and an element of chance here enters biology. From the study of replication of DNA (5), one gains the impression that DNA is a high-order supermachine (perhaps of the fourth or fifth order), and the development of life to the present state is very much dependent on the special circumstances that make the DNA possible to serve a number of independent functions.

The recent works by Wigner (7) and Landsberg (8), which seem to imply that quantum mechanics exclude life, bring out sharply the difficulty of duplicating an individual organism, a complex molecular system no matter how small, from physical point of view. The difficulty is partly solved by developing the concomitant linearly-multiplying system by which the molecular system that has to be duplicated is reduced to a much simpler one (the genetic molecule) and the phase space requirement is reduced substantially. The remaining difficulty of duplicating the genetic molecule is solved by substituting the homogeneous, n=2 exponentially multiplying system for the n=1 system (3). Thus the quantum mechanical difficulty is avoided by two acts of ingenious strategy, which, of course, are the results of evolution.

Another point is in order here concerning the self-reproducing automata of von Neumann (9). He proved that a self-reproducing machine is possible from computer engineering point of view, though he did not consider quantum mechanics and thermodynamics. His automata may be classified as the n=1 exponentially multiplying system; there is no separation of reproduction and growth and the automata are machines, not supermachines. The genetic material is totally conservative. The progeny is fully mature at birth (instant man) like automobiles coming off assembly line ready to perform in full capacity. While such a system may be considered as a form of generalized life (see later discussion), its bearing on the understanding of the presently known life is rather remote. His theroem does not tell us how and why the presently known life, which is a n=2 system, a supermachine, semi-conservative, and non-instant, arises and operates. Furthermore, if he considered quantum mechanics when constructing a molecular system, he would encounter the difficulty raised by Wigner and Landsberg for being a n=1 system. If he considered thermodynamics he would have the difficulty of eliminating all irreversible processes that tend to decrease the amount of information. From the evolutional point of view, this kind of life is so much less efficient than the presently known life that its spontaneous generation is highly improbable.

The question how the DNA dual-function supermachine comes into being has been discussed in another paper (10) in connection with the mechanism of transcription. It is proposed that the transcription process is closely analagous to replication, so much so that it may be regarded as a "mutant" of replication. The biological evolution is assumed to start with the appearance of nonsense self-replication molecules. "Mutation" of the replication process produces irrelevant product (trash) instead of replica progeny. Among the many trash products some, by probability, may happen to be useful when associated with the precursor. The combination thus survives better than others and becomes the dominant species. This is the beginning of the individual organism which is already endowed with a dual-function genetic molecule. This is also the beginning of sense, and the end of nonsense of the genetic molecule. The special circumstances that make the dual-function possible lie in the fact that both replication and transcription involve the synthesis of a new nucleotide chain with an old chain as template. The actual appearance of the dual-function system is the result of population statistics in evolution. Thus the emergence of the supermachine is understandable in terms of dynamic and statistical analysis.

3. Self-controlled system

Another characteristic of life is the control mechanisms that put the chemical reactions and physical processes in order in the development of the individual, in the carrying out of the functions, in the adaptation of the individual to the environment, and in reproduction---in other words, the mechanisms that organize the physical and chemical processes into linearly and exponentially multiplying systems according to a specific schedule. These characteristic vital activities have been analysed and can be understood in terms of physics and chemistry. In genetics the operon theory (11) contributed to the understanding of the control mechanism. In other areas the feedback control mechanism (12) and allosteric control mechanism (13) have been developed. Other mechanisms may be developed later. Much work has been and is being done which greatly clarifies the mechanism of self-control which used to be considered a vital characteristic not subject to physical analysis.

It seems that the above three aspects are sufficient to cover the behavior of virus (the host cell is considered as the nutrient medium) and some bacteria. With these three characteristics understood in terms of physics and chemistry the behavior of these lower organisms may be understood from the physical point of view. It may be noted that the three aspects involve only properties of molecules and thermodynamic systems in proper combination and proper sequence. Besides the combination and sequence the basic processes are not different from inanimate material systems in physics and chemistry and therefore it is not surprising that these life forms sometimes behave like the inanimate material system--i.e., viruses may exist in crystal form and bacteria may exist in the dehydrated form for a long time without change and without activity. To put it symbolically, the transformation between life and "death" (14) is reversible. In higher organisms this characteristic disappears with the emergence of another characteristic discussed below.

4. Self-maintained system

This is the characteristic responsible for the fact that life in the higher forms is constantly active (cannot take a break) and the transformation from life to death is irreversible. It manifests itself in biology in the appearance of processes, one leading into another in succession and the last one leading into the first, thus operating in a cycle. The cycle, taken as a whole, is not a thermodynamic system nor, of course, a mere molecule, and therefore is not a familiar object but a new entity in physics. Though the cycle may eventually be analysed in terms of elementary physical and chemical processes, the whole exhibits characteristics quite different from and even contradictory to those of thermodynamic systems and molecules. This is the origin of many vital characteristics that seem to be different from or contradictory to the behavior of physical and chemical systems (usually either thermodynamic systems or molecular systems). To introduce the concept of self-maintained system, we consider an example in physics: the discharge tube from which the term "self-maintained" originates.

The gas in a discharge tube before discharge is a thermodynamic system; its properties are completely specified by a few parameters and are independent of the past history. One may study a number of cause-effect relations--e.g., to determine its conductivity under the action of a field, which is very low. The discharge phenomenon begins with the Townsend discharge which is not self-maintained. Though the gas in the tube increases the current by multiple ionization, the maintenance of the current depends on the supply of initial ions from external sources (cosmic rays, etc.). If the external source of ions is completely eliminated the current stops. As the voltage supply increases the discharge passes through a stage called breakdown, after which the discharge is called glow discharge which is self-maintained. In this stage, even if the external source of ions is completely eliminated the current will not stop. The tube now has its own supply of electrons and thus the current is self-maintained. What happens is that the accumulation of positive ions at the cathode produces electrons by secondary emission, upon bombardment tion. The superior efficiency of the self-maintained system is demonstrated by the simple example in daily life that it is easier to keep the motor running idle than to stop and start it again, and also by the example that it is easier to maintain a fire at all times than to make a new fire every time it is needed. In fact, the keeping of the self-maintained fire is one of the indispensable operations of a primitive civilization (a form of generalized life--see later discussion). The superior efficiency makes the evolutional process converge in this direction and is the reason for the appearance of the self-maintained system in higher organisms and for the important role it plays in them.

e. Higher stability. Self-maintained systems are stable in two respects: in operation and in evolution. One of the necessary conditions for constructing a self-maintained system is the built-in stabilizing mechanism that enables the cycle to be operated in steady state (not diverging or converging). This is exemplified by the glow discharge tube which exhibits remarkably stable terminal voltage, so much so that it may be used a voltage regulator. The operational stability is a desirable feature in biological systems; the evolution into higher organisms is marked by the development of systems of higher stability (constant body temperature, for example) and thus by the appearance of self-maintained systems. From evolutional point of view, the operation of the cycle depends on the exact coordination of the elementary processes the cycle is made of, and any mutation changing one elementary process may disrupt the operation of the whole cycle and may become lethal. Thus, once a cycle is established, it tends to prevent evolutional processes to change the operations away from the cycle. The evolutional process before the establishment of the self-maintained system is random; afterwards it becomes stabilized and no longer changes at random. This is a fact that has both advantages and disadvantages. For example, once the DNA-RNA-protein cycle is established, it is impossible for the system to evolve by infinitesimal changes from the n=2 system to the n=3 system, which is superior in a certain sense. Also the linear information storage system of DNA is a rather poor system for information retrieval and this shortcoming can never be improved by infinitesimal changes in evolution; the significance of this point in developmental biology will be discussed in Paper II. Once the evolutional process is no longer random, the concept that evolution develops the system of maximum efficiency should be modified. Evolution by infinitesimal changes seeks not the absolute maximum but the local maximum subject to the constraints developed by evolution itself (it is near-sighted and biased). The advantages of the self-maintained systems make the evolutional process proceed towards them; the stability of the systems prevents the process to develop away from them. The result is a large accumulation of self-maintained systems, and this is why higher organisms are characterized by them.

The glow discharge tube operates in a wide range of voltage of the power supply and remains stable. On the other hand, under higher supply voltage it may pass into another self-maintained discharge, namely, the arc discharge with the emergence of a new mechanism of electron supply, namely, the high field emission. Thus change of self-maintained system is not impossible but is a discontinuous, catastrophic affair, not the result of continuous evolution.

f. Dynamic characteristics. In glow discharge the gas changes from a good insulator to a good conductor. In passing from glow discharge to arc discharge the tube may even exhibit negative resistance which is against the laws of nature of ordinary substances (thermodynamic systems). Thus the self-maintained system, compared with ordinary substance, exhibits a number of unusual properties, yet they are not mysterious and can be understood in terms of physical principles by analysing the operation of the cycle. Many of the unusual and even mysterious properties of life may be understood in terms of self-maintained operations.

The crux of the matter is that self-maintained systems (such as a discharge tube) have input-output relations just as thermodynamics systems (such as a resistor) have and thus may be used to perform the same functions of thermodynamics systems but are not thermodynamics systems themselves and have characteristic quite different from the latter. In physics and engineering design one usually deals with molecules (microscopic) or thermodynamics systems (macroscopic). A thermodynamics system is completely specified by a few parameters (thermodynamical variable); the past history of the system is completely forgotten and irrelevant. The input-output relations are uniquely determined by the equation of state. The behavior of the system is completely determined by the external factors (intensive properties of the system in equilibrium with the environment determines the extensive properties through the equation of state). These are characteristics of "mechanical" systems in the usual sense. Because most systems discussed in physics and engineering design are of this kind, one tends to regard the whole physical universe to be operated on this basis and life phenomena become difficult to understand. The self-maintained system is history dependent. The behavior of the system is determined not only by the external factors but also by the characteristics of the elementary processes of the cycle, which we may define on a phenomenological basis as the "self", in the sense that they are not specified in the external. Whereas the self may be analysed in terms of the mechanical behavior of the elementary processes, the emergence of the self as a determining factor of the output is a new manifestation. While we are still far from an understanding of the mental processes in terms of physics and chemistry, we do find room in the self-maintained system to explain phenomena that cannot be explained by thermodynamics systems, without introducing anything beyond the principles of physical science. (Even the concepts of the individual and the will may be susceptible to physical analysis and the age-old philosophical problem of the matter and the mind may eventually be settled on scientific basis.) This point is not self-evident even from the standpoint of physics, as exemplified by Wigner's recent view that quantum mechanics is not suitable for a complete description of all natural phenomena including life and at least should be modified to include new concepts, such as consciousness, which are not necessary in physics (7). That this is not necessarily so has been discussed in another paper (3).

The emergence of self-maintained systems in the course of evolution is determined by their efficiency and stability. The emergence of the self is thus an incidental affair in the course of evolution as a manifestation happened to be associated with a particular system favored by population statistics. We may thus surmise that mind is not absolute; there are various kinds of mind associated with various kinds of life (and generalized life). The present kind of mind happens to be the one associated with the present kind of life.

A discussion concerning the second law of thermodynamics is in order here. According to this law a closed system tends to reach thermal equilibirum, a state which will not change any further. From the statistical point of view this tendency corresponds to a change from the ordered state to the random state. If the whole universe is taken as a closed system, we would expect this tendency to take place and the universe is heading to the state of heat-death (the whole universe is in thermal equilibrium). On the other hand, life is constantly active and the evolution of life proceeds in the direction of from the simple to the complex. The contrast leaves the frequently expressed opinion that the phenomena of life are not compatible with the second law of thermodynamics. This difference will now be analysed. First of all, if life were a closed system there would be real contradiction. But life is not a closed system; it exchanges matter and energy with the outside world. Second, the whole universe is not yet in thermal equilibrium. The part of the universe where life thrives (biosphere of the earth) is actually in a steady state rather than an equilibrium state--i.e., energy flows into it from a high temperature source (the sun) and out of it into a low temperature sink (the outer space). The second law does not apply to steady state and thus no contradiction. Before heat-death occurs many things such as life may still happen.

A related problem occurs here. Most physical systems, such as gases, liquids and solids, are thermodynamic systems which are not isolated but are in equilibrium with the surroundings. The thermodynamic systems, being in the equilibrium state, do not change unless the external conditions are changed. Life, being a sequence of ceaseless changes, cannot be understood on the basis of thermodynamic systems which would require a sequence of ceaseless changes of the external conditions to give rise to the activities of the system. Even if the activities of life form a sequence (not cyclic), thus one initiates another, the whole sequence will eventually come to thermodynamic equilibrium according to the second law and everything will stop. If life were a thermodynamic system, its activities must be the results of acts of some external agents that manipulate the thermodynamic system. The question of life thus is shifted to the nature and behavior of the agents. The agents cannot be thermodynamic systems themselves because the behavior of the agents cannot be explained if they were thermodynamic systems, unless they were manipulated by other agents, and so on, ad infinitum. The ultimate agent, therefore, would have to be supernatural. If we want to consider life that is constantly active as a natural phenomenon, it cannot be a thermodynamic system. What else are there in physics that are not thermodynamic systems? There are non-equilibrium systems, which always eventually reach equilibrium according to the second law, and combinations of non-equilibrium systems, which in the long last generally reach equilibrium. The deadlock is broken in one exceptional case when a sequence of non-equilibrium processes form a closed cycle; under proper conditions the cycle may maintain itself without coming to thermodynamic equilibrium, and the sequence of activities, once started, will keep on repeating itself without coming to a stop with no external manipulation. This is the establishment of a self-maintained system. When this happens we call it life (or life-like system). The requirement of an external agent to pull the wire to give rise to life is thus eliminated; the wires are pulled by the components of the cycle, each one acting on the next and eventually returning to the first, forming a closed cycle. The proper condition that makes self-maintained system possible, in the case of the discharge tube, is just the steady state voltage input and output across the tube. All living systems are more or less in a steady state with regard to the exchange of matter and energy with the surroundings. In fact, under steady state condition, whatever changes take place must be cyclic. Moreover, the external world does not manipulate through the input and output; it merely provides a steady state condition. Manipulation involves a sequence of changes (instructions) but the steady state does not change in time. It may also be concluded that life is a manifestation of the steady state and therefore there will be no life in the heat-death state.

It may now be said that the idea of the cycle is the one only important "philosophical" idea necessary for the understanding of life (15). It is the cycle that makes the exponentially multiplying system possible so that life may perpetuate; it is the cycle that makes the self-maintained system possible so that life may be constantly active. It is also the cycling of material between life and physical world in life-death cycles that makes evolution possible so that more complicated, more ingenious forms may develop. If some species would not die, thus breaking the cycle of circulation and therefore "hoarding" the building material, evolution will stop and nothing more advanced will appear (16).

The four characteristics discussed so far probably are enough for an understanding of the basic behavior of life up to the plant kingdom. They cover a few aspects of life that are seemingly different from ordinary physical systems and they are analysed and understood in terms of physical principles. The emergence of the animal kingdom, which is actually a parasite to the plant kingdom, involves the appearance of several additional characteristics of life which are discussed below. These characteristics are also present in rudimentary form in the plant kingdom, and they cannot be taken as the basis to draw a sharp line to demarcate the animal kingdom.

5. Motor system

Most animals are characterized by the ability of exerting mechanical energy, most obviously in locomotion. That a physical system, given energy supply, will exert mechanical energy and execute locomotion is no surprise (all engines (17) and vehicles are of this kind); thus the motor system per se is within the realm of physical science. The problem is how such a system appears as the product of a linearly multiplying system concomitant with an exponentially multiplying system. The mechanism of muscle action is a major topic in biophysics and biochemistry and the generation of mechanical energy has been analysed on the physical basis.

6. Sensory system

Most animals are also characterized by the capacity to respond to external physical stimuli such as electromagnetic waves, static mechanical pressure, mechanical vibrations, chemicals in solution and chemicals in air; thus arise the senses of vision, touch, hearing, taste and smell. Like in the motor system, it is no surprise to find a physical system capable of responding to one of the stimuli (all measuring instruments are of this kind), and the problem again is to see how such a system built into the living system. Sensory perception is another major topic in biophysics and the process may be analysed into elementary phsyical processes.

7. Sensory-motor coordination system (Brain system)

The advantages of the motor system that are responsible for the appearance of the system in the course of evolution are obviously the greater accessibility to necessities and greater safety in avoiding danger. Without a sensory system these functions will have to be carried out by trial and error, which is rather inefficient. The advantage of the sensory system is to enable the organism to recognize necessities and danger. But the sensory systems will not be useful unless the information received is used to direct the action of the motor system. Thus a sensory-motor coordination system is called for and is favored to develop in the evolutional process. The brain of higher animals, particularly of man, which is so highly developed and so highly distinguishes man from all others, is basically a sensory-motor coordination system. In fact, the various parts of the brain develop concomitantly with the various sense perceptions for their coordination, though not necessarily limited to it later; thus tectum develops with vision, thalamus develops with touch and hearing, and cortex develops with smell (the recognition of complex molecules is more difficult than other physical stimuli). Many of the mental activites, no matter how complicated they may appear, can eventually be analysed as sensory-motor coordination action, even though the sensing may take place a long time ago, in different locality, even by other individuals, and the motor action may be programmed for many years hence, in different locality by different individuals (such as the writing of a will).

Sensory-motor coordination action in physical world is also no surprise to find, such as a door controlled by an electric eye. Simple sensory-motor coordination actions in animals may not be difficult to analyse in terms of elementary physical processes. The more complicated ones involving memory, learning, reasoning and calculation, are of course more difficult. The work in this field is just beginning, but there is no reason why these cannot be analysed. After all, computers that possess these properties have been constructed.

The above discussed characteristics cover aspects of the life phenomena that are apparently different from the usual physical systems. The foregoing discussion intends to show that they can eventually be analysed on the physical basis. Thus life phenomena are not intrinsically different from physical phenomena (18). The only difference is that they are rare and are special cases that occur only in rather special circumstances. The interplay of the special circumstances and the development of life is what we call the evolutional history. The understanding of life phenomena is thus closely tied to the problem of evolution. This dynamical aspect of the problem of life is left to Paper II. In the present phenomenological study, general principles (static) of the various characteristics are developed; in Paper II general dynamical principles will be developed, the two together being the general principles of biology.

Definition of life

We may now consider the problem of the definition of life. Since life phenomena are not intrinsically different from physical phenomena, there is no compelling need nor is it possible to make an exact definition to demarcate life from non-life. Thus any definition of life may be made only for the sake of convenience. Actually, different forms of life have different characteristics and no single definition is equally appropriate for all. Therefore it is convenient to define a variety of life forms by a variety of combinations of the characteristics discussed above. Thus virus may be defined by the first three characteristics. Plants may be defined by the first four characteristics. Animals may be defined by all seven characteristics.

With this flexibility of definition we are able to define other forms of life not presently existing on earth by other combinations of the characteristics or other variations of the characteristics. After all, these characteristics strike us as life-like and any system possessing these may be considered as a sort of life-like object. This attitude is useful and convenient because each characteristic has its general principles and, once understood, may be usefully applied to other systems having the same characteristic. Thus we may define primordial life (now extinct) and sub-life (may still exist) by requiring merely the first characteristic of exponential multiplication. We may define exo-life that have the same characteristics as ours (thus life-like) but carry them out by different schemes (such as the n=3 exponentially multiplying system). When we look for life in outer space we certainly should not limit ourselves to life forms exactly the same as ours (say, those using DNA or RNA as genetic material). The other forms are, in fact, much more interesting. We may define super-life by requiring additional characteristics currently not in existence but theoretically possible. No one has seriously considered what are the other characteristics possible.

With the same spirit we may generalize further in defining a variety of pseudo-lives by requiring any one of the characteristics from 2 to 7. Thus a servo-mechanism may be considered as a pseudo-life defined by being a self-controlled system; a computer may be considered as a pseudo-life defined by being a sensory-motor coordination system. These objects are obviously not life from usual standards but they are life-like to a certain extent, and it is not unjustified to consider them pseudo-lives. However, such definitions would be merely a game of words unless they serve a useful purpose. And we do find them useful in that the basic principles of each characteristic are equally applicable to these inanimate material systems as to life systems. The study of one helps the understanding of the other. The life and life-like systems defined above may be considered as special cases of a more general class called generalized life defined by any one or several characteristics discussed previously.

Civilization as generalized life

As a matter of fact, the present world minus the physical world is nearly all life or life-like. The life-like part comes into being by the same evolutional principles that bring life into being. The subject matter of economics, politics, sociology and history, the arts, the cultures, and the civilization are not physical nor biological, but they are life-like to a certain extent and may be considered as pseudo-lives and may be investigated by the general principles of the characteristics of life. Of course, they are not limited to the characteristics of the present form of life, but the new characteristics may also be analysed by the same methodology employed in the analysis of life. This opens up a whole new area of investigation and this approach may eventually make the humanities and the social studies into sciences.

For example, the modern economical system is a self-maintained system as defined above. To illustrate in a rather naive way, we notice that steel mill is needed to produce steel, but steel itself is needed in building the steel mill, thus forming a cycle. The cycle comes into being by a long evolutional process in which primitive smeltering processes were first developed to make steel without ferrous metal. In other parts of the world the cycle may be established by a catastrophic act of importing steel and technology from outside. If all steel processing facilities of the world are destroyed at once, the cycle is broken and cannot be reestablished except by the primitive smeltering method, which may no longer be available in the future. Actually the economic system as a whole is a self-maintained system; the various industries and segments form a complicated network supporting one another on a cyclic basis. The problem the underdeveloped countries face is not just building one industry or another (establishing linearly multiplying systems) but is building a viable economy (to break into a self-maintained system). The difficulty is comparable to that of the breakdown of a discharge tube. The economic aid to Europe after the Second World War served as a catastrophic act to reestablish the broken self-maintained system; Europe is now on its own. The economic aid to many other parts of the world still has not succeeded in establishing self-maintained systems, where there were none before. Moreover, the history of economic development is characterized by the transition of industrial products from the status of luxury item to that of necessity (starting from the savage's apron to the medieval watch to the modern television). The luxury item is the trash we discussed in the linearly multiplying system. Once the trash is built into a self-maintained system it becomes a necessity. The development of the economical system thus follows closely the general principles of the linearly multiplying system and the self-maintained system.

The same kind of reasoning shows that the civilization as a whole is a self-maintained system; the various segments of it help support one another in complicated cyclic networks. The economic system is just one segment of it and operates within an even larger network. Many of the characteristics we discussed of economic systems apply equally well to the civilization as a whole. Thus once a civilization breaks down it is either dead or difficult to revive. The Western civilization, after the fall of Rome, took a thousand

years to
/revive (is it still Rome?). The concepts of injury, revival and death can be applied to economic systems and civilization as a whole, not because these systems are mysteriously anthromorphic, but because they are self-maintained systems and follow the same general principles of the system which also govern life systems.

The idea of introducing biological concepts (organismic, anthromorphic) in humanistic studies is not new; Spengler and Toynbee are among the authors engaged in this endeavor. While some of their conclusions seem valid, they are not universally accepted because their works are intuitive and mostly analogy. As such it is hard to establish the limit within which analogy may apply. Indiscriminate application of analogy is certain to lead to ridiculous conclusions. We have shown that certain aspects of human activities follow the general principles in common with some of the biological systems, and biological analogy is valid in these aspects. The discussion also points the way how to apply the analogy discriminately. In fact, within the limits, the general principles may be applied thoroughly to their logical conclusion; beyond the limits, new principles may be developed by the same methodology. This is the way an art becomes a science. This article is not the place to discuss humanistic studies in detail. On the other hand, human beings are a part of the biological world, and therefore human activities cannot be isolated from the principles of the biological world. In fact, biological studies cannot avoid human activities and will not be complete without them.

References and Notes

1. Peter Fong, Thermodynamic and Statistical Theory of Life, to be published.
2. See, for example, Peter Fong, Phys. Rev. 120, 1388 (1960).
3. Peter Fong, Does Quantum Mechanics Exclude Life, to be published. The quantum mechanical argument was originated by Wigner and developed later by Landsberg for a different purpose; see references 7 and 8.
4. J. D. Watson, Molecular Biology of the Gene (W. A. Benjamin, Inc., New York, 1965), p. 317.
5. Peter Fong, Proc. Nat. Acad. Sci. 52, 641 (1964).
6. H. J. Curtis, Science, 141, 686 (1963).
7. E. P. Wigner, The Logic of Personal Knowledge, Essays Presented to Michael Polanyi (Routledge and Kegan Paul, London, 1961).
8. P. T. Landsberg, Nature, 203, 928 (1964).
9. John von Neumann, The General and Logical Theory of Automata, in Cerebral Mechanism in Behavior, The Hixon Symposium, edited by L. A. Jeffress (Wiley, New York, 1951).
10. Peter Fong, The Transcription of the DNA Molecule, to be published.
11. F. Jacob and J. Monod, J. Mol. Biol. 3, 318 (1961).
12. See, for example, Norbert Wiener, Cybernetics, 2nd Edition (The M.I.T. Press, Cambridge, Mass., 1961).
13. J. Monod, J. Wyman and J. P. Changeux, J. Mol. Biol. 12, 88 (1965).
14. A piece of crystal in a bottle on a shelf is considered "dead". In this sense the virus crystal in a bottle on a shelf is considered "dead". Higher animals in sleep still carry on physiological activities. Plant seeds still breathe air. Higher organisms cannot be "dead" for awhile and come back alive again.

15. While the Greeks may claim originality on all scientific ideas in the Western civilization, the idea of the cycle is conspicuously absent in Helenic thought. This may be the reason why the understanding of life is so far behind that of the physical world. While the idea of the cycle is present in the Sinic thought as embodied in the Five Rank theory, the most elaborate development of the idea is to be found in the Indic thought as manifested in Buddhism.

16. Interestingly, stellar evolution is one of this kind; thus helium is the hoarder of stellar material in hydrogen-burning stars, etc. The "evolution" is actually the successive appearance of stages, each characterized by a more effective hoarder than the previous one. Thus the process is leading to a dead end (probably the neutron star). The absence of the cycle is responsible to the absence of nuclear life--a form of life based on nuclear reactions instead of chemical reactions.

17. The idea of the cycle enters here again; all heat engines work on a cyclic basis, thus making continuous conversion of heat to work possible. The idea of cycle may be extended from temporal to spatial; thus the large scale, precisely regular structure of crystal is possible from infinitesimal molecules because of the exact spatial cyclic repeat. The crystal form (such as that of DNA) is responsible for important biological functions.

18. This does not mean to degrade life to the level of inanimate material system, which is the fear of many who object to a physical analysis of life. The very purpose of this paper is to delineate the properties of life that are not possessed by simple mechanical systems. Life grows out of the parentage of the physical world but has established a new world

in its own right. In fact, only in these characteristics the meaning and value of life may be found. The nobility of an individual is never eclipsed by his humble parentage. It is more gratifying to be certain of one's parentage, no matter how humble, than to inherit a glamorous title trainted with the doubt of illegitimacy.

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