▽ The information contained in a single human sperm cell is equivalent to that of 133 volumes, each of the size and fineness of print of *Webster's Unabridged Dictionary*. Yet we now can understand how this information could have come into being through natural selection. We understand how natural selection can extract order from chaos, if there are self-replicating and mutating systems in a non-static environment. But we are again faced with the question of the origin of the first such system.

▽ The origin of life on Earth seems intimately tied to the prebiological origin of proteins and nucleic acids. We do not know that proteins and nucleic acids must be intimately involved in living systems on other planets, although some evidence supporting this view will be presented in Chapter 18. But if we are to design for the detection of extraterrestrial life equipment which is not hopelessly parochial in outlook, we must have some general approach to living systems. △ We may well encounter phenomena on other planets which, while possessing all the essential attributes of life on Earth—perhaps even intelligence—exist in different forms, and function according to different principles. It would be useful to have a purely operational definition of life which is not confined to familiar terrestrial chemistry. ▽ We conclude the chapter by returning to this question. △

Some interesting preliminary ideas on the subject have been formulated, in terms of cybernetics, by the Soviet mathematician A. A. Liapunov. Cybernetics, ▽ a term coined by the American mathematician Norbert Weiner, △ is concerned with the study of control processes and the construction of control systems. ▽ Cybernetics developed at the same time that the first large electronic computing machines were constructed. △ Liapunov believes that control, in its broadest sense, is the most universal property of life, independent of form.

▽ Because of the necessity for evolution by natural selection in order to develop living systems of any complexity, one possibly useful definition of life is this: a living system is any self-reproducing and mutating system which reproduces its mutations, and which exercises some degree of environmental control. This definition is much narrower than that of Liapunov. △

Another definition of life, supported by the Soviet biochemist A. I. Oparin of the A. N. Bach Institute, is expressed in terms of complexity and a highly regulated metabolic system for material exchange with the environment. Metabolism, of course, is an essential attribute of life. But in the context of origins, does life lead to metabolism, or does metabolism lead to life? No entirely satisfactory answer has been found to date. It should be noted that simple forms of material interchange (which are not highly regulated, and thus not metabolic processes) can be observed in non-living systems—for example, in liquid solutions.

In Liapunov's view, living systems have the following special characteristic: through definitely prescribed channels, the transmission of small quantities of energy or material containing a large volume of information is responsible for the subsequent control of vast amounts of energy and materials. (An obvious example is the control by the genetic material in man of the form, development, and chemical processes of the much larger individual.) Liapunov points out that heredity, irritability, and so forth can be described in cybernetic terms as information storage, feedback, communication channeling, etc.

All biological materials are dependent upon their mass, chemical composition, energy state, electric and magnetic properties, and so forth. Generally speaking, these properties will change over a period of time. But a small fraction of the materials will remain relatively stable. These substances maintain their stability despite changes which occur in the external environment. Liapunov calls such reactions, in which the substance survives changes in the external environment, *maintaining reactions*. Maintaining reactions underlie all biological processes. Indeed, life is characterized by its adaptation to the external environment.

In the language of cybernetics, maintaining reactions can be outlined as follows: the sensing material receives information about the external environment in the form of coded signals. This information is reprocessed and sent in the form of new signals through defined channels, or networks. This new information brings about an internal reorganization of the system which contributes to the preservation of its integrity. The mechanism which reprocesses the information is called the control system. It consists of a vast number of input and output elements, connected by channels through which the signals are transmitted. The information can be stored in a recall or memory system, which may consist of separate elements, each of which can be in one of several stable states. The particular state of the element varies, under the influence of the input signals. When a number of such elements are in certain specified states, information is, in effect, recorded in the form of a text of finite length, using an alphabet with a finite number of characters. ▽ These processes underlie contemporary electronic computing machines and are, in a number of respects, strongly analogous to biological memory systems. △

The control system directs the maintaining reactions of the organism or computing machine and their response to the external environment. The response occurs by collecting information about the external stimuli, analyzing it into its component parts, and comparing it with information which is already recorded in the memory. The greater the amount of information previously stored, the more adaptable the control system. An important property of the maintaining reaction is its speed of response. If the reactions are slow, the survival of the system is jeopardized. Thus, a large information storage capacity is required for the memory bank, and the information must be stored in an exact and stable manner.

Liapunov suggests that individual molecules, consisting of sufficiently large numbers of atoms, can conceivably act as stable physical information carriers. Such molecules are quantum systems. In order to reach another information state, they must be raised to another energy level, sufficiently distant from the original state that few transitions will occur due to random thermal motion.

The energy supply for the maintaining reactions must not run down. Nevertheless, such systems will constantly lose heat and energy because of their activity. According to the laws of thermodynamics, the energy levels in a closed system—one completely isolated from its environment—must eventually reach equilibrium. If a living system were closed, any loss of energy would endanger its stability. Thus, a stable state will not be maintained unless energy is obtained from the external environment, and the living system becomes an open system.

An important thermodynamic characteristic of any such system is its entropy. Entropy may be defined as a measure of the unavailability of energy in a thermodynamic system; ▽ or, alternatively, as a measure of the disorder of a system. In any closed system, no process can occur in which the entropy decreases; that is, the disorder of any closed system will increase as time goes on. In an infinite amount of time, disorder should be complete, and the atoms randomly distributed, in the absence of other influences. If a living system is represented as a closed system, its entropy would continuously increase. The burgeoning disorder would, in time, bring all biological processes to a halt. Consequently, a living organism must systematically lose entropy, to maintain internal order. This is possible only at the expense of the external environment. The organism must extract energy from, and increase the entropy of, the external environment, so that its own entropy may be continuously decreased, and its structural and functional integrity maintained. As we pointed out earlier, this is one reason why cells metabolize. △

Older definitions of life, which identified life with metabolism, were inadequate. Such definitions, in our opinion, are entirely worthless. Liapunov characterizes life as a highly stable material system which uses information coded by molecular states for the production of maintaining reactions.

The actual organization of living systems into subcellular organelles, cells, organs, organisms, populations, species, and so forth is analogous to a hierarchy of control systems. Each structural unit is controlled by its own semiautonomous control system, which acts upon all those units subordinate to it, and in turn is acted upon by those control systems which are above it in the hierarchy.

There is a distinction between the control systems within an individual organism and those acting upon an ensemble of organisms (for example, populations, species, and so forth). In the former case, the control system consists of units acting directly down through the hierarchy. Liapunov calls this the structural method of control. In the latter case, we have a large number of more or less independent statistically equal systems which interact by chance meetings. Liapunov calls this the statistical method of control. Those systems of higher rank order—for example, the species—are significantly more stable than any given individual constituent (here, an individual organism). But this greater stability of the higher system is possible only if the constituent parts are replaceable; that is, if reproduction occurs.

For the newly synthesized constituent part to partake of its measure of stability, it must contain a pre-formed supply of information, stored in its memory bank, which guarantees its maintaining reactions. It is quite inconceivable that this information supply could arise spontaneously within the constituent itself. Thus, a new constituent must obtain this store of information necessary for its functions from other constituents—most reasonably from other similar constituents which we may refer to as the previous generation. Thus, reproduction is seen to be in large measure information replication.

The transmission of information from generation to generation occurs in a background of interference which can partially alter its character. ▽ If such an alteration of the hereditary information cache is itself replicated identically—that is, if the altered information is transmitted to succeeding generations—then such an alteration can be called a "mutation." △ Such mutations change the control system, modifying the maintaining reactions, and thereby changing the character of the interaction of the system with its environment; they can radically alter the efficiency with which a given individual copes with its environment.

▽ It is possible therefore to describe living systems from a cybernetic point of view. At the moment, this is perhaps no more than a useful analogy. It has provided an insight, but not yet any new information. △ It is possible that in the future a synthesis of such a cybernetic approach with molecular biology will lead to a complete understanding of the nature of life, an understanding which we do not yet have, as Liapunov himself is fully aware. These ideas, and the related viewpoint of the Soviet physicist Kolmogorov—discussed in Chapter 35—may ultimately prove to be of great significance in the analysis of the problem of the origin of life on Earth and the probable widespread distribution of life in the universe.