Definitions of life

by Carl Sagan

A great deal is known about life. Anatomists and taxonomists have studied the forms and relations of more than a million separate species of plants and animals. Physiologists have investigated the gross functioning of organisms. Biochemists have probed the biological interactions of the organic molecules that make up life on our planet. Molecular biologists have uncovered the very molecules responsible for reproduction and for the passage of hereditary information from generation to generation, a subject that geneticists had previously studied without going to the molecular level. Ecologists have inquired into the relations between organisms and their environments, ethologists the behavior of animals and plants, embryologists the development of complex organisms from a single cell, evolutionary biologists the emergence of organisms from pre-existing forms over geological time. Yet despite the enormous fund of information that each of these biological specialties has provided, it is a remarkable fact that no general agreement exists on what it is that is being studied. There is no generally accepted definition of life. In fact, there is a certain clearly discernible tendency for each biological specialty to define life in its own terms. The average person also tends to think of life in his own terms. For example, the man in the street, if asked about life on other planets, will often picture life of a distinctly human sort. Many individuals believe that insects are not animals, because by "animals" they mean "mammals." Man tends to define in terms of the familiar. But the fundamental truths may not be familiar. Of the following definitions, the first two are in terms familiar in everyday life; the next three are based on more abstract concepts and theoretical frameworks.

Physiological

For many years a physiological definition of life was popular. Life was defined as any system capable of performing a number of such functions as eating, metabolizing, excreting, breathing, moving, growing, reproducing, and being responsive to external stimuli. But many such properties are either present in machines that nobody is willing to call alive, or absent from organisms that everybody is willing to call alive. An automobile, for example, can be said to eat, metabolize, excrete, breathe, move, and be responsive to external stimuli. And a visitor from another planet, judging from the enormous numbers of automobiles on the Earth and the way in which cities and landscapes have been designed for the special benefit of motorcars, might well believe that automobiles are not only alive but are the dominant life form on the planet. Man, however, professes to know better. On the other hand, some bacteria do not breathe at all but instead live out their days by altering the oxidation state of sulfur.

Metabolic

The metabolic definition is still popular with many biologists. It describes a living system as an object with a definite boundary, continually exchanging some of its materials with its surroundings, but without altering its general properties, at least over some period of time. But again there are exceptions. There are seeds and spores that remain, so far as is known, perfectly dormant and totally without metabolic activity at low temperatures for hundreds, perhaps thousands, of years but that can revive perfectly well upon being subjected to more clement conditions. A flame, such as that of a candle in a closed room, will have a perfectly defined shape with fixed boundary and will be maintained by the combination of its organic waxes with molecular oxygen, producing carbon dioxide and water. A similar chemical reaction, incidentally, is fundamental to most animal life on Earth. Flames also have a well-known capacity for growth.

Biochemical

A biochemical or molecular biological definition sees living organisms as systems that contain reproducible hereditary information coded in nucleic acid molecules and that metabolize by controlling the rate of chemical reactions using proteinaceous catalysts known as enzymes. In many respects, this is more satisfying than the physiological or metabolic definitions of life. There are, however, even here, the hints of counterexamples. There seems to be some evidence that a virus-like agent called scrapie contains no nucleic acids at all, although it has been hypothesized that the nucleic acids of the host animal may nevertheless be involved in the reproduction of scrapie. Furthermore, a definition strictly in chemical terms seems peculiarly vulnerable. It implies that, were a person able to construct a system that had all the functional properties of life, it would still not be alive if it lacked the molecules that earthly biologists are fond of--and made of.

Genetic

All organisms on Earth, from the simplest cell to man himself, are machines of extraordinary powers, effortlessly performing complex transformations of organic molecules, exhibiting elaborate behavior patterns, and indefinitely constructing from raw materials in the environment more or less identical copies of themselves. How could machines of such staggering complexity and such stunning beauty ever arise? The answer, for which today there is excellent scientific evidence, was first discerned by the evolutionist Charles Darwin in the years before the publication in 1859 of his epoch-making work, the Origin of Species. A modern rephrasing of his theory of natural selection goes something like this: Hereditary information is carried by large molecules known as genes, composed of nucleic acids. Different genes are responsible for the expression of different characteristics of the organism. During the reproduction of the organism the genes also reproduce, or replicate, passing the instructions for various characteristics on to the next generation. Occasionally, there are imperfections, called mutations, in gene replication. A mutation alters the instructions for a particular characteristic or characteristics. It also breeds true, in the sense that its capability for determining a given characteristic of the organism remains unimpaired for generations until the mutated gene is itself mutated. Some mutations, when expressed, will produce characteristics favorable for the organism; organisms with such favorable genes will reproduce preferentially over those without such genes. Most mutations, however, turn out to be deleterious and often lead to some impairment or to death of the organism. To illustrate, it is unlikely that one can improve the functioning of a finely crafted watch by dropping it from a tall building. The watch may run better, but this is highly improbable. Organisms are so much more finely crafted than the finest watch that any random change is even more likely to be deleterious. The accidental beneficial and inheritable change, however, does on occasion occur; it results in an organism better adapted to its environment. In this way organisms slowly evolve toward better adaptation, and, in most cases, toward greater complexity. This evolution occurs, however, only at enormous cost: man exists today, complex and reasonably well adapted, only because of billions of deaths of organisms slightly less adapted and somewhat less complex. In short, Darwin's theory of natural selection states that complex organisms developed, or evolved, through time because of replication, mutation, and replication of mutations. A genetic definition of life therefore would be: a system capable of evolution by natural selection.

This definition places great emphasis on the importance of replication. Indeed, in any organism enormous biological effort is directed toward replication, although it confers no obvious benefit on the replicating organism. Some organisms, many hybrids for example, do not replicate at all. But their individual cells do. It is also true that life defined in this way does not rule out synthetic duplication. It should be possible to construct a machine that is capable of producing identical copies of itself from preformed building blocks littering the landscape but that arranges its descendants in a slightly different manner if there is a random change in its instructions. Such a machine would, of course, replicate its instructions as well. But the fact that such a machine would satisfy the genetic definition of life is not an argument against such a definition; in fact, if the building blocks were simple enough, such a machine would have the capability of evolving into very complex systems that would probably have all the other properties attributed to living systems. The genetic definition has the additional advantage of being expressed purely in functional terms: it does not depend on any particular choice of constituent molecules. The improbability of contemporary organisms--dealt with more fully below--is so great that these organisms could not possibly have arisen by purely random processes and without historical continuity. Fundamental to the genetic definition of life then is the belief that a certain level of complexity cannot be achieved without natural selection.

Thermodynamic

Thermodynamics distinguishes between open and closed systems. A closed system is isolated from the rest of the environment and exchanges neither light, heat, nor matter with its surroundings. An open system is one in which such exchanges do occur. The second law of thermodynamics states that, in a closed system, no processes can occur that increase the net order (or decrease the net entropy) of the system (see thermodynamics). Thus the universe taken as a whole is steadily moving toward a state of complete randomness, lacking any order, pattern, or beauty. This fate has been known since the 19th century as the heat death of the universe. Yet living organisms are manifestly ordered and at first sight seem to represent a contradiction to the second law of thermodynamics. Living systems might then be defined as localized regions where there is a continuous increase in order. Living systems, however, are not really in contradiction to the second law. They increase their order at the expense of a larger decrease in order of the universe outside. Living systems are not closed but rather open. Most life on Earth, for example, is dependent on the flow of sunlight, which is utilized by plants to construct complex molecules from simpler ones. But the order that results here on Earth is more than compensated by the decrease in order on the sun, through the thermonuclear processes responsible for the sun's radiation.

Some scientists argue on grounds of quite general open-system thermodynamics that the order of a system increases as energy flows through it, and moreover that this occurs through the development of cycles. A simple biological cycle on the Earth is the carbon cycle. Carbon from atmospheric carbon dioxide is incorporated by plants and converted into carbohydrates through the process of photosynthesis. These carbohydrates are ultimately oxidized by both plants and animals to extract useful energy locked in their chemical bonds. In the oxidation of carbohydrates, carbon dioxide is returned to the atmosphere, completing the cycle. It has been shown that similar cycles develop spontaneously and in the absence of life by the flow of energy through a chemical system. In this view, biological cycles are merely an exploitation by living systems of those thermodynamic cycles that pre-exist in the absence of life. It is not known whether open-system thermodynamic processes in the absence of replication are capable of leading to the sorts of complexity that characterize biological systems. It is clear, however, that the complexity of life on Earth has arisen through replication, although thermodynamically favored pathways have certainly been used.

The existence of diverse definitions of life surely means that life is something complicated. A fundamental understanding of biological systems has existed since the second half of the 19th century. But the number and diversity of definitions suggest something else as well. As detailed below, all the organisms on the Earth are extremely closely related, despite superficial differences. The fundamental ground pattern, both in form and in matter, of all life on Earth is essentially identical. As will emerge below, this identity probably implies that all organisms on Earth are evolved from a single instance of the origin of life. It is difficult to generalize from a single example, and in this respect the biologist is fundamentally handicapped as compared, say, to the chemist or physicist or geologist or meteorologist, who now can study aspects of his discipline beyond the Earth. If there is truly only one sort of life on Earth, then perspective is lacking in the most fundamental way.