THIS IS BIOLOGY

The Science of the Living World

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CHAPTER ONE

What Is the Meaning of "Life"?

Primitive humans lived close to nature. Every day they were occupied with animals and plants, as gatherers, hunters, or herdsmen. And death—of infants and elders, women in childbirth, men in strife—was forever present. Surely our earliest ancestors must have wrestled with the eternal question, "What is life?"

Perhaps, at first, no clear distinction was made between life in a living organism and a spirit in a nonliving natural object. Most primitive people believed that a spirit might reside in a mountain or a spring as well as in a tree, an animal, or a person. This animistic view of nature eventually waned, but the belief that "something" in a living creature distinguished it from inanimate matter and departed from the body at the moment of death held strong. In ancient Greece this something in humans was referred to as "breath." Later, particularly in the Christian religion, it was called the soul.

By the time of Descartes and the Scientific Revolution, animals (along with mountains, rivers, and trees) had lost their claim to a soul. But a dualistic split between body and soul in human beings continued to be almost universally accepted and is even today still believed by many people. Death was a particularly puzzling problem for a dualist. Why should this soul suddenly either die or leave the body? If the soul left the body, did it go somewhere, such as to some nirvana or heaven? Not until Charles Darwin developed his theory of evolution through natural selection was a scientific, rational explanation for death possible. August Weismann, a follower of Darwin at the end of the nineteenth century, was the first author to explain that a rapid sequence of generations provides the number of new genotypes required to cope permanently with a changing environment. His essay on death and dying was the beginning of a new era in our understanding of the meaning of death.

When biologists and philosophers speak of "life," however, they usually are not referring to life (that is, living) as contrasted with death but rather to life as contrasted with the lifelessness of an inanimate object. To elucidate the nature of this entity called "life" has been one of the major objectives of biology. The problem here is that "life" suggests some "thing"—a substance or force—and for centuries philosophers and biologists have tried to identify this life substance or vital force, to no avail. In reality, the noun "life" is merely a reification of the process of living. It does not exist as an independent entity.[1] One can deal with the process of living scientifically, something one cannot do with the abstraction "life." One can describe, even attempt to define, what living is; one can define what a living organism is; and one can attempt to make a demarcation between living and nonliving. Indeed, one can even attempt to explain how living, as a process, can be the product of molecules that themselves are not living.[2]

What life is, and how one should explain living processes, has been a subject of heated controversy since the sixteenth century. In brief, the situation was this: There was always a camp claiming that living organisms were not really different at all from inanimate matter; sometimes these people were called mechanists, later physicalists. And there was always an opposing camp—called vitalists—claiming instead that living organisms had properties that could not be found in inert matter and that therefore biological theories and concepts could not be reduced to the laws of physics and chemistry. In some periods and at certain intellectual centers the physicalists seemed to be victorious, and in other times and places the vitalists seemed to have achieved the upper hand. In this century it has become clear that both camps were partly right and partly wrong.

The physicalists had been right in insisting that there is no metaphysical life component and that at the molecular level life can be explained according to the principles of physics and chemistry. At the same time, the vitalists had been right in asserting that, nevertheless, living organisms are not the same as inert matter but have numerous autonomous characteristics, particularly their historically acquired genetic programs, that are unknown in inanimate matter. Organisms are many-level ordered systems, quite unlike anything found in the inanimate world. The philosophy that eventually incorporated the best principles from both physicalism and vitalism (after discarding the excesses) became known as organicism, and this is the paradigm that is dominant today.

The Physicalists

Early beginnings of a natural (as opposed to supernatural) explanation of the world were made in the philosophies of various Greek thinkers, including Plato, Aristotle, Epicurus, and many others. These promising beginnings, however, were largely forgotten in later centuries. The Middle Ages were dominated by a strict adherence to the teachings of the Scriptures, which attributed everything in nature to God and His laws. But medieval thinking, particularly in folklore, was also characterized by a belief in all sorts of occult forces. Eventually this animistic, magical thinking was reduced, if not eliminated, by a new way of looking at the world that was aptly called "the mechanization of the world picture" (Maier 1938).[3]

The influences leading up to the mechanization of the world picture were manifold. They included not only the Greek philosophers, transmitted to the Western world by the Arabs along with rediscovered original writings, but also technological developments in late medieval and early Renaissance times. There was great fascination with clocks and other automata—and indeed with almost any kind of machine. This eventually culminated in Descartes's claim that all organisms except humans were nothing *but* machines.

Descartes (1596–1650) became the spokesman for the Scientific Revolution, which, with its craving for precision and objectivity, could not accept vague ideas, immersed in metaphysics and the supernatural, such as souls of animals and plants. By restricting the possession of a soul to humans and by declaring animals to be nothing but automata, Descartes cut the Gordian knot, so to speak. With the mechanization of the animal soul, Descartes completed the mechanization of the world picture.[4]

It is a little difficult to understand why the machine concept of organisms could have had such long-lasting popularity. After all, no machine has ever built itself, replicated itself, programmed itself, or been able to procure its own energy. The similarity between an organism and a machine is exceedingly superficial. Yet the concept did not die out completely until well into this century.

The success of Galileo, Kepler, and Newton in using mathematics to reinforce their explanations of the cosmos also contributed to the mechanization of the world picture. Galileo (1623) succinctly captured the prestige of mathematics in the Renaissance when he said that the book of nature "cannot be understood unless one first learns to comprehend the language and read the letters in which it is composed. It is written in the language of mathematics, and its characters are triangles, circles, and other geometric figures without which it is humanly impossible to understand a single word of it; without these one wanders about in a dark labyrinth."

The rapid development of physics shortly thereafter carried the Scientific Revolution a step further, turning the more general mechanicism of the early period into a more specific physicalism, based on a set of concrete laws about the workings of both the heavens and the earth.[5]

The physicalist movement had the enormous merit of refuting much of the magical thinking that had generally characterized the preceding centuries. Its greatest achievement perhaps was providing a natural explanation of physical phenomena and eliminating much of the reliance on the supernatural that was previously accepted by virtually everybody. If mechanicism, and particularly its outgrowth into physicalism, went too far in some respects, this was inevitable for an energetic new movement. Yet because of its one-sidedness and its failure to explain any of the phenomena and processes particular to living organisms, physicalism induced a rebellion. This countermovement is usually described under the umbrella term vitalism.

From Galileo to modern times there has been a seesawing in biology between strictly mechanistic and more vitalistic explanations of life. Eventually, Cartesianism reached its culmination in the publication of de La Mettrie's *L'homme machine* (1749). Next followed a vigorous flowering of vitalism, particularly in France and in Germany, but further triumphs of physics and chemistry in the mid-nineteenth century inspired yet another physicalist resurgence in biology. It was largely confined to Germany, perhaps not surprisingly so, since nowhere else did biology flourish in the nineteenth century to the extent it did in Germany.

THE FLOWERING OF PHYSICALISM

The nineteenth-century physicalist movement arrived in two waves. The first one was a reaction to the quite moderate vitalism adopted by Johannes Müller (1801–1858), who in the 1830s switched from pure physiology to comparative anatomy, and of Justus von Liebig (1803–1873), well known for his incisive critiques which helped to bring the reign of inductivism to an end. It was set in motion by four former students of Müller—Hermann Helmholtz, Emil DuBois-Reymond, Ernst Brücke, and Matthias Schleiden. The second wave, which began around 1865, is identified with the names Carl Ludwig, Julius Sachs, and Jacques Loeb. Undeniably, these physicalists made important contributions to physiology. Helmholtz (along with Claude Bernard in France) deprived "animal heat" of its vitalistic connotation, and DuBois-Reymond dispelled much of the mystery of nerve physiology by offering a physical (electric) explanation of nerve activity. Schleiden advanced the fields of botany and cytology through his insistence that plants consist entirely of cells and that all the highly diverse structural elements of plants are cells or cell products. Helmholtz, DuBois-Reymond, and Ludwig were particularly outstanding in the invention of ever-more sophisticated instruments to record the precise measurements in which they were interested. This permitted them, among other achievements, to rule out the existence of a "vital force" by showing that work could be translated into heat without residue. Every history of physiology written since that time has documented these and other splendid accomplishments.

Yet, the underlying philosophy of this physicalist school was quite naive and could not help but provoke disdain among biologists with a background in natural history. In historical accounts of the many achievements of the physicalists, their naivete when it came to living processes has frequently been ignored. But one cannot understand the vitalists' passionate resistance to the claims of the physicalists unless one is acquainted with the actual explanatory statements the physicalists offered.

It is ironic that the physicalists attacked the vitalists for invoking an unanalyzed "vital force," and yet in their own explanations they used such equally unanalyzed factors as "energy" and "movements." The definitions of life and the descriptions of living processes formulated by the physicalists often consisted of utterly vacuous statements. For example, the physical chemist Wilhelm Ostwald defined a sea urchin as being, like any other piece of matter, "a spatially discrete cohesive sum of quantities of energy." For many physicalists, an unacceptable vitalistic statement became acceptable when vital force was replaced by the equally undefined term "energy." Wilhelm Roux (1895), whose work brought experimental embryology into full flower, stated that development is "the production of diversity owing to the unequal distribution of energy."

Even more fashionable than "energy" was the term "movement" to explain living processes, including developmental and adaptational ones. DuBois-Reymond (1872) wrote that the understanding of nature "consists in explaining all changes in the world as produced by the movement of atoms," that is, "by reducing natural processes to the mechanics of atoms . . . By showing that the changes in all natural bodies can be explained as a constant sum . . . of potential and kinetic energy, nothing in these changes remains to be further explained." His contemporaries did not notice that these assertions were only empty words, without substantial evidence and with precious little explanatory value.

A belief in the importance of the movement of atoms was held not only by the physicalists but even by some of their opponents. For Rudolf Kölliker (1886)—a Swiss cytologist who recognized that the chromosomes in the nucleus are involved in inheritance and that spermatozoa are cells—development was a strictly physical phenomenon controlled by differences in growth processes: "It is sufficient to postulate the occurrence in the nuclei of regular and typical movements controlled by the structure of the idioplasm."

As exemplified in statements by the botanist Karl Wilhelm von Nägeli (1884), another favorite explanation of the mechanists was to invoke "movements of the smallest parts" to explain "the mechanics of organic life."[6] The effect of a nucleus on the rest of the cell—the cytoplasm—was seen by E. Strasburger, a leading botanist of the time, as "a propagation of molecular movements . . . in a manner which might be compared to the transmission of a nervous impulse." Thus it did not involve the transport of material; this notion was, of course, entirely wrong. These physicalists never noticed that their statements about energy and movement did not really explain anything at all. Movements, unless directed, are random, like Brownian motion. Something has to give direction to these movements, and this is exactly what their vitalist opponents always emphasized.

The weakness of a purely physicalist interpretation was particularly obvious in explanations of fertilization. When F. Miescher (a student of His and Ludwig) discovered nucleic acid in 1869, he thought that the function of the spermatozoon was the purely mechanical one of getting cell division going; as a consequence of his physicalist bias, Miescher completely missed the significance of his own discovery. Jacques Loeb claimed that the really crucial agents in fertilization were not the nucleins of the spermatozoon but the ions. One is almost embarrassed when reading Loeb's statement that "Branchipus is a freshwater crustacean which, if raised in concentrated salt solution, becomes smaller and undergoes some other changes. In that case it is called Artemia." The sophistication of the physicalists in chemistry, particularly physical chemistry, was not matched by their biological knowledge. Even Sachs, who studied so diligently the effects of various extrinsic factors on growth and differentiation, never seems to have given any thought to the question why seedlings of different species of plants raised under identical conditions of light, water, and food would give rise to entirely different species.

Perhaps the most uncompromising mechanistic school in modern biology was that of Entwicklungsmechanik, founded in the 1880s by Wilhelm Roux. This school of embryology represented a rebellious reaction to the one-sidedness of the comparative embryologists, who were interested only in phylogenetic questions. Roux's associate, the embryologist Hans Driesch, was at first, if anything, even more mechanistic, but he eventually experienced a complete conversion from an extreme mechanist to an extreme vitalist. This happened when he separated a sea urchin embryo at the two-cell stage into two separate embryos of one cell each and observed that these two embryos did not develop into two half organisms, as his mechanistic theories demanded, but were able to compensate appropriately and develop into somewhat smaller but otherwise perfect larvae.

In due time, the vacuousness and even absurdity of these purely physicalistic explanations of life became apparent to most biologists, who, however, were usually satisfied to adopt the agnostic position that organisms and living processes simply could not be exhaustively explained by reductionist physicalism.

The Vitalists

The problem of explaining "life" was the concern of the vitalists from the Scientific Revolution until well into the nineteenth century; it did not really become the subject matter of scientific analysis until the rise of biology after the 1820s. Descartes and his followers had been unable to persuade most students of plants and animals that there were no essential differences between living organisms and inanimate matter. Yet after the rise of physicalism, these naturalists had to take a new look at the nature of life and attempted to advance *scientific* (rather than metaphysical or theological) arguments against Descartes's machine theory of organisms. This requirement led to the birth of the vitalistic school of biology.[7]

The reactions of the vitalists to physicalist explanations were diversified, since the physicalist paradigm itself was composite, not only in what it claimed (that living processes are mechanistic and can be reduced to the laws of physics and chemistry) but also in what it failed to take account of (the differences between living organisms and simple matter, the existence of adaptive but much more complex properties—Kant's Zweckmässigkeit—in animals and plants, and evolutionary explanations). Each of these claims and omissions was criticized by one or the other opponent of physicalism. Some vitalists focused on unexplained vital properties, others on the holistic nature of living creatures, still others on adaptedness or directedness (as in the development of the fertilized egg).

All these opposing arguments to the various aspects of physicalism have traditionally been lumped together as vitalism. In some sense, this is not altogether wrong, because all of the antiphysicalists defended the life-specific properties of living organisms. Yet the label vitalist conceals the heterogeneity of this group.[8] For instance, in Germany some biologists (which Lenoir calls teleomechanists) were willing to explain physiological processes mechanically but insisted that this failed to account for either adaptation or directed processes, such as the development of the fertilized egg. These legitimate questions were raised again and again by distinguished philosophers and biologists from 1790 until the end of the nineteenth century, but they had remarkably little effect on the writings of the leading physicalists such as Ludwig, Sachs, or Loeb.

Vitalism, from its emergence in the seventeenth century, was decidedly an antimovement. It was a rebellion against the mechanistic philosophy of the Scientific Revolution and against physicalism from Galileo to Newton. It passionately resisted the doctrine that the animal is nothing but a machine and that all manifestations of life can be exhaustively explained as matter in motion. But as decisive and convincing as the vitalists were in their rejection of the Cartesian model, they were equally indecisive and unconvincing in their own explanatory endeavors. There was great explanatory diversity but no cohesive theory.

Life, according to one group of vitalists, was connected either with a special substance (which they called protoplasm) not found in inanimate matter, or with a special state of matter (such as the colloidal state), which, it was claimed, the physicochemical sciences were not equipped to analyze. Another subset of vitalists held that there is a special vital force (sometimes called Lebenskraft, Entelechie, or élan vital) distinct from the forces physicists deal with. Some of those who accepted the existence of such a force were also teleologists who believed that life existed for some ultimate purpose. Other authors invoked psychological or mental forces (psychovitalism, psycho-Lamarckism) to account for aspects of living organisms that the physicalists had failed to explain.

Those who supported the existence of a vital force had highly diverse views of the nature of this force. From about the middle of the seventeenth century on, the vital agent was most frequently characterized as a fluid (not a liquid), in analogy to Newton's gravity and to caloric, phlogiston, and other "imponderable fluids." Gravity was invisible and so was the heat that flowed from a warm to a cold object; hence, it was not considered disturbing or unlikely that the vital fluid was also invisible, even though not necessarily something supernatural. For instance, the influential late eighteenth-century German naturalist J. F. Blumenbach (who wrote extensively on extinction, creation, catastrophes, mutability, and spontaneous generation) considered this vital fluid, though invisible, to be nevertheless very real and subject to scientific study, much as gravity was.[9] The concept of a vital fluid was eventually replaced by that of a vital force. Even such a reputable scientist as Johannes Müller accepted a vital force as indispensable for explaining the otherwise inexplicable manifestations of life.

In England, all the physiologists of the sixteenth, seventeenth, and eighteenth centuries had vitalistic ideas, and vitalism was still strong in the 1800–1840 period in the writings of J. Hunter, J. C. Prichard, and others. In France, where Cartesianism had been particularly powerful, it is not surprising that the vitalists' countermovement was equally vigorous. The outstanding representatives in France were the Montpellier school (a group of vitalistic physicians and physiologists) and the histologist F. X. Bichat. Even Claude Bernard, who studied such functional subjects as the nervous and digestive systems and considered himself an opponent of vitalism, actually supported a number of vitalistic notions. Furthermore, most Larmarckians were rather vitalistic in some of their thinking.

It was in Germany that vitalism had its most extensive flowering and reached its greatest diversity. Georg Ernst Stahl, a late seventeenth-century chemist and physician best known for his phlogiston theory of combustion, was the first great opponent of the mechanists. Perhaps he was more of an animist than a vitalist, but his ideas played a large role in the teaching of the Montpellier school.

The next impetus to the vitalistic movement in Germany was the preformation versus epigenesis controversy, which dominated developmental biology in the second half of the eighteenth century. Preformationists held that the parts of an adult exist in smaller form at the very beginning of development. The epigenesists held that the adult parts appear as products of development but are not present as parts in the beginning. In 1759, when the embryologist Caspar Friedrich Wolff refuted preformation and replaced it by epigenesis, he had to invoke some causal agent that would convert the completely unformed mass of the fertilized egg into the adult of a particular species. He called this agent the *vis essentialis.*

J. F. Blumenbach rejected the vague *vis essentialis* and proposed instead that a specific formative force, *nisus formativus,* plays a decisive role not only in the development of the embryo but also in growth, regeneration, and reproduction. He accepted still other forces, such as irritability and sensibility, as contributing to the maintenance of life. Blumenbach was quite pragmatic about these forces, considering them essentially as labels for observed processes of which he did not know the causes. They were black boxes for him, rather than metaphysical principles.

The branch of German philosophy called Naturphilosophie, advanced by F. W. J. Schelling and his followers early in the nineteenth century, was a decidedly metaphysical vitalism, but the practical philosophies of working biologists such as Wolff, Blumenbach, and eventually Müller were antiphysicalist rather than metaphysical. Müller has been maligned as an unscientific metaphysician, but the accusation is unfair. A collector of butterflies and plants from his boyhood on, he had acquired the naturalist's habit of looking at organisms holistically. This perception was lacking in his students, whose leanings were more toward mathematics and the physical sciences. Müller realized that the slogan "life is a movement of particles" was meaningless and without explanatory value, and his alternative concept of Lebenskraft (vital force), though a failure, was closer to the concept of a genetic program than the shallow physicalist explanations of his rebellious students.[10]

Many of the arguments put forth by the vitalists were intended to explain specific characteristics of organisms which today are explained by the genetic program. They advanced a number of perfectly valid refutations of the machine theory but, owing to the backward state of biological explanation available at that time, were unable to come up with the correct explanation of vital processes that were eventually found during the twentieth century. Consequently, most of the argumentation of the vitalists was negative. From the 1890s on Driesch argued, for example, that physicalism could not explain self-regulation in embryonic structures, regeneration and reproduction, and psychic phenomena, like memory and intelligence. Yet it is remarkable how often perfectly sensible sentences emerge in Driesch's writings whenever his word "Entelechie" is replaced by the phrase "genetic program." These vitalists not only knew that there was something missing in the mechanistic explanations but they also described in detail the nature of the phenomena and processes the mechanists were unable to explain.[11]

Given the many weaknesses and even contradictions in vitalist explanations, it may seem surprising how widely vitalism was adopted and how long it prevailed. One reason, as we have seen, is that at that time there was simply no other alternative to the reductionist machine theory of life, which, to many biologists, was clearly out of the question. Another reason is that vitalism was strongly supported by several other then-dominant ideologies, including the belief in a cosmic purpose (teleology or finalism). In Germany, Immanuel Kant had a strong influence on vitalism, particularly on the school of teleomechanism, an influence still evident in Driesch's writings. A close connection with finalism is evident in the writings of most vitalists.[12]

In part because of their teleological leanings, the vitalists strongly opposed Darwin's selectionism. Darwin's theory of evolution denied the existence of any cosmic teleology and substituted in its place a "mechanism" for evolutionary change—natural selection: "We see in Darwin's discovery of natural selection in the struggle for existence the most decisive proof for the exclusive validity of mechanically operating causations in the whole realm of biology, and we see in this the definitive demise of all teleological and vitalistic interpretations of organisms" (Haeckel 1866). Selectionism made vitalism superfluous in the realm of adaptation.

Driesch was a rabid anti-Darwinian, as were other vitalists, but his arguments against selection were consistently ridiculous and showed clearly that he did not in the least understand this theory. Darwinism, by supplying a mechanism for evolution while at the same time denying any finalistic or vitalistic view of life, became the foundation of a new paradigm to explain "life."

THE DECLINE OF VITALISM

When vitalism was first proposed and widely adopted, it seemed to provide a reasonable answer to the nagging question, "What is life?" Furthermore, at that time it was a legitimate theoretical alternative not just to the crude mechanicism of the Scientific Revolution but also to nineteenth-century physicalism. Vitalism seemingly explained the manifestations of life far more successfully than the simplistic machine theory of its opponents.

Yet considering how dominant vitalism was in biology and for how long a period it prevailed, it is surprising how rapidly and completely it collapsed. The last support of vitalism as a viable concept in biology disappeared about 1930. A considerable number of different factors contributed to its downfall.

First, vitalism was more and more often viewed as a metaphysical rather than a scientific concept. It was considered unscientific because the vitalists had no method to test it. By dogmatically asserting the existence of a vital force, the vitalists often impeded the pursuit of a constitutive reductionism that would elucidate the basic functions of living organisms.

Second, the belief that organisms were constructed of a special substance quite different from inanimate matter gradually lost support. That substance, it was believed through most of the nineteenth century, was protoplasm, the cellular material outside the nucleus.[13] Later it was called cytoplasm (a term introduced by Kölliker). Because protoplasm seemed to have what was called "colloidal" properties, a flourishing branch of chemistry developed: colloidal chemistry. Biochemistry, however, together with electron microscopy, eventually established the true composition of cytoplasm and elucidated the nature of its various components: cellular organelles, membranes, and macromolecules. It was found that there was no special substance "protoplasm," and the word and concept disappeared from the biological literature. The nature of the colloidal state was likewise explained biochemically, and colloidal chemistry ceased to exist. Thus all evidence for a separate category of living substance disappeared, and it became possible to explain the seemingly unique properties of living matter in terms of macromolecules and their organization. The macromolecules, in turn, are composed of the same atoms and small molecules as inanimate matter. Wöhler's synthesis in the laboratory of the organic substance urea in 1828 was the first proof of the artificial conversion of inorganic compounds into an organic molecule.

Third, all of the vitalists' attempts to demonstrate the existence of a nonmaterial vital force ended in failure. Once physiological and developmental processes began to be explained in terms of physicochemical processes at the cellular and molecular level, these explanations left no unexplained residue that would require a vitalistic interpretation. Vitalism simply became superfluous.

Fourth, new biological concepts to explain the phenomena that used to be cited as proof of vitalism were developed. Two advances in particular were crucial for this change. One was the rise of genetics, which ultimately led to the concept of the genetic program. This made it possible to explain all goal-directed living phenomena, at least in principle, as teleonomic processes controlled by genetic programs. Another seemingly teleological phenomenon to be newly interpreted was Kant's Zweckmässigkeit. This reinterpretation was achieved by the second advance, Darwinism. Natural selection made adaptedness possible by making use of the abundant variability of living nature. Thus, two major ideological underpinnings of vitalism—teleology and antiselectionism—were destroyed. Genetics and Darwinism succeeded in providing valid interpretations of the phenomena claimed by the vitalists not to be explicable except by invoking a vital substance or force.

If one were to believe the writings of the physicalists, vitalism was nothing but an impediment to the growth of biology. Vitalism took the phenomena of life, so it was claimed, out of the realm of science and transferred them to the realm of metaphysics. This criticism is indeed justified for the writings of some of the more mystical vitalists, but it is not fair when raised against reputable scientists such as Blumenbach and, even more so, Müller, who specifically articulated all the aspects of life that were left unexplained by the physicalists. That the explanation Müller adopted was a failure does not diminish the merit of his having outlined the problems that still had to be solved.

There are many similar situations in the history of science where unsuitable explanatory schemes were adopted for a clearly visualized problem because the groundwork for the real explanation had not yet been laid. Kant's explanation of evolution by teleology is a famous example. It is probably justifiable to conclude that vitalism was a necessary movement to demonstrate the vacuity of a shallow physicalism in the explanation of life. Indeed, as François Jacob (1973) has rightly stated, the vitalists were largely responsible for the recognition of biology as an autonomous scientific discipline.

Before turning to the organicist paradigm which replaced both vitalism and physicalism, we might note in passing a rather peculiar twentieth-century phenomenon—the development of vitalistic beliefs among physicists. Niels Bohr was apparently the first to suggest that special laws not found in inanimate nature might operate in organisms. He thought of these laws as analogous to the laws of physics except for their being restricted to organisms. Erwin Schrödinger and other physicists supported similar ideas. Francis Crick (1966) devoted a whole book to refuting the vitalistic ideas of the physicists Walter Elsasser and Eugene Wigner. It is curious that a form of vitalism survived in the minds of some reputable physicists long after it had become extinct in the minds of reputable biologists.

A further irony, however, is that many biologists in the post-1925 period believed that the newly discovered principles of physics, such as the relativity theory, Bohr's complementarity principle, quantum mechanics, and Heisenberg's indeterminacy principle, would offer new insight into biological processes. In fact, so far as I can judge, none of these principles of physics applies to biology. In spite of Bohr's searching in biology for evidence of complementarity, and some desperate analogies to establish this, there really is no such thing in biology as that principle. The indeterminacy of Heisenberg is something quite different from any kind of indeterminacy encountered in biology.

Vitalism survived even longer in the writings of philosophers than in the writings of physicists. But so far as I know, there are no vitalists among the group of philosophers of biology who started publishing after 1965. Nor do I know of a single reputable living biologist who still supports straightforward vitalism. The few late twentieth-century biologists who had vitalistic leanings (A. Hardy, S. Wright, A. Portmann) are no longer alive.

The Organicists

By about 1920 vitalism seemed to be discredited. The physiologist J. S. Haldane (1931) stated quite rightly that "biologists have almost unanimously abandoned vitalism as an acknowledged belief." At the same time, he also said that a purely mechanistic interpretation cannot account for the coordination that is so characteristic of life. What particularly puzzled Haldane was the orderly sequence of events during development. After showing the invalidity of both the vitalistic and the mechanistic approaches, Haldane stated that "we must find a different theoretical basis of biology, based on the observation that all the phenomena concerned tend towards being so coordinated that they express what is normal for an adult organism."

The demise of vitalism, rather than leading to the victory of mechanicism, resulted in a new explanatory system. This new paradigm accepted that processes at the molecular level could be explained exhaustively by physicochemical mechanisms but that such mechanisms played an increasingly smaller, if not negligible, role at higher levels of integration. There they are supplemented or replaced by emerging characteristics of the organized systems. The unique characteristics of living organisms are not due to their composition but rather to their organization. This mode of thinking is now usually referred to as *organicism.* It stresses particularly the characteristics of highly complex ordered systems and the historical nature of the evolved genetic programs in organisms.

According to W. E. Ritter, who coined the term organicism in 1919,[14] "Wholes are so related to their parts that not only does the existence of the whole depend on the orderly cooperation and interdependence of its parts, but the whole exercises a measure of determinative control over its parts" (Ritter and Bailey 1928). J. C. Smuts (1926) explained his own holistic view of organisms as follows: "A whole according to the view here presented is not simple, but composite and consists of parts. Natural wholes, such as organisms, are . . . complex or composite, consisting of many parts in active relation and interaction of one kind or another, and the parts may be themselves lesser wholes, such as cells in an organism." His statements were later condensed by other biologists into the concise statement that "a whole is more than the sum of its parts."[15]

Since the 1920s, the terms holism and organicism have been used interchangeably. Perhaps, at first, holism was more frequently used, and the adjective "holistic" is still useful today. But holism is not a strictly biological term, since many inanimate systems are also holistic, as Niels Bohr has pointed out correctly. Therefore, in biology the more restricted term "organicism" is now used more frequently. It encompasses the recognition that the existence of a genetic program is an important feature of the new paradigm.

The objection of the organicists was not so much to the mechanistic aspects of physicalism as to its reductionism. The physicalists referred to their explanations as mechanistic explanations, which indeed they were, but what characterized them far more was that they were also reductionist explanations. For reductionists, the problem of explanation is in principle resolved as soon as the reduction to the smallest components has been accomplished. They claim that as soon as one has completed the inventory of these components and has determined the function of each of them, it should be an easy task to explain also everything observed at the higher levels of organization.

The organicists demonstrated that this claim is simply not true, because explanatory reductionism is quite unable to explain characteristics of organisms that emerge at higher levels of organization. Curiously, even most mechanists admitted the insufficiency of a purely reductionist explanation. The philosopher Ernest Nagel (1961), for instance, conceded "that there are large sectors of biological study in which physico-chemical explanations play no role at present, and that a number of outstanding biological theories have been successfully exploited which are not physico-chemical in character." Nagel tried to save reductionism by inserting the words "at present," but it was already rather evident that such purely biological concepts as territory, display, predator thwarting, and so on could never be reduced to the terms of chemistry and physics without entirely losing their biological meaning.[16]

The pioneers of holism (for example, E. S. Russell and J. S. Haldane) argued effectively against the reductionist approach and described convincingly how well a holistic approach fits the phenomena of behavior and development. But they failed to explain the actual nature of the holistic phenomena. They were unsuccessful when trying to explain the nature of "the whole" or the integration of parts into the whole. Ritter, Smuts, and other early proponents of holism were equally vague (and somewhat metaphysical) in their explanations. Indeed, some of Smuts's wordings had a rather teleological flavor.[17]

Alex Novikoff (1947), however, spelled out in considerable detail why an explanation of living organisms has to be holistic. "What are wholes on one level become parts on a higher one . . . both parts and wholes are material entities, and integration results from the interaction of parts as a consequence of their properties." Holism, since it rejects reduction, "does not regard living organisms as machines made of a multitude of discrete parts (physico-chemical units), removable like pistons of an engine and capable of description without regard to the system from which they are removed." Owing to the interaction of the parts, a description of the isolated parts fails to convey the properties of the system as a whole. It is the organization of these parts that controls the entire system.

There is an integration of the parts at each level, from the cell to tissues, organs, organ systems, and whole organisms. This integration is found at the biochemical level, at the developmental level, and in whole organisms at the behavioral level.[18] All holists agree that no system can be exhaustively explained by the properties of its isolated components. The basis of organicism is the fact that living beings have organization. They are not just piles of characters or molecules, because their function depends entirely on their organization, their mutual interrelations, interactions, and interdependencies.

EMERGENCE

It is now clear that two major pillars in the explanatory framework of modern biology were missing in all the early presentations of holism. One, the concept of the genetic program, was absent because it had not yet been developed. The other missing pillar was the concept of emergence—that in a structured system, new properties emerge at higher levels of integration which could not have been predicted from a knowledge of the lower-level components. This concept was absent because either it had not been thought of or it had been dismissed as unscientific and metaphysical. By eventually incorporating the concepts of the genetic program and of emergence, organicism became antireductionist and yet remained mechanistic.

Jacob (1973) describes emergence this way: "At each level, units of relatively well-defined size and almost identical structure associate to form a unit of the level above. Each of these units formed by the integration of sub-units may be given the general name 'integron'. An integron is formed by assembling integrons of the level below it; it takes part in the construction of the integron of the level above." Each integron has new characteristics and capacities not present at any lower level of integration; these can be said to have emerged.[19]

The concept of emergence first received prominence in Lloyd Morgan's book on emergent evolution (1923). Darwinians who adopted emergent evolution nevertheless had some misgivings about it because they were afraid that it was antigradualistic. Indeed, some early emergentists were also saltationists, particularly during the period of Mendelism; that is, they believed that evolution proceeded in large, discontinuous leaps, or saltations. These misgivings have now been overcome, because it is now understood that the population (or species), rather than the gene or the individual, is the unit of evolution; one can have different forms (phenetic discontinuities) within populations—by recombination of existing DNA—while a population as a whole must by necessity evolve gradually. A modern evolutionist would say that the formation of a more complex system, representing the emergence of a new higher level, is strictly a matter of genetic variation and selection. Integrons evolve through natural selection, and at every level they are adapted systems, because they contribute to the fitness of an individual. This in no way conflicts with the principles of Darwinism.

To sum up, organicism is best characterized by the dual belief in the importance of considering the organism as a whole, and at the same time the firm conviction that this wholeness is not to be considered something mysteriously closed to analysis but that it should be studied and analyzed by choosing the right level of analysis. The organicist does not reject analysis but insists that analysis should be continued downward only to the lowest level at which this approach yields relevant new information and new insights. Every system, every integron, loses some of its characteristics when taken apart, and many of the important interactions of components of an organism do not occur at the physicochemical level but at a higher level of integration. And finally, it is the genetic program which controls the development and activities of the organic integrons that emerge at each successively higher level of integration.

The Distinguishing Characteristics of Life

Today, whether one consults working biologists or philosophers of science, there seems to be a consensus on the nature of living organisms. At the molecular level, all—and at the cellular level, most—of their functions obey the laws of physics and chemistry. There is no residue that would require autonomous vitalist principles. Yet, organisms are fundamentally different from inert matter. They are hierarchically ordered systems with many emergent properties never found in inanimate matter; and, most importantly, their activities are governed by genetic programs containing historically acquired information, again something absent in inanimate nature.

As a result, living organisms represent a remarkable form of dualism. This is not a dualism of body and soul, or body and mind, that is, a dualism partly physical and partly metaphysical. The dualism of modern biology is consistently physicochemical, and it arises from the fact that organisms possess both a genotype and a phenotype. The genotype, consisting of nucleic acids, requires for its understanding evolutionary explanations. The phenotype, constructed on the basis of the information provided by the genotype, and consisting of proteins, lipids, and other macromolecules, requires functional (proximate) explanations for its understanding. Such duality is unknown in the inanimate world. Explanations of the genotype and of the phenotype require different kinds of theories.

We may tabulate some of the phenomena that are specific to living beings:

Evolved programs. Organisms are the product of 3.8 billion years of evolution. All their characteristics reflect this history. Development, behavior, and all other activities of living organisms are in part controlled by genetic (and somatic) programs that are the result of the genetic information accumulated throughout the history of life. Historically there has been an unbroken stream from the origin of life and the simplest prokaryotes up to gigantic trees, elephants, whales, and humans.

Chemical properties. Although ultimately living organisms consist of the same atoms as inanimate matter, the kinds of molecules responsible for the development and function of living organisms—nucleic acids, peptides, enzymes, hormones, the components of membranes—are macromolecules not found in inanimate nature. Organic chemistry and biochemistry have shown that all substances found in living organisms can be broken down into simpler inorganic molecules and can, at least in principle, be synthesized in the laboratory.

Regulatory mechanisms. Living systems are characterized by all sorts of control and regulatory mechanisms, including multiple feedback mechanisms, that maintain the steady state of the system, mechanisms of a sort never found in inanimate nature.

Organization. Living organisms are complex, ordered systems. This explains their capacity for regulation and for control of the interaction of the genotype, as well as their developmental and evolutionary constraints.

Teleonomic systems. Living organisms are adapted systems, the result of countless previous generations having been subjected to natural selection. These systems are programmed for teleonomic (goal-directed) activities from embryonic development to the physiological and behavioral activities of the adults.

Limited order of magnitude. The size of living organisms occupies a limited range in the middle world, from the smallest viruses to the largest whales and trees. The basic units of biological organization, cells and cellular components, are very small, which gives organisms great developmental and evolutionary flexibility.

Life cycle. Organisms, at least sexually reproducing ones, go through a definite life cycle beginning with a zygote (fertilized egg) and passing through various embryonic or larval stages until adulthood is reached. The complexities of the life cycle vary from species to species, including in some species an alternation of sexual and asexual generations.

Open systems. Living organisms continuously obtain energy and materials from the external environment and eliminate the end-products of metabolism. Being open systems, they are not subject to the limitations of the second law of thermodynamics.

These properties of living organisms give them a number of capacities not present in inanimate systems:

A capacity for evolution

A capacity for self-replication

A capacity for growth and differentiation via a genetic program

A capacity for metabolism (the binding and releasing of energy)

A capacity for self-regulation, to keep the complex system in steady state (homeostasis, feedback)

A capacity (through perception and sense organs) for response to stimuli from the environment

A capacity for change at two levels, that of the phenotype and that of the genotype.

All these characteristics of living organisms distinguish them categorically from inanimate systems. The gradual recognition of this uniqueness and separateness of the living world has resulted in the branch of science called biology, and has led to a recognition of the autonomy of this science, as we will see in Chapter 2.