THE AUTONOMY OF BIOLOGY

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It took more than two hundred years and the occurrence of three sets of events before a separate science of the living world—biology—was recognized. As I will show, one can assign these events to three different sets: (A) the refutation of certain erroneous principles; (B) the demonstration that certain basic principles of physics cannot be applied to biology, and (C) the realization of the uniqueness of certain basic principles of biology that are not applicable to the inanimate world. An analysis of these three sets of developments has to be done before one can accept the view of an autonomy of biology. For an earlier support of the autonomy of biology see Ayala (1968).

THE REFUTATION OF CERTAIN ERRONEOUS BASIC ASSUMPTIONS

Under this heading, I deal with the support for certain basic ontological principles that later were shown to be erroneous. Biology could not be recognized as a science of the same rank as physics as long as most biologists accepted certain basic explanatory principles not supported by the laws of the physical sciences and eventually found to be invalid. The two major principles here involved are *vitalism* and a belief in cosmic *teleology*. As soon as it had been demonstrated that these two principles are invalid and, more broadly, that none of the phenomena of the living world is in conflict with the natural laws of the physicalists, there was no longer any reason for not recognizing biology as a legitimate autonomous science equivalent to physics.

VITALISM

The nature of life, the property of being living, has always been a puzzle for philosophers. Descartes tried to solve it by simply ignoring it. An organism is really nothing but a machine, he said. And other philosophers, particularly those with a background in mathematics, logic, physics, and chemistry, tended to follow him and operated as if there were no difference between living and inanimate matter. But this did not satisfy most naturalists. They were convinced that in a living organism certain forces

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Ludus Vitalis, vol. XII, num. 21, 2004, pp. 15-27.

are active that do not exist in inanimate nature. They concluded that, just as the motion of planets and stars is controlled by an occult, invisible force called gravitation by Newton, the movements and other manifestations of life in organisms are controlled by an invisible force, *Lebenskraft* or *vis vitalis*. Those who believed in such a force were called vitalists.

Vitalism was popular from the early seventeenth century to the early twentieth century. It was a natural reaction to the crass mechanism of Descartes. Henri Bergson (1859-1941) and Hans Driesch (1867-1941) were prominent vitalists in the early twentieth century. The end of vitalism came when it no longer could find any supporters. Two causes were largely responsible for this: first, the failure of literally thousands of unsuccessful experiments conducted to demonstrate the existence of a *Lebenskraft*; second, the realization that the new biology, with the methods of genetics and molecular biology, was able to solve all the problems for which scientists traditionally had invoked the *Lebenskraft.* In other words, the proposal of a *Lebenskraft* had simply become unnecessary.

It would be ahistorical to ridicule vitalism. When one reads the writings of some of the leading vitalists, like Driesch, one is forced to agree with him that many of the basic problems of biology simply cannot be solved by Cartesian philosophy, in which the organism is considered nothing but a machine. The developmental biologists, in particular, asked some very challenging questions. For example, how can a machine regenerate lost parts, as many kinds of organisms are able to do? How can a machine replicate itself? How can two machines fuse into a single one like the fusion of two gametes to produce a zygote? The critical logic of the vitalists was impeccable. But all their efforts to find a scientific answer to the so-called vitalistic phenomena were failures. Generations of vitalists labored in vain to find a scientific explanation for the *Lebenskraft* until it finally became quite clear that such a force simply does not exist. That was the end of vitalism.

TELEOLOGY

Teleology is the second invalid principle that had to be eliminated from biology before it qualified as a science equivalent to physics. Teleology deals with the explanation of natural processes that seem to lead automatically to a definite end or goal. To explain the development of the fertilized egg to the adult of a given species, Aristotle invoked a fourth cause, the *causa finalis*. Eventually, one invoked this cause for all phenomena in the cosmos that led to an end or goal. Kant in his *Critique of Judgment* at first tried to explain the biological world in terms of Newtonian natural laws but was completely unsuccessful in this endeavor. Frustrated he ascribed all *Zweckmässigkeit* (adaptedness) to teleology. This was, of course, no solution. A widely supported school of evolutionists, for instance, the so-called orthogenesists, invoked teleology to explain all progressive evolutionary phenomena. They believed that in living nature there is an intrinsic striving ("orthogenesis") toward perfection. Here belongs also Lamarck's theory of evolution, and orthogenesis had many followers before the Evolutionary Synthesis. Alas, no evidence for the existence of such a teleological principle could ever be found and the discoveries of genetics and paleontology eventually totally discredited cosmic teleology. For a more detailed discussion of teleology see Mayr (1992).

WHAT IS BIOLOGY?

When we try to answer this question, we find that biology actually consists of two rather different fields, mechanistic (functional) biology and historical biology. *Functional biology* deals with the physiology of all activities of living organisms, particularly with all cellular processes, including those of the genome. These functional processes ultimately can be explained purely mechanistically by chemistry and physics.

The other branch of biology is *historical biology*. A knowledge of history is not needed for the explanation of a purely functional process. However, it is indispensable for the explanation of all aspects of the living world that involve the dimension of historical time—in other words, as we now know, all aspects dealing with evolution. This field is evolutionary biology.

The two fields of biology also differ in the nature of the most frequently asked questions. To be sure in both fields one asks "what?" questions to get the facts needed for further analysis. The most frequently asked question in functional biology, however, is "how?"; in evolutionary biology "why?" is the most frequently asked question. This difference is not complete because in evolutionary biology one also occasionally asks "how" questions—for instance, how do species multiply? Anyhow, as we will see, to obtain its answers, particularly in cases in which experiments are inappropriate, evolutionary biology has developed its own methodology, that of *historical narratives* (tentative scenarios).

To truly appreciate the nature of biology one must know the remarkable difference between these two branches of biology. Indeed, some of the most decisive differences between the physical sciences and biology are true for only one of these branches, for evolutionary biology.

THE EMERGENCE OF MODERN BIOLOGY

The two-hundred-year period from about 1730 to 1930, witnessed a radical change in the conceptual framework of biology. The period from1828 to 1866 was particularly innovative. Within these 38 years, both branches of modern biology—functional and evolutionary biology—were established. Yet biology was still largely ignored by the philosophers of science, from Carnap, Hempel, Nagel, and Popper to Kuhn. Biologists, even though they now rejected vitalism and cosmic teleology, were unhappy with a purely mechanistic (Cartesian) philosophy of biology. But all endeavors to escape from this dilemma—such as, for example, the writings of Jonas, Porcmann, von Uexküll, and several others—invariably invoked some nonmechanical forces that were not acceptable to most biologists. The solution had to satisfy two demands: it had to be completely compatible with the natural laws of the physicists, and no solution was acceptable that would invoke any occult forces. It was not until almost the middle of the twentieth century that it became evident that a solution could not be found by a philosopher who did not have a background in biology. But no such philosopher made the attempt.

It turned out that to develop an autonomous science of biology one had to do two further things. First, one had to undertake a critical analysis of the conceptual framework of the physical sciences. This revealed that some of the basic principles of the physical sciences are simply not applicable to biology. They had to be eliminated and replaced by principles pertinent to biology. Second, it was necessary to investigate whether biology is based on certain additional principles that are inapplicable to inanimate matter. This required a restructuring of the conceptual world of science that was far more fundamental than anyone had imagined at that time. It became apparent that the publication in 1859 of Darwin's *Origin of Species* was really the beginning of an intellectual revolution that ultimately resulted in the establishment of biology as an autonomous science.

PHYSICALIST IDEAS NOT APPLICABLE TO BIOLOGY

Darwin's ideas were particularly important in the discovery that a number of basic concepts of the physical sciences, which up to the middle of the nineteenth century were also widely held by most biologists, are not applicable to biology. I will now discuss four of these basic physicalist concepts for which it had to be demonstrated that they are not applicable to biology before it was realized how different biology is from the physical sciences.

1. ESSENTIALISM (TYPOLOGY). From the Pythagoreans and Plato on, the traditional concept of the diversity of the world was that it consisted of a limited number of sharply delimited and unchanging *eide* or essences. This viewpoint was called typology or essentialism. The seemingly endless variety of phenomena, it was said, actually consisted of a limited number of natural kinds (essences or types), each forming a class. The members of each class were thought to be identical, constant, and sharply separated from the members of any other essence. Therefore, variation was nonessential and accidental. The essentialists illustrated this concept by the

example of the triangle. All triangles have the same fundamental characteristics and are sharply delimited against quadrangles or any other geometric figure. An intermediate between a triangle and a quadrangle is inconceivable.

Typological thinking, therefore, is unable to accommodate variation and has given rise to a misleading conception of human races. Caucasians, Africans, Asians, and Inuits are types for a typologist that differ conspicuously from other human ethnic groups and are sharply separated from them. This mode of thinking leads to racism. Darwin completely rejected typological thinking and instead used an entirely different concept, now called *population thinking*.

2. DETERMINISM. One of the consequences of the acceptance of deterministic Newtonian laws was that it left no room for variation or chance events. The famous French mathematician and physicist Laplace boasted that a complete knowledge of the current world and all its processes would enable him to predict the future to infinity. Even the physicists soon discovered the occurrence of enough randomness and contingencies to refute the validity of Laplace's boast. The refutation of strict determinism and of the possibility of absolute prediction freed the way for the study of variation and of chance phenomena, so important in biology.

3. REDUCTIONISM. Most physicalists were reductionists. They claimed that the problem of the explanation of a system was resolved in principle as soon as the system had been reduced to its smallest components. As soon as one had completed the inventory of these components and had determined the function of each one of them, they claimed, it would be an easy task also to explain everything observed at the higher levels of organization.

4. THE ABSENCE OF UNIVERSAL NATURAL LAWS IN BIOLOGY. The philosophers of logical positivism, and indeed all philosophers with a background in physics and mathematics, base their theories on natural laws, and such theories are therefore usually strictly deterministic. In biology there are also regularities, but various authors (Smart 1963, Beatty 1995) severely question whether these are the same as the natural laws of the physical sciences. There is no consensus yet in the answer to this controversy. Laws certainly play a rather small role in theory construction in biology. The major reason for the lesser importance of laws in biological theory formation is perhaps the greater role played in biological systems by chance and randomness. Other reasons for the small role of laws are the uniqueness of a high percentage of phenomena in living systems as well as the historical nature of events.

Owing to the probabilistic nature of most generalizations in evolutionary biology, it is impossible to apply Popper's method of falsification for theory testing because a particular case of a seeming refutation of a certain law may not be anything but an exception, as are common in biology. Most theories in biology are based not on laws but on concepts. Examples of such concepts are, for instance, selection, speciation, phylogeny, competition, population, imprinting, adaptedness, biodiversity, development, ecosystem, and function.

The inapplicability to biology of these four principles that are so basic in the physical sciences has contributed a great deal to the insight that biology is not the same as physics. To get rid of these inappropriate ideas was the first, and perhaps the hardest, step in developing a sound philosophy of biology.

AUTONOMOUS CHARACTERISTICS OF BIOLOGY

The last step in the development of the autonomy of biology was the discovery of a number of biology-specific concepts or principles.

THE COMPLEXITY OF LIVING SYSTEMS

There are no inanimate systems in the mesocosmos that are even anywhere near as complex as the biological systems of the macromolecules and cells. These systems are rich in emergent properties because forever new groups of properties emerge at every level of integration. An analysis contributes nearly always to a better understanding of these systems, even though reduction in the strict sense of the word is impossible. Biological systems are open systems; the principles of entropy therefore are not applicable. Owing to their complexity, biological systems are richly endowed with capacities such as reproduction, metabolism, replication, regulation, adaptedness, growth, and hierarchical organization. Nothing of the sort exists in the inanimate world.

Another biology-specific concept is that of *evolution*. To be sure, even before Darwin geologists knew about changes on the Earth's surface and cosmologists were aware of the probability of changes in the universe, particularly in the solar system. However, on the whole, the world was seen as something quite constant, something that had not changed since the day of Creation. This view totally changed after the middle of the nineteenth century when science became aware of the comprehensiveness of the evolution of the living world.

The adoption of the concept of the *biopopulation* is responsible for what now seems probably the most fundamental difference between the inanimate and the living world. The inanimate world consists of Plato's classes, essences and types, with the members of each class being identical, and with the seeming variation being "accidental" and therefore irrelevant. In a biopopulation, by contrast, every individual is unique, while the statistical mean value of a population is an abstraction. No two of the six billion humans are the same. Populations as a whole do not differ by their essences but only by statistical mean values. The properties of populations change from generation to generation in a gradual manner. To think of the living world as a set of forever variable populations grading into each other from generation to generation results in a concept of the world that is totally different from that of a typologist. The Newtonian framework of unalterable laws predisposes the physicist to be a typologist, seemingly almost as if by necessity. Darwin introduced population thinking into biology rather casually, and it took a long time before it was realized that this is an entirely different concept from the typological thinking traditional in the physical sciences (Mayr 1959).

Population thinking and populations are not laws but concepts. It is one of the most fundamental differences between biology and the so-called exact sciences that in biology theories usually are based on concepts while in the physical sciences they are based on natural laws. Examples of concepts that became important bases of theories in various branches of biology are territory, female choice, sexual selection, resource, and geographic isolation. And even though, by means of appropriate rewording, some of these concepts can be phrased as laws, they are something entirely different from the Newtonian natural laws.

Furthermore, all biological processes differ in one respect fundamentally from all processes in the inanimate world: they are subject to dual causation. In contrast to purely physical processes, these biological ones are controlled not only by natural laws but also by genetic programs. This duality fully provides a clear demarcation between inanimate and living processes.

The dual causality, however, which is perhaps the most important diagnostic characteristic of biology, is a property of both branches of biology. When I speak of dual causality I am of course not referring to Descartes' distinction of body and soul but rather to the remarkable fact that all living processes obey two causalities. One of them is the natural laws that, together with chance, control completely everything that happens in the world of the exact sciences. The other causality consists of the generic programs that characterize the living world so uniquely. There is not a single phenomenon or a single process in the living world that is not in part controlled by a genetic program contained in the genome. There is not a single activity of any organism that is not affected by such a program. There is nothing comparable to this in the inanimate world. Dual causation, however, is not the only unique property of biology to support the thesis of the autonomy of biology. Indeed it is reinforced by some six or seven additional concepts. I will now discuss some of these.

The most novel and most important concept introduced by Darwin was perhaps that of *natural selection*. Natural selection is a process that is both so simple and so convincing, that it is almost a puzzle why after 1858 it took almost eighty years before it was universally adopted by evolutionists. To be sure, the process has been somewhat modified in the course of time. It is rather a shock for some biologists to learn that natural selection, taken strictly, is not a selection process at all, but rather a process of elimination and differential reproduction. It is the least adapted individuals that in every generation are eliminated first, while those that are better adapted have a greater chance to survive and reproduce.

There has long been a great deal of argument about what is more important, variation or selection? But there is no argument. The production of variation and true selection are inseparable parts of a single process. At the first step, variation is produced by mutation, recombination, and environmental effects, and at the second step the varying phenotypes are sorted by selection. Of course, during sexual selection real selection takes place. Natural selection is the driving force of organic evolution and represents a process quite unknown in inanimate nature. This process enabled Darwin to explain the "design" so important in the arguments of the natural theologians. The fact that all organisms are seemingly so perfectly adapted to each other and to their environment was attributed by the natural theologians to God's perfect design. Darwin, however, showed that it could be equally well, indeed even better, explained by natural selection. This was the decisive refutation of the principle of cosmic teleology.

EVOLUTIONARY BIOLOGY IS A HISTORICAL SCIENCE

It is very different from the exact sciences in its conceptual framework and methodology. It deals, to a large extent, with unique phenomena, such as the extinction of the dinosaurs, the origin of humans, the origin of evolutionary novelties, the explanation of evolutionary trends and rates, and the explanation of organic diversity. There is no way to explain these phenomena by laws. Evolutionary biology tries to find the answer to "why?" questions. Experiments are usually inappropriate for obtaining answers to evolutionary questions. We cannot experiment about the extinction of the dinosaurs or the origin of mankind. With the experiment unavailable for research in historical biology, a remarkable new heuristic method has been introduced, that of *historical narratives*. Just as in much of theory formation, the scientist starts with a conjecture and thoroughly tests it for its validity, so in evolutionary biology the scientist constructs a historical narrative, which is then tested for its explanatory value.

Let me illustrate this method by applying it to the extinction of the dinosaurs, which occurred at the end of the Cretaceous, about sixty-five million years ago. An early explanatory narrative suggested that they had become the victims of a particularly virulent epidemic against which they had been unable to acquire immunity. However, a number of serious objections were raised against this scenario, which was therefore replaced by a new proposal, according to which the extinction had been caused by a climactic catastrophe. Yet, neither climatologists nor geologists were able to find any evidence for such a climatic event and this hypothesis also had to be abandoned. Then, when the physicist Walter Alvarez postulated that the extinction of the dinosaurs had been caused by the consequences of an asteroid impact on earth, all observations fitted this new scenario. The discovery of the impact crater in Yucatan further strengthened the Alvarez theory. No subsequent observations were in conflict with this theory.

The methodology of historical narratives is clearly a methodology of historical sciences. Indeed, evolutionary biology, as a science, in many respects is more similar to the *Geisteswissenschaften*, than to the exact sciences. When drawing the borderline between the exact sciences and the *Geisteswissenschaften*, this line would go right through the middle of biology and attach functional biology to the exact sciences while classifying evolutionary biology with the *Geisteswissenschaften.* This, incidentally, shows the weakness of the old classification of the sciences, which was made by philosophers familiar with the physical sciences and the humanities but ignorant of the existence of biology.

Observation plays as important a role in the physical as in the biological sciences. The experiment is the most frequently used methodology in the physical sciences and in functional biology, while in evolutionary biology the testing of historical narratives and the comparison of a variety of evidence are the most important methods. This methodology is used in the physicalist sciences only in some historical disciplines such as geology and cosmology. The important role of historical narratives in the historical sciences has been almost entirely ignored by philosophers up to now. It is important to point out that comparison is perhaps an even more important and more frequently applied methodology in the biological sciences, from comparative anatomy and comparative physiology to comparative psychology, than in the method of historical narratives. This is also true for molecular biology because comparison is indispensable in most researches in this field. Indeed, much of genomics consists of the comparison of base pair sequences.

CHANCE

The natural laws usually effect a rather deterministic outcome in the physical sciences. Neither natural nor sexual selection guarantees such determinism. Indeed, the outcome of an evolutionary process is usually the result of an interaction of numerous incidental factors. Chance with respect to functional and adaptive outcome is rampant in the production of variation. During meiosis, in the reduction division it governs both crossing-over and the movement of chromosomes. Curiously, it was this chance aspect of natural selection for which this theory was most often criticized. Some of Darwin's contemporaries, for instance the geologist Adam Sedgwick, declared that invoking chance in any explanation was unscientific. Actually, it is precisely the chanciness of variation that is so characteristic of Darwinian evolution. Even today there is still much argument about the role of chance in the evolutionary process. Selection, of course, always has the last word.

HOLISTIC THINKING

Reductionism is the declared philosophy of the physicalists. Reduce everything to the smallest pares, determine the properties of these parts, and you have explained the whole system. However, in a biological system there are so many interactions among the parts—for instance, among the genes of the genotype—that a complete knowledge of the properties of the smallest parts gives necessarily only a partial explanation. Nothing is as characteristic of biological processes as interactions at all levels, among genes of the genotype, between genes and tissues, between cells and other components of the organism, between the organism and its inanimate environment and between different organisms. It is precisely this interaction of parts that gives nature as a whole, or the ecosystem, or the social group, or the organs of a single organism, its most pronounced characteristics. Rejecting the philosophy of reductionism is not an attack on analysis. No complex system can be understood except through careful analysis. However, the interactions of the components must be considered as much as the properties of the isolated components. How the smaller units are organized into larger units is critically important for the particular properties of the larger units. This aspect of organization and the resulting emergent properties are what the reductionists had neglected.

LIMITATION TO THE MESOCOSMOS

As far as their accessibility to the human sense organs is concerned, one can distinguish three worlds. One is the microcosmos or the subatomic world of elementary particles and their combinations, the second is the mesocosmos extending from atoms to galaxies, and the third is the macrocosmos, the world of cosmic dimensions. On the whole, only the mesocosmos is relevant to biology, even though in cellular physiology electrons and protons are sometimes involved. To the best of my knowledge, none of the great discoveries made by physics in the twentieth century has contributed anything to an understanding of the living world.

Observation and comparison are highly important methods also in the humanities, and therefore biology functions as an important bridge between the physicalist sciences and the humanities. The foundation of a philosophy of biology is particularly important for the explanation of mind and consciousness. Evolutionary biology has revealed that in such explanations there is no fundamental difference between humans and animals. Evolutionary thinking and the recognition of the role of chance and of uniqueness are now also appreciated in the humanities.

This explains why all earlier endeavors to construct a philosophy of biology within the conceptual framework of the physical sciences were such failures. Biology, we now realize, is indeed largely an autonomous science and a philosophy of biology must be based primarily on the peculiar characteristics of the living world, recognizing at the same time that this is not in conflict with a strictly physicochemical explanation at the cellular-molecular level [1].

CAN AN AUTONOMOUS BIOLOGY BE UNIFIED WITH PHYSICS?

In the two hundred years after Galileo there was a unified science; it was physics. There was no biology to cause problems. But the comforting belief in a unified science became increasingly more difficult to uphold with the rise of biology. This difficulty was widely appreciated and whole organizations were founded to undertake a unification of science. The way to accomplish this was through reduction. This view was based on the conviction that all tangible phenomena of this world "are based on material processes that are ultimately reducible ... to be laws of physics" (Wilson 1998, p. 266). But this suggestion was based on a faulty analysis of biology, neglecting its autonomous components. Such a reduction would be possible only if all of the theories of biology could be reduced to the theories of physics and molecular biology, but this is impossible. Wilson thought consilience was a mechanism that would make such reduction possible. Indeed he claimed "consilience is the key to unification" (1998, p. 8) and "consilience is to be achieved by reduction to the laws of physics." This is a beautiful dream but none of the autonomous features of biology can possibly be unified with any of the laws of physics. The endeavor of a unification of the sciences is a search for a Fata Morgana. As is said in the vernacular, "you cannot unify apples with oranges."

This conclusion is so important because it has numerous consequences. One of them is that one cannot base a philosophy of biology on the conceptual framework of the physical sciences. Nor can a philosophy of biology be expressed by the explanations of a single branch of biology, let us say molecular biology. Instead, it must be based on the facts and fundamental concepts of the entire living world, as was presented in this paper.

We need a similar analysis of all other sciences and this will permit us to determine what the various sciences have in common. But such analyses, as presented in this paper for biology, have not yet been undertaken for any of the other sciences.

THE IMPORTANCE OF BIOLOGY FOR THE UNDERSTANDING OF HUMANS

Until 1859, there was almost complete consensus that humans are fundamentally different from the remainder of creation. Theologians, philosophers, and scientists completely agreed with each other on this point. Darwin's theory of the descent of all species from common ancestors and its application to humans resulted in a fundamental change. One then realized that the human species is a member of the ape family and is, as such, a legitimate object of scientific research. The consequences of this new insight can be seen in the modern developments of anthropology, behavioral biology, cognitive psychology, and sociobiology.

What was perhaps the most shocking finding was how incredibly similar the human genome is to that of the chimpanzee (Diamond 1992). But precisely the comparison with the chimpanzee has led to a better understanding of humans. For instance, it could no longer be denied that many humans have an inborn tendency for strongly aggressive behavior after one discovered that chimpanzees may also show similar aggressive behavior. Yet, altruism also occurs widely among primates (de Waal 1997) and this ancestry facilitates an understanding of human altruism. Comparisons with primates have revealed that it is entirely justified to investigate humans with the same methods used with animals. Part of the philosophy of humans can therefore by merged with biophilosophy.

ACKNOWLEDGMENT

The text of this article will appear, with slight modifications, in Ernst Mayr (2004), *What Makes Biology Unique?* New York and Cambridge: Cambridge University Press, pp. 21-38.

NOTE

1 For a review of some of the controversies between supporters and opponents of the autonomy of biology, see Mayr (1996).

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