From E. Mayr, Toward a New Philosophy of Biology (Harvard 1988)
Essay One IS BIOLOGY AN AUTONOMOUS SCIENCES

ALL RECENT volumes on the philosophy of biology begin with the question: What is the position of biology in the sciences? "Whether and how biology differs from the other natural sciences ... is the most prominent, obvious, frequently posed, and controversial issue the philosophy of biology faces," according to Rosenberg (1985:13). This battle over the status of biology has been waged between two distinct camps. One claims that biology does *not* differ in principles and methods from the physical sciences, and that further research, particularly in molecular biology, will in time lead to a reduction of all of biology to physics. Ruse (1973), for example, wondered "whether or not we can look forward to the day when biology as an autonomous discipline will vanish." The other camp claims that biology fully merits status as an autonomous science because it differs fundamentally in its subject matter, conceptual framework, and methodology from the physical sciences (Ayala 1968).

Part of the controversy arose from a different interpretation of the word *autonomy*. If one could plot the domains of the physical and biological sciences on a map, one would find a considerable area of overlap, particularly at the molecular level, where the laws of physics and chemistry dominate. Does this argue against autonomy for biology? For those who define autonomy as a complete separation of the two sciences, this important area of overlap refutes the claim for autonomy. Proponents of the opposing viewpoint, on the other hand, point to the equally important areas *not* overlapped by the physical sciences and insist that only **an** autonomous science can adequately study them.

This unfortunate controversy is a product of history. When science reawakened after the Middle Ages, in the work of Galileo and Newton and later Lavoisier, it was almost exclusively a movement **of** the physical sciences. Biology as a discipline was still dormant and did not really come to life until the 1830s and 1840s. For the philosophers, from Bacon and Descartes to Locke and Kant, the physical sciences, and in particular mechanics, were the paradigm of science. The proper way to study the natural world, according to this view, was to define phenomena in terms of movements and forces that obeyed universal laws—that is, laws which were not in any way restricted in time or space nor subject to any exceptions. Such deterministic laws allowed a strict prediction of future events, once the present conditions were understood. The role of chance in natural processes was completely ignored. Consequently, the controlled experiment was considered the only respectable scientific method, whereas observation and comparison were viewed as considerably less scientific.

As everyone was willing to concede, the universality and predictability that seemed to characterize studies of the inanimate world were missing from biology. Because life was restricted to the earth, as far as anyone knew, any statements and generalizations one could make concerning living organisms would seem to be restricted in space and time. To make matters worse, such statements nearly always seemed to have exceptions. Explanations usually were not based on universal laws but rather were pluralistic. In short, the theories of biology violated every canon of "true science," as the philosophers had derived them from the methods and principles of classical physics.

Even after the conceptual framework of physics changed quite fundamentally during the nineteenth and twentieth centuries, a mechanistic approach continued to dominate the philosophy of science. As a result, biology was referred to as a "dirty science," an activity, according to the physicist Ernest Rutherford, not much better than "postage stamp collecting." At best it was a second-class, "provincial" science.

Biologists responded to the claims of the physicists and philosophers in one of three ways. Many of them, particularly those working in physiology and other branches of functional biology, adopted physicalism and attempted to explain all biological processes in terms of movements and forces. Everything was mechanistic, everything was deterministic, and there was no unexplained residue. Jacques Loeb, Carl Ludwig, and Julius Sachs were perhaps the leaders of physicalist biology. As productive as this approach was, particularly in physiology, it left a vast number of phenomena in the living world totally unexplained.

"Other biologists, by contrast, felt that a living organism had some constituent that distinguished it from inert matter. These people were customarily lumped together under the term *vitalists*^ even though, as we shall see, they held widely differing views of what that constituent might be.1

Most biologists, though, simply ignored **the** philosophical problems of “the nature of life” and instead concentrated on making new discoveries and elaborating new theories. The result was the unprecedented flowering of evolutionary biology, ecology, ethology, population genetics, cytology, and many other biological disciplines. Each of these fields had its own terminology, methodology, and conceptual framework, and maintained only a minimal contact with the others or with the physical sciences. The worry spread, particularly among philosophers, that science as a whole would be lost, replaced by a large number of independent individual sciences. To counteract this threat, a movement got under way for the unification of science.

But how was unification to be achieved? There seemed to be two broad possibilities:

(1) To bring all sciences down to the common denominator of the physical sciences; in other words, as it was phrased by certain philosophers, "by reducing all sciences to physics."

(2) To adopt a new, broader concept of science that would fit not only the physical sciences but also the life sciences.

It has become quite clear from the discussion of the modern philosophers of science that the validity of the claim of an autonomy of biology depends entirely on the success of the postulated reduction. What we need, then, is an answer to the question: "Can the phenomena, laws, and concepts of biology be successfully reduced to those of the physical sciences?" If such a reduction is impossible, then the autonomy of biology is, so to speak, automatically established.

The 1960s and early 1970s saw quite a few uncompromising reductionists (Schaffner 1967a,b; Ruse 1973), but their number has dwindled in the last ten years. Only one strict reductionist has come to my attention since 1980. One problem in the reductionist camp was that the term *reduction* was being used by different authors in very different senses. One can distinguish three major kinds of reduction (Mayr 1982:59—63; Ayala 1974; 1977).

(i) The term *constitutive reduction* has been applied to any dissection of phenomena, events, and processes into the constituents of which they are composed. Such analysis is not opposed by the modern biologist, since he does not question that all organic processes can ultimately be reduced to or explained by physico-chemical processes. None of the events and processes encountered in the world of living organisms is in any conflict with a physico-chemical explanation at the level of atoms and molecules. What is controversial are two other kinds of reduction, explanatory reduction and theory reduction.

(2) *Explanatory reduction* claims that all the phenomena and processes at higher hierarchical levels can be explained in terms of the actions and interactions of the components at the lowest hierarchical level. Organicists, by contrast, claim that new properties and capacities *emerge* at higher hierarchical levels and can be explained only in terms of the constituents at those levels. For instance, it would be futile to try to explain the flow of air over the wing of an airplane in terms of elementary particles. Almost any phenomenon studied by a biologist relates to a highly complex system, the components of which are usually several hierarchical levels above the level studied by physical scientists.

(3) Finally, there is *theory reduction*, which postulates that the theories and laws formulated in biology are only special cases of theories and laws formulated in the physical sciences, and that such biological theories can thus be reduced to physical theories. All authors in recent years who have studied this claim, including even several former reductionists, have come to the conclusion that such theory reduction is virtually never successful (Mayr 1982). As a matter of fact, theory reduction has been only partially successful even within the physical sciences, and has been singularly unsuccessful within the biological sciences. Indeed, none of the more complex biological laws has ever been reduced to and explained in terms of the composing single processes (Mainx 1955).

The splendid successes of molecular biology are sometimes cited as evidence for successful reduction, but these cases concern constitutive reduction, and furthermore they are limited almost exclusively to functional biology. Ernest Nagel (1961) was the chief proponent of theory reduction, but most other philosophers of science (Feyerabend, Kuhn, and Kitcher) have vigorously opposed his arguments.

I think it is fair to say that the attempt to unify science by reducing biology to physics has been a failure, as pointed out by Popper (1974), Beckner (1974), Kitcher (1984), and others. Fortunately, changes have taken place in the last several decades in both physics and biology that

will greatly facilitate an eventual unification of the two sciences on a very different, much broader basis.

The changes in the physical sciences involve, among other things, a rejection of the strict determinism of classical physics (Mayr 1985). Scientists now recognize that most physical laws are not universal but are rather statistical in nature, and that prediction therefore can only be probabilistic in most cases. They have also realized that stochastic processes operate throughout the universe, at every level, from subatomic particles to weather systems, to ocean currents, to galaxies. In the study of these processes, observation has been elevated to the status of a valid scientific method wherever the experiment is difficult or impossible to perform, as in meteorology and cosmology. And finally, physicists are beginning to recognize that the development of *concepts* can be as powerful a tool as the formulation of laws in understanding physical phenomena.

The changes in biology were, if anything, even more drastic (Mayr 1985). Physiology lost its position as the exclusive paradigm of biology in 1859 when Darwin established evolutionary biology. When behavioral biology, ecology, population biology, and other branches of modern biology developed, it became even more evident how unsuitable mechanics was as the paradigm of biological science^ At the same time that an exclusively physicalist approach to organisms was being questioned, the influence of the vitalists was also diminishing, as more and more biologists recognized that all processes in living organisms are consistent with the laws of physics and chemistry, and that the differences which do exist between inanimate matter and living organisms are due not to a difference in substrate but rather to a different organization of matter in living systems.

In the eighteenth and nineteenth centuries, the label *vitalist* was attached to anyone who did not accept the mechanist dogma that matter in motion is an adequate explanatory basis for all aspects of life, and that organisms are simply machines. All those who rejected this characterization were united in their belief that a living organism has some sort of constituent by which it can clearly be distinguished from inert matter. Where a controversy arose, however, was in the interpretation of this constituent.

The classical vitalist ascribed life to the organism's possession of a tangible thing, a real object, whether called a vital fluid, life force, or *Entelechie.* He believed that this vital force was outside the realm of physico-chemical laws; in fact, it had a rather metaphysical flavor in the writings of some vitalists. All attempts to substantiate the existence of this force failed, and the need for it became obsolete when the phenomena it had tried to explain were eventually accounted for by other means, for example, the genetic program.

Other biologists agreed with the classical vitalists that organisms have some unique property that exists in every part of the body, one that **is** extinguished by death. They attributed to it everything that distinguishes living bodies from inert matter, particularly the form-giving processes of ontogeny. But these authors rejected the idea that this was a nonmaterial force; rather, they viewed life as an organizational property of certain material systems. In the absence of an appropriate term, some of these authors, like the famous physiologist Johannes Miller, referred to these life-giving properties as *Lebenskraft*, but as Delbruck (1971) pointed out, there is a remarkably close analogy between the postulated properties of the *Lebenskraft* of many authors from Aristotle on and the actual properties of the genetic program (DNA).

This second group of biologists might be best referred to as organicists. In any case, it is quite misleading to attach the label *vitalist* to them. Anyone who does this and insists on the strict matter-in-motion definition of organisms will have to call everybody a vitalist who acknowledges the genetic program. Vitalism has become so disreputable a belief in the last fifty years that no biologist alive today would want to be classified as a vitalist. Still, the remnants of vitalist thinking can be found in the work of Alistair Hardy, Sewall Wright, and Charles Birch, who seem to believe in some sort of nonmaterial principle in organisms.

Vitalistic ideas, curiously, were widespread among certain nonbiologists whose simplistic ideas about the nature of physico-chemical systems forced them into vitalism (Crick 1966). Some of the leaders of quantum mechanics, such as Bohr, Schroedinger, Heisenberg, and Pauli, postulated that someday someone would discover physical laws in organisms that were different from those which operate in inert matter. Indeed, when Max Delbruck switched from physics to biology, one of his original objectives was to discover such laws (Kay 1985).

The Emancipation of Biology

Establishing and substantiating the autonomy of biology has been a slow and painful process. It has meant getting rid not only of standard concepts of physicalism, such as essenrialism and determinism, but also of some metaphysical concepts favored by certain biologists who intuitively felt the separate status of biology but ascribed it to such metaphysical factors as vitalism or teleology. Even today, many attacks against the notion that biology is an independent science concentrate on refuting vitalism, as though this was still part of the conceptual framework of modern biology. That some early autonomists, like Bertalanffy (1949), supported their position with such vague arguments as dynamics, energy gradients, formative movements, and so on did not enhance the credibility of the new movement. Despite these handicaps, the evidence in support of the autonomy of biology has grown exponentially in recent years.

Let me now describe, one by one, some of the fundamental differences between organisms and inert matter.

THE COMPLEXITY OF LIVING SYSTEMS

Living systems are characterized by a remarkably complex organization which endows them with the capacity to respond to external stimuli, to bind or release energy (metabolism), to grow, to differentiate, and to replicate. Biological systems have the further remarkable property that they are open systems, which maintain a steady-state balance in spite of much input and output. This homeostasis is made possible by elaborate feedback mechanisms, unknown in their precision in any inanimate system.

Such complexity has often been singled out as the most characteristic feature of living systems. Actually, complexity in and of itself is not a fundamental difference between organic and inorganic systems. The world's weather system or any galaxy is also a highly complex system. On the average, however, organic systems are more complex by several orders of magnitude than those of inanimate objects. Even at the molecular level, the macromolecules that characterize living beings do not differ in principle from the lower-molecular-weight molecules that are the regular constituents of inanimate nature, but they are much larger and more complex. This complexity endows them with extraordinary properties not found in inert matter.

The complexity of living systems exists at every hierarchical level, from the nucleus, to the cell, to any organ system (kidney, liver, brain), to the individual, to the species, the ecosystem, the society. The hierarchical structure within an individual organism arises from the fact that the entities at one level are compounded into new entities at the next higher level—cells into tissues, tissues into organs, and organs into functional systems.

To be sure, hierarchical organization is not altogether absent in the inanimate world, where elementary particles form atoms, which in turn form molecules, and then crystals, and so on. But order in the inanimate realm is several levels of magnitude below the order of ontogenetic development, as illustrated by the growth of the peacock's tail or the organization of the central nervous system.

Systems at each hierarchical level have two properties. They act as wholes (as though they were a homogeneous entity), and their characteristics cannot be deduced (even in theory) from the most complete knowledge of the components, taken separately or in other combinations^ In other words, when such a system is assembled from its components, new characteristics of the whole emerge that could not have been predicted from a knowledge of the constituents. Such *emergence* of new properties occurs also throughout the inanimate world, but only organisms show such dramatic emergence of new characteristics at every hierarchical level of the system. Indeed, in hierarchically organized biological systems one may even encounter downward causation (Campbell 1974).

ORGANIZATION INTO POPULATIONS

Western thinking for more than 2,000 years after Plato was dominated by essentialism. For Plato and his followers, variable classes of entities consist of imperfect reflections of a fixed number of constant, discontinuous *eide* or essences. This is vividly illustrated by Plato's allegory of the shadows on the cave wall. This concept fits classes of inanimate objects, say the class of chairs or the class of lakes—objects that have no special relation with each other except that they share the same definition (see Essay 20).

In 1859 Darwin introduced the entirely new concept of variable populations composed of unique individuals. For those who have accepted population thinking, the variation from individual to individual within the population is the reality of nature, whereas the mean value (the "type") is only a statistical abstraction. Biopopulations differ fundamentally from classes of inanimate objects not only in their propensity for variation but also in their internal cohesion and their spatio-temporal restriction. There is nothing in -inanimate nature that corresponds to biopopulations, and this perhaps explains why philosophers whose background is in mathematics or physics seem to have such a difficult time understanding this concept (see Essay 20). The ability to make the switch from essentialist thinking to population thinking is what made the theory of evolution through natural selection possible.

The concept of biopopulations also made possible the recognition that there are, in nature, two entirely different kinds of evolution, designated by Lewontin (1983) as developmental (transformational) evolution and variational evolution. Any change in an object or system simply as a result of its intrinsic potential, such as the change of a white star to a red star, is developmental evolution. It is entirely due to the action of teleomaric (physical) processes. By contrast, the evolution of organisms is variational i evolution, and is due to the selection of certain entities from highly *Q* variable populations of unique individuals, and the production of new variation in every generation.

To say that all members of a population are unique does not mean that they differ from one another in every respect. On the contrary, they may agree with one another in most respects, as do conspecific individuals, for instance. Yet each member of a species has a unique constellation of characteristics, some of which are found in no other individual.

Although highly characteristic of the living world, uniqueness is not exclusive to it. Each mountain is unique; so is each weather system, and each planet and star. However, such uniqueness in the inanimate world is limited to complex systems, while the basic building blocks of these systems (elementary particles, atoms, molecules, and crystals) consist of identical components. In the living world, uniqueness is seen even at the molecular level, in the form ofDNA or RNA.

POSSESSION OF A GENETIC PROGRAM

Organisms are unique at the molecular level because they have a mechanism for the storage of historically acquired information, while inanimate matter does not. Perhaps there was an intermediate condition at the time of the origin of life, but for the last three billion years or more this distinction between living and nonliving matter has been complete. All organisms possess a historically evolved genetic program, coded in the DNA of the nucleus (or RNA in some viruses). Nothing comparable exists in the inanimate world, except in man-made machines. The presence of this program gives organisms a peculiar duality, consisting of a genotype and a phenotype. The genotype (unchanged in its components except for *J* occasional mutations) is handed on from generation to generation, but, '• owing to recombination (Essay 6), in ever new variations. In interaction with the environment, the genotype controls the production of the phenotype, that is, the visible organism which we encounter and study.

The genotype (genetic program) is the product of a history that goes back to the origin of life, and thus it incorporates the "experiences" of all ancestors, as Delbruck (1949) said so rightly. It is this which makes organisms historical phenomena. The genotype also endows them with the capacity for goal-directed (teleonomic) processes and activities, a capacity totally absent in the inanimate world.

Since each genetic program is a unique combination of thousands of different genes, the differences among them cannot be expressed in quantitative but qualitative terms. Thus, quality becomes one of the dominant aspects of living organisms and their characteristics. Qualitative differences are particularly obvious when one compares properties and activities of different species, be it their courtship displays, pheromones, niche occupation, or whatever else may characterize a particular species.

COMPARATIVE VERSUS EXPERIMENTAL METHOD

The experiment has traditionally been the primary means of investigation in the physical sciences, and some philosophers have claimed that it is the only legitimate method of science. In fact, since the days of Copernicus and Kepler, observation and comparison have been exceedingly successful methods in such physical sciences as astronomy, geology, oceanography, and meteorology. And in biology, where observation and comparison have always been of paramount importance, experimental methods have been incorporated into the methodological repertory of many originally observational disciplines, including ecology and ethology.

The roles of the experimental and comparative methods in biology can be understood only if one realizes that biology actually consists of two rather different major fields of study. The first is the biology of proximate causations (broadly, functional biology), and the second is the biology of ultimate causations (evolutionary biology; see Essay 2).

There is nothing in the physical sciences that corresponds to the biology of ultimate causations. The claims that the evolution of galaxies or radioactive decay correspond to biological processes are quite erroneous. Evolution in galaxies is transformational, not variational, evolution (Lewontin 1983), and radioactive decay, controlled by physical laws, is a teleomatic process, not a teleonomic one, as claimed by Nagel (1977). 7

Early in the century there was virtually no communication between the two biologies of proximate and ultimate causations. As we have seen, the functional biologists tended to be physicalists and inductionists, accepting only the experiment as the method of science. The evolutionary biologists tended to have an opposite point of view, dependent as they were on observation and comparison. Since then, biologists have realized that functional and evolutionary questions are equally legitimate, even though they may require very different approaches. No biological phenomenon can be fully explained until both sets of causations have been explored.

Broadly speaking, functional biology deals with the decoding of the gerieric program and with the reactions of an organism to its surrounding yworld from the moment of fertilization to the moment of death. Evolutionary biology, on the other hand, deals with the history of genetic programs and the changes that they have undergone since the origin of life. A philosopher who fails to recognize both of these two very important and very different aspects of biology will arrive at conclusions that are at best incomplete, but more likely wrong.

CONCEPTS IN BIOLOGY

The conceptual framework of biology is entirely different from that of the physical sciences and cannot be reduced to it] The role that such biological processes as meiosis, gastrulation, and predation play in the life of an organism cannot be described by reference only to physical laws or chemical reactions, even though physico-chemical principles are operant. The broader processes that these biological concepts describe simply do not exist outside the domain of the living world. Thus, the same event may have entirely different meanings in several different conceptual domains. The courtship of a male animal, for instance, can be described in the language and conceptual framework of the physical sciences (locomotion, energy turnover, metabolic processes, and so on), but it can also be described in the framework of behavioral and reproductive biology. And the latter description and explanation cannot be reduced to theories of the physical sciences. Such biological phenomena as species, competition, mimicry, territory, migration, and hibernation are among the thousands of examples of organismic phenomena for which a purely physical description is at best incomplete if not irrelevant (Mayr 1982:62-63). For a long time concepts were rather neglected in the physical sciences. Their importance, under the name of *themata,* has recently been emphasized by Holton (1973).

LAWS VERSUS THEORIES

There is perhaps no better way to demonstrate the epistemological differences between the physical sciences and organismic biology than to point to the different roles of laws in the two sciences. In classical physics, laws were considered universal, and Popper's falsifiability principle was based on this conception. Up to the end of the nineteenth century, biologists also tended to explain all phenomena and processes as being due to the operation of laws. Darwin's *Origin of Species* refers to laws controlling certain biological processes no fewer than 106 times in 490 pages.

Today, the word *law* is used sparingly, if at all, in most writings about evolution. Generalizations in modern biology tend to be statistical and probabilistic and often have numerous exceptions. Moreover, biological generalizations tend to apply to geographical or otherwise restricted domains. One can generalize from the study of birds, tropical forests, freshwater plankton, or the central nervous system but most of these generalizations have so limited an application that the use of the word *law*, in the sense of the laws of physics, is questionable.

At the same time, some very comprehensive biological *theories* have been formulated concerning the mechanisms of inheritance, the basic processes of evolutionary change, and certain physiological phenomena from the molecular level up to that of organs. These theories of biology "appear comparable in scope, explanatory power, and evidential support to those of the physical sciences," according to Munson (1975:433). Yet every student of biology is impressed by the fact that there is hardly a theory in biology for which some exceptions are not known.

The so-called laws of biology are not the universal laws of classical physics but are simply high-level generalizations. Hence, as Kitcher (ms.) has stated: "There are a number of sciences that proceed extraordinarily well without employing any statements which can uncontroversially be called laws."

\ In the physical sciences it is axiomatic that a given process or condition must be explained by a single law or theory^ In the life sciences, by contrast, various forms of pluralism are frequent^ For instance, a particular adaptation may have been produced by several different evolutionary pathways (Bock 1959). A condition of adapredness of the phenotype of an individual may have been due to a particular response by the norm of reaction—or it may have been strictly determined by the genotype. The response of a complex system is virtually never a strict response to a single extrinsic factor but rather the balanced response to several factors, and the end result of an evolutionary process may be a compromise between several selection forces. In the study of causations the biologist must always be aware of this potential pluralism.

PREDICTION

A belief in universal, deterministic laws implies a belief in absolute prediction. The ability to predict was therefore the classical test of the goodness of an explanation in physics! In biology, the pluralism of causations and solutions makes prediction probabilistic, if it is possible at all! Prediction in the vernacular sense, that is, the foretelling of future events, is as precarious in biology as it is in meteorology and other physical sciences dealing with complex systems (Mayr 1985:49-50)- As Scriven (1959) has pointed out, the ability to predict is not a requirement for the validity of a biological theory.

TELEOLOGY

Since the Greeks, philosophers and theologians have been impressed by the frequency of seemingly end-directed processes in living matter—the growth of an organism from egg to adult, the annual migrations of animals, the perfection of the eye and other organs. The belief that there is a purpose, a predetermined end, in the processes of nature has been referred to as *teleology.* Actually, the term has been applied to four entirely different and independent phenomena, and this has led to considerable confusion (see Essay 3).

Natural selection is not a teleological but a strictly *a posteriori* process (see Essay 6). Adaptedness, as the result of a process of selection, is a condition unknown in the inanimate world. More smoothing and rounding does not make a pebble better adapted for its existence in a riverbed. Snow is not an adaptation of water to cold temperature. But many arctic animals (ptarmigans, snowshoe hares) have adaptations that prevent their feet from sinking into the snow (Mayr 1982:47—52, 69—72). Since adaptedness is a result of the past and not an anticipation of the future, it does not qualify for the epithet "teleological."

The Autonomy of Biology and the Unification of Science

The preceding list of biology's unique characteristics as a science explains why attempts to reduce biology and its theories to physics have been a failure. Does this mean that a unification of science is impossible? Not in the least. All it means is that such a unification cannot be achieved by reducing biology to physics. Rather, we have to search for a new foundation for such a unification.
What should it be? G. G. Simpson (1964) has proposed a somewhat extreme interpretation:

> Insistence that the study of organisms requires principles additional to those of the physical sciences does not imply a dualistic or vitalistic view of nature. Life ... is not thereby necessarily considered as nonphysical or nonmaterial. It is just that living things have been affected for ... billions of years by historical processes. . . . The results of those processes are

> systems different in kind from any nonliving systems and almost incomparably more complicated. They are not for that reason any less material or less physical in nature. The point is that *all* known material processes and explanatory principles apply to organisms, while only a limited number of them apply to nonliving systems. Biology, then, is the science that stands at the center of all science, and it is here, in the field where all the principles of all the sciences are embodied, that science can truly become unified.

We may not need to accept all these sweeping claims. However, Simpson has clearly indicated the direction in which we have to move. I believe that a unification of science is indeed possible if we are willing to expand the concept of science to include the basic principles and concepts of not only the physical but also the biological sciences. Such a new philosophy of science will need to adopt a greatly enlarged vocabulary—one that includes such words as biopopulation, teleonomy, and program. It will have to abandon its loyalty to a rigid essentialism and determinism in favor of a broader recognition of stochastic processes, a pluralism of causes and effects, the hierarchical organization of much of nature, the emergence of unanticipated properties at higher hierarchical levels, the internal cohesion of complex systems, and many other concepts absent from—or at least neglected by—the classical philosophy of science.

Twenty-nine years ago the physicist C. P. Snow vividly described the unbridgeable gap between the physical sciences and the humanities. If biologists, physicists, and philosophers working together can construct a broad-based, unified science that incorporates both the living and the nonliving world, we will have a better base from which to build bridges to the humanities, and some hope of reducing this unfortunate rift in our culture. Paradoxical as it may seem, recognizing the autonomy of biology is the first step toward such a unification and reconciliation.

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