In Defense of Biology

The integrity of biology must be maintained if physics and chemistry are to be properly applied to the problems of life.

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A great deal has been said of late about the flourishing state of biology and its exciting progress toward the solution of basic problems. There would appear to be little need for a defense of biology, zoology, botany, or any other part of the sciences of life.

Certainly much of this is true. Remarkable progress has been made in our understanding of important biological processes: metabolism, photosynthesis, the biosynthesis of macromolecules, the structure of viruses. Yet certain equally fundamental questions that have long been of concern to biologists have firmly resisted the recent winds of progress. We still have but inadequate answers to the questions: What is the cause of speciation? How do cells differentiate? What processes dictate their division, growth, and cessation of growth? How does inheritance control these developmental processes? Obviously, some areas of biology are still making relatively slow progress.

A Divided Science

What distinguishes the slower areas of biology from those which seem to grow by startling jumps ("breakthroughs" in newspaper parlance) and which surround themselves with glamor? The fast-growing fields, which appear to represent the cutting edge of progress in biology, are those in which the biological problem has been reduced to chemical or physical terms. The slower-paced areas are those which have thus far largely resisted this advance. When a biological problem can be restated in molecular terms the enormously powerful insights and instruments of modern chemistry, physics, and engineering can be brought to bear on it. Under such a massive attack, quite rapid and sometimes spectacular discoveries are made.

Of course, there is a more homely way to distinguish between the two types of studies. In the fast-moving fields the laboratories are large and densely packed with expensive electromechanical apparatus, students, and postdoctoral fellows. In the other areas of biology, we see some microscopes (optical, that is), herbarium sheets, and fewer people.

From almost any viewpoint there seems to be a widening gap between the more traditional areas of biology and those which are closely related to modern chemistry and physics.

It is true, of course, that chemistry and physics have come to occupy an increasingly important place in *all* areas of biological research, including the traditional ones. But the levels of application current in the two segments of biology are vastly different. While investigations of the more traditional sort may concern themselves with *p*H or oxygen consumption, really modern biological studies feature semiconductors, charge-transfer complexes, radioisotopes, and information theory.

How well can such a divided science work? Will the very problems that attract the more glamorous laboratories be advanced, in the long run, in circumstances which preclude a close contact with taxonomy, evolution, and morphogenesis?

One view is that this separation is inevitable and healthy—that traditional biology has served its purpose and must now give way to biochemistry and biophysics. A recent review of Isaac Asimov's new book about modern biology states that "For him . . . biology is a system that proceeds from biochemistry to the associated subjects of neurophysiology and genetics. All else, as they used to say of the nonphysical sciences, is stamp collecting." "I happen to agree firmly with Asimov about what is central in science and what is not," the reviewer writes, "and I will defend him to the death against traditionalists who might deplore his not starting with 'Heat, Light, and Sound' or his giving short shrift to 'Natural History'" (*1*).

Having rarely been accused of being a traditionalist, perhaps I may be permitted to disagree with this view.

I believe that the increasing separation between "traditional" and "modern" biology is regrettable. In the narrow view, this process may have unfortunate effects on the number and competence of students in traditional departments of biology, zoology, and botany, and may be reflected in the level of support these departments command both within and without the university. But what is a far more serious matter is the harmful effect on science itself.

Process of Alienation

The view that biology is only an unresolved form of chemistry and physics is not new. Biology has always produced adventitious areas of investigation which quickly lose their contact with the mother science. So long as the chemistry of rubber was poorly understood, the problem of the role of latex in the plant, of its composition and properties, belonged to biology. As soon as chemistry had advanced sufficiently to deal with such a complex substance, the problem was taken over by biochemists, physical chemists, and engineers. Certainly we have gained from this process and our knowledge of rubber is vastly increased. But how much of this new knowledge has been reflected back upon plant biology?

A similar estrangement characterizes the history of research on starch. Classical plant morphologists have produced monumental works on starch grains, which have unique structural organization closely correlated with the plant's specific character. In more recent years an equally impressive body of knowledge about the chemical substances

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extractable from the starch grain—amylose and amylopectin—has accumulated. Moreover, enzymes that synthesize these substances have been isolated. Yet an analysis of the information available from studies of extracts shows that we do not understand how the enzymes could possibly account for the presence together in the starch grain of both amylose and amylopectin in proportions which are under genetic control. Clearly, our attention must now return to the developing starch grain, and we must learn how the enzymes are disposed within it, and how the cellular environment can give rise to a precise correlation between the two paths of biosynthesis that cannot be accounted for in terms of test-tube chemistry. The stage is set for a fascinating marriage between the classical studies of the starch grain and modern starch biochemistry and biophysics. But to my knowledge no proposals have been made, consummation is a distant prospect, and fruitful results are even more remote. Why? I believe that we can blame the unfortunate separation between the classical and the more modern aspects of biology.

I believe that there is some justification for a generalization: as soon as an interesting and important biological problem becomes susceptible to chemical or physical attack, a process of alienation begins, and the question becomes, in the end, lost to biology. But in each case, the purely chemical—or physical—studies run their course and come to the blank wall that still surrounds the intimate events which occur within the *living* cell. The obvious need is to return home to biology. But now the errant science has long forgotten its home, and the mother is too bewildered by its fast-talking offspring to be very happy about welcoming it back into the family.

Clearly, such a course of events cannot go on indefinitely, for there are, after all, only a limited number of substances and processes that can be removed without finally leaving nothing at all behind. So long as this process of alienation affected only the end products of metabolism (such as starch, rubber, or pigments), the parent science suffered some damage but no really lethal blow. But now biochemistry and biophysics have reached deep into the core of biology—to reproduction and inheritance—and the question arises as to how biology will sustain this more penetrating attack.

Biology under Attack

One view of the result of this latest event is readily obtained from the new volume that has already been referred to. The book is a summary of the present state of the biological sciences written for "the intelligent man." It opens with the following sentence: "Modern science has all but wiped out the borderline between life and non-life" (*2*).

Since biology is the science of life, any successful obliteration of the distinction between living things and other forms of matter ends forever the usefulness of biology as a separate science. If the foregoing sentence is even remotely correct, biology is not only under attack; it has been annihilated.

An explanation of the basis for this remarkable assertion is of course necessary, and it will, I believe, reveal that this statement is the crowning and wholly logical conclusion of a series of ideas which have attained considerable approval among scientists.

What evidence is offered in support of this statement? We can begin with Asimov's consideration of that marvelously meaningful problem that has for so long intrigued biologists: At what moment in the history of matter did life appear? The answer given is this: "Then, eventually, must have come the key step—the formation, through chance combinations, of a nucleic acid molecule, capable of inducing replication. That moment marked the beginning of life" (*2*, p. 542).

Why is this so? Because "All of the substances of living matter—enzymes and all the others, whose production is catalyzed by enzymes—depend in the last analysis on DNA" (*2*, p. 535).

Deoxyribonucleic Acid

This story is, of course, well known. The DNA molecule is a code which contains all the information required to specify the inheritable characteristics of the organism. The information is translated into protein structure by a process in which DNA dictates the specificity of protein synthesis. Once the information has been so translated, all of the chemical reactions of the cell —which are wholly determined by the structure of enzyme proteins—have also been specified. Moreover, the genes, which according to biological evidence regulate the inherited characteristics of a species, consist of DNA, and the self-duplication of DNA is the basis of genetics. In sum, DNA is the vehicle for the continuity of life.

All of us have heard this story told at every level of the ladder of scientific discourse, from research papers, through review articles to textbooks and the latest issues of the news magazines. The basic ideas are attractive and widely accepted in the scientific community. Many of us have heard them in the classroom—sometimes from our own lips. And so I must apologize—and hereby do—to our helpful author whom I have rudely represented as leader of an attack in which so many others participate.

But can it be true that the familiar "DNA story" is really an attack on biology? Let us return for a moment to the assertion that "the boundary between life and non-life has all but disappeared," for most of us will agree that, if this statement is not an attack on biology, it is at least a pretty fair insult.

If we agree both that nucleic acid is an encoded form of life, capable of self-duplication, and that it can bring about the translation of its own code into the remaining aspects of life, then it follows that, given a reasonably healthy environment, nucleic acid can indeed create life and perpetuate it. Since it is also indisputable that nucleic acid is a chemical substance, then we must agree (if all this is true) that life is essentially nothing more than an expression of the chemistry of nucleic acid. Following this closely reasoned logic, we end inevitably with the conversion of biology into the chemistry of nucleic acid and its creations.

Is Biology Worth Saving?

Now the problem is more evident. Biology *does* appear to be dwindling, and in need of defense. I believe that in the last decade every academic biologist has begun to feel the realistic effects of the atrophy of biology on the life of his laboratory, his classroom, and his institution. Twenty-five years ago, bright young people eager to conquer the world of science were proud to become biologists, to study *Drosophila* genetics, plant taxonomy, or embryology. Nowadays, a student with a budding interest in genetics often ends up mating strands of DNA rather than fruit flies, and greenhouses are built to grow plants for the purpose of producing viruses. Bright young biologists, if they are good enough, become biochemists and biophysicists.

Biology does seem to be in some need of a defense. But is it worth saving? To be explicit, what I mean is this: Is there any good reason why we should resist the progressive isolation of taxonomy, morphology, physiology, and the rest of the "less exciting" fields from the areas that have apparently been won over to modern chemistry and physics?

I believe that this process should be resisted, not because the traditional fields of biology ought to be protected from the effects of chemistry and physics, but because unless biology itself survives, the great powers of these modern sciences cannot be fully used. I believe, for example, that the proper correlation of physics and biology requires that *the integrity of both sciences* be maintained in the collaborative process.

Part of the argument in support of this view has already been made: that in many instances the pursuit of a purely physical or chemical line of attack runs out of momentum and needs to return to the truly living system.

But the chief argument that I should like to propose is this: Analysis of living systems, based on modern physical and chemical theory, leads to the conclusion that life is unique and that it cannot be reduced to the property of a single substance or of a system less complex than a living cell. I propose to cite several examples of such analyses in order to show that fundamental theories of physics and chemistry support the view that there is, in modern science, no justification for the "obliteration of the boundary between life and non-life."

An interesting case in point is the matter of information theory, which now plays such an important role in proposals regarding the genetic function of DNA. The basic notion is well known: The DNA in the germ cell is supposed to contain in an encoded form all the information required to specify in detail the inheritable features of the adult organism.

Elsasser

Now this question has been given a searching examination by a distinguished physicist, W. M. Elsasser, in his book *The Physical Foundation of Biology* and in a subsequent article (*3*). While space does not permit even an approximate description of Elsasser's work, certain aspects of it can be simply stated. Elsasser points out that from recent advances in computer theory one can set certain fairly precise requirements on the above hypothesis. Two critical requirements are (i) The information content of the amount of DNA present in the germ cell of a complex organism, such as a horse, should greatly exceed that present in the cell of a more simple organism, such as an ameba. (ii) Cells should contain a device for translating the code library contained in the DNA into the biological characters which it determines; computer experience indicates that the translation device ought to be considerably more massive than the library.

The available facts suggest that living things do not meet these requirements: (i) Organisms which must differ considerably in their genetic complexity often have similar cellular DNA contents (*4*), and there is no evidence that the discrepancy can be accounted for by differences in genetic redundancy or in the inertness of some chromosome sections. Conversely, organisms which are nearly identical in genetic complexity may differ considerably in cellular DNA content (*5*). The available evidence does not support the idea of a one-to-one correspondence between genetic information and the information represented by the structure of DNA, or for that matter of any other molecular component of the cell. (ii) No cytologist has discovered a ubiquitous structure, considerably larger than the chromosomes (the code library) which shows evidence of serving as a translator. While recent biochemical evidence suggests possible means whereby DNA-borne information may be translated into genetically effective protein specificity, there is still no sign of a device capable of translating the DNA code into the numerous anatomical features (fingerprints, for example) that are also inherited.

Thus, a strict analysis of the problem of inheritance in accordance with modern information theory leads to the remarkable result that the organism's specificity must be determined, at least in part, by agencies not present in the initial germ cell and certainly not in the DNA alone. Elsasser points out that this view, which can be derived directly from modern physical theory, is identical with a principle already well established in biology—*epigenesis*. This view holds that the fertilized egg begins with a limited amount of specificity, which develops into more detail in progressive, superimposed, stages. Strong evidence from embryology supports this conclusion, and recently some investigators have suggested that certain specific types of inheritance, especially in protozoa, are epigenetic in character (*6*).

These results have an important bearing on the customary ideas about DNA, for they call into question the basic assumption that DNA (or for that matter any other single component of the germ cell) can possibly serve, by itself, as the final arbiter of biological specificity. There are many fascinating questions that arise from these considerations, but these will need to be taken up at another time.

Bohr

Another notable defense of life as something unique and distinct from non-life comes from one of the great physicists of our time, Niels Bohr. Bohr has written several remarkable papers (*7*) about the relation between biology and physics, which have for too long been neglected by biologists and biophysicists alike. One of Bohr's contributions to physics is the theory of complementarity, which holds, for example, that the electron is characterized by both particulate and wave properties, which are nevertheless mutually contradictory (the more precisely the wavelength is defined the less certain we become of the electron's position).

According to Bohr this relationship is an example of a *general* law of complementarity which applies as well to biology. Bohr suggests that complementarity regulates the relationship between two coeval aspects of biological systems: the existence of life in the whole intact cell, and the separate physicochemical events that occur within it. The more precisely we try to determine the internal events of a cell the more likely we are to destroy its life. Bohr concludes: "On this view, the very existence of life must in biology be considered an elementary fact, just as in atomic physics the existence of a quantum of action has to be taken as a basic fact that cannot be derived from ordinary mechanical physics."

Now, no one should conclude from

this statement that the property of life is somehow nonmaterial and innately mysterious. Bohr is not a vitalist. On the contrary, Bohr's principle simply serves as a warning that we cannot study the property of life without retaining it in our experiments. Again, this view raises a host of fascinating questions that we cannot go into here. It is pertinent here only to show that the penetrating insight of modern physical theory reveals certain inconsistencies in the notion that life can be reduced to the chemistry of some special substance.

Hinshelwood

An equally cogent analysis of the problem, this time from the viewpoint of the kinetics of complex chemical systems has been made by one of the founders of that field, Sir Cyril Hinshelwood. He points out that "the view that nucleoproteins are the basis of genes which could ever be self-replicating in isolation and merely in virtue of their structure is probably a dangerous over-simplification. . . . The picture presented is essentially static. The phenomena of growth, adaptation and reproduction need a dynamic one." From a straightforward analysis of the kinetic behavior of the complex metabolic processes of bacterial cells, Hinshelwood suggests an alternative source for the self-regulation of living cells. "The building blocks of the cells, wonderful as they may be as structures, are useless by themselves. Cell function depends upon the rhythm and harmony of their reciprocal actions: the mutual dependence of protein and nucleic acid; the spatial and temporal relations of a host of elementary processes which with their sequences and bifurcations make up the reaction pattern of the cell. A system of mutually dependent parts, each of which performs something like enzymatic functions in relation to another, will, as can easily be shown, in the steady state appear as a whole to be autosynthetic. No individual part need be credited with a new and mysterious virtue by which to duplicate itself" (*8*). In effect, it is Hinshelwood's view that nothing less complex than an entire cell is capable of *self*-duplication.

A True Alliance

These brief descriptions of the views of life developed by Elsasser, Bohr, and Hinshelwood reveal a considerable unanimity, and—what is perhaps more surprising—a remarkable agreement with the biologist's long-held opinion that life is inherently complex and unique. How can we explain this unexpected convergence of conclusions reached, separately, by such different routes as information theory, the theory of complementarity, the physical chemistry of complex systems, and the manifest properties of living things? I believe that what is common—and to some degree unusual—in these physical and chemical views of life is that they are profound. They apply modern physical and chemical theory to the problem of life with the same standards of depth and rigor that are required in the treatment of purely physical and chemical problems. Perhaps I am permitted to generalize: Whether the approach to the problem of life is through physics, through chemistry, or through biology itself, the results are consistent—provided that the analysis is fundamental and thorough.

Perhaps the remedy for the declining fortunes of biology is now clear. Biologists should not regard chemistry or physics as a nemesis but as an ally. If modern physical theory requires that epigenesis govern biological development, and if the cell theory can be deduced from physical chemistry, then physics and chemistry must be regarded as biology's most powerful friends.

If this mutual relationship is to bear fruit there must be a true alliance between real sciences rather than the creation of rootless hybrids. If we allow classical biology to decline, the full powers of modern physics and chemistry cannot be brought to bear on the study of life. I believe that in our university organization we must discover how to combine biology, chemistry, and physics in ways that will retain the integrity of each discipline.

A final point is in order, for the problem of the future of biology, however important to us, does not exist apart from the society in which we live. It appears to me that in the recent applications of science to social problems, there has been an increasing tendency to ignore the facts of life. Too often, we are prepared to expose miles of countryside to substances known chiefly for their power to kill. By the time we have dispersed insecticides, herbicides, fungicides, nematocides, pesticides, and other assorted agents, the adaptive latitude of the ecological environment, which is so vital to the success of plant, beast, and man, may have been fatally restricted. I sometimes think that the difficulties we now face in controlling water, air, and soil pollution, and the undue dissemination of radioactive materials, are the result of a common impression that "the boundary between life and non-life has all but disappeared." In fact, if we do not mend our ways, the statement may, after all, turn out to be true.

I believe that the time has come to restore the science of life. We need to do this for the sake of the science, and for the sake of that which is the goal of all science—the welfare of man (*9*).

References and Notes

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