Complementarity, physics, and biology[1)]

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The views of Niels Bohr on complementarity are examined, both in physics and in other fields. N. Bohr's opinions on the relationship between physics and biology are discussed in detail. It is shown that, over a number of years, Bohr viewed as complementary the study of organisms as atomic-molecular and as integral systems. Subsequently, owing to the development of molecular biology, Bohr rejected the idea of the complementarity in principle of the stated two types of studies. The current status of the physical theory of biological phenomena is examined, and the role of synergetics in this field is noted. The so-called antireductionism is criticized. It is shown that the views of contemporary eminent theoretical biologists reveal them to be unfamiliar with physics. The very important role of physics in the further development of biology and its practical applications is emphasized.

INTRODUCTION

The second half of the 20th century has been marked by the powerful growth of integratism in science, and by the union of a number of its fields and the establishment of new links among them. Of greatest value for contemporary natural science is the penetration of science into foundations of theoretical biology heretofore not considered. This penetration has been governed by the integration of biology, physics, and chemistry. On the one hand, molecular biology has arisen, in which the physics of atoms and molecules could answer a number of questions pertaining to the nature of the fundamental phenomena of life. On the other hand, the physics of dissipative systems, or synergetics, is developing, and has already yielded an overall understanding of the phenomena of life that are governed by the unitary system of the organism, the biocenosis, and the biosphere. Both approaches prove to be closely connected with cybernetics and with information theory.

We shall begin the study of the problem of the interrelation of physics and biology with the views of Niels Bohr. The activity of N. Bohr has to a large extent governed the development of both physics and the philosophy of natural science of our time. N. Bohr was one of the few physicists who paid serious attention to this problem. This is not fortuitous.

The creators of modern science, Einstein, Bohr, Heisenberg, Schrödinger, and Dirac, have been characterized by their striving to solve its most general problems having philosophical significance. Along this path the physicists have been able to do far more than the professional philosophers, as is quite natural. It has fallen to the lot of the philosophers and historians of science primarily to study and make sense of what the physicists have created.

While concerning himself with the general problems of science, Bohr turned to the problem of the relationship between physics and biology. This was more than opportune—the last articles and reports of Bohr on this problem appeared at the initial state of the construction of molecular biology and biocybernetics.

Bohr's turning to biology followed a family tradition. His father Christian Bohr was a major physiologist. When the molecular biologists and biochemists speak of the Bohr effect, they are speaking of the discovery of Christian Bohr of the law of the effect of the pH of the medium on the affinity of hemoglobin for oxygen. Christian Bohr was actively interested in the philosophical, fundamental problems of natural science. In particular, this is indicated by the extensive excerpt from an article by Ch. Bohr given in the article of N. Bohr, "Physical science and the problem of life." [1] Ch. Bohr discusses the meaning and content of the concept of expediency applied in biology.

The studies of Niels Bohr on the relationship between physics and biology are of outstanding interest, just as is all that he created. Here we must bear in mind that Bohr's views on biology varied in line with its rapid development. These changes are *per se* very instructive.

COMPLEMENTARITY

As is widely known, the concept of complementarity takes first place in the philosophy of Niels Bohr. This concept arose as a broad generalization of the discoveries of quantum mechanics. The uncertainty relationships are special cases of complementarity. Bohr speaks "of the existence of relationships of a new type having no analog in classical physics, which it is convenient to denote by the term *complementarity* to stress the fact that in mutually contradictory phenomena we are dealing with differing, but equally real aspects of a unitary, sharply defined complex of information on the objects." [2] Further he discusses noncommutativities of the type

$$\Delta q \cdot \Delta p = \frac{h}{4\pi} .$$

Here Δq and Δp are the errors in determining the coordinate q and the corresponding projection of the momentum p, and h is Planck's constant. These relationships, as well as

$$\Delta \varepsilon \cdot \Delta t = \frac{h}{4\pi}$$

(t is the time, ε the energy) express the complementarity of the space-time (q, t) and dynamic (p, ε) descriptions of microscopic systems.

"The complementary manner of description actually does not imply an arbitrary rejection of the usual requirements imposed on any explanation; on the contrary, it aims at an appropriate dialectic expression of the real conditions of analysis and synthesis in atomic physics." [3]

For Bohr complementarity is an expression of the dialectic inherent in the real work and the knowledge of it. This idea is repeatedly mentioned in the subsequent works of Bohr.

Bohr emphasizes the meaning of the strict, fundamental complementarity in quantum mechanics: "In atomic physics the word "complementarity" is used to characterize the connection between the data that can be obtained under different conditions of experiment and can be interpreted pictorially only on the basis of mutually exclusive concepts." [4] Guided by quantum-mechanical complementarity, Bohr employed thought experiments and subtle and exact arguments to reject Einstein's objections to the incompleteness of quantum mechanics. Further, L. I. Mandel'shtam developed a deep analysis of this problem and confirmed Bohr's concept in five lectures on the foundations of quantum mechanics devoted to the theory of indirect measurements.[6] I had the fortune to hear these lectures, which were given in 1939. They were a revelation. I. E. Tamm, V. A. Fok, M. A. Leontovich, and other first-class physicists heard these lectures, sitting alongside the students.

An extensive interpretation of the concept of complementarity that goes outside the bounds of strict quantum-mechanical theory implies that we face the need of a dual, dialectical description and study in the most varied fields of natural science, in psychology, sociology, and philosophy. We are compelled to employ incompatible, yet mutually complementary concepts. The ultimate reason for complementarity is that we perceive and study the real world and matter, while ourselves being a part of it: "we ourselves are both spectators and actors in the great drama of existence." [7]

Let us study some examples of complementarity having no direct relation to quantum mechanics.

The uncertainty relationships hold in the classical physics of wave phenomena. Mandel'shtam said "The more sharply localized a wave is in space, the less it is monochromatic, and the greater the region that its spectrum covers. This pertains to the distribution of the wave in space. An analogous situation also holds for the time-dependence. A brief pulse—a sharp localization in time—is incompatible with a narrow frequency spectrum, and vice versa. This circumstance is of top-ranking practical importance in radiotelegraphy. By tuning, applying a sharp resonance, we protect ourselves from extraneous stations and interference. The sharper the tuning of the receiver, the less extraneous stations will interfere. Yet such a sharply selective receiver cannot receive brief signals, since a brief signal has a broad spectrum .... Here, in essence, the same relationship plays a role as in the uncertainty principle. Therefore the uncertainty principle can be easily explained to people who know radiotelegraphy." [8]

These words refute Bohr's statement given above on the lack of an analog of the complementarity relationships in classical physics.

Let us explain these statements (see, e.g., Ref. 9).

A plane monochromatic light wave propagating along the x axis can be represented by the formula

$$E = A \sin [2\pi (\nu t - kx)].$$

Here E is the electric field intensity of the wave, ν is the frequency, $k = 1/\lambda$, λ is the wavelength, and A is the amplitude.

In writing this expression we have tacitly assumed that the light wave propagates from infinity to infinity and is characterized throughout its extent by the single frequency ν, the wavelength $\lambda = 1/k$, and the amplitude A. Actually the wave has a beginning and an end in space and in time. A bounded light pulse exists.

Light waves are studied with spectral instruments. Such an instrument is a harmonic analyzer. This means that the prism of the spectrograph (or diffraction grating) resolves the pulse into a continuous set of infinite sinusoids characterized by their values of A, ν, and λ. The pulse is expanded into a Fourier integral. If a wave of infinite extent enters the spectrograph, then a line appears in the spectrum with the frequency ν and the wavelength λ. If a pulse of finite length enters, then a band appears in the spectrum—a continuous set of lines of varying intensity in a certain interval Δk of wave numbers. This is explained by the fact that any light pulse of finite length can be represented by a set of infinite sinusoids of different frequencies, amplitudes, and phases selected so that they interfere with one another in the regions of space where there is no wave and yield the correct pattern in the region Δx occupied by the pulse. One requires a greater number of such sinusoids and the interval Δk will be broader for a shorter pulse, i.e., for smaller Δx. One can show that the condition is satisfied that

$$\Delta x \cdot \Delta k = 1.$$

This is the complementarity relationship. The narrower the interval Δx is, the greater the uncertainty in the value of k, i.e., λ, and vice versa.

Let us perform two experiments on a light pulse. In the first of them we wish to determine exactly the time of passage of the light wave through a given point. To do this we shall record the light wave on a [moving—*translator's* insertion] photographic plate lying in a plane perpendicular to the light ray. If the wave is infinite, $\Delta x \to \infty$, then a dark trace will pass across the entire plate—the trace of the light wave, and its time of passage is uncertain, $\Delta t' \to \infty$. The smaller Δx is, the shorter the trace on the plate and the smaller the time interval Δt. In the second experiment we pass light through the prism of a spectrograph and again photograph the transmitted light, but this time on a stationary plate. As $\Delta x \to \infty$ and $\Delta t \to \infty$, the value of the frequency ν is fully determined, and one observes an infinitely narrow spectral line, $\Delta \nu \to 0$. If the pulse is finite, then as we have said, the line blurs into a band. The second uncertainty relationship holds, i.e., the complementarity

$$\Delta t \cdot \Delta \nu = 1.$$

The physical meaning of these relationships is that, when one uses a harmonic analyzer, the concepts of frequency and wavelength have exact values only for an infinite sinusoidal wave. Quantum mechanics does not figure here.

One can go formally from these classical relationships to quantum-chemical ones by using the de Broglie expression for the wavelength. For a microparticle we have

$$k=\frac{1}{\lambda}=\frac{mv}{h}\equiv\frac{p}{h}.$$

Here m is the mass and v the velocity of the particle. Upon substituting $\Delta k=\Delta p/h$ into the relationship $\Delta x\cdot\Delta k=1$, we obtain

$$\Delta x\cdot\Delta p=h.$$

Analogously, by using the expression for the energy of a quantum

$$\varepsilon=h\nu,$$

we obtain $\Delta\nu=\Delta\varepsilon/h$. The $\Delta\nu\cdot\Delta t=1$ implies that

$$\Delta t\cdot\Delta\varepsilon=h.$$

The presented relationships, which hold for electromagnetic waves serve as a good illustration of the principle of complementarity.

COMPLEMENTARITY OUTSIDE PHYSICS

In Bohr's thought complementarity extends far beyond physics—quantum and classical. These ideas are developed in an article in 1954, "The unity of knowledge." [10] On the meaning of complementarity for understanding biology, we shall carry the theme further. Let us take up some problems of psychology and of culture.

Bohr speaks of the complementarity of intuition and logic, complementarity of art and science, complementarity of thought and action. "All knowledge presents itself within a conceptual framework adapted to account for previous experience, and any such frame may prove too narrow to comprehend new experiences." This holds not only for knowledge, but for understanding and behavior. "An especially striking example, writes Bohr, "is the relationship between situations in which we ponder on the motives for our actions and in which we experience a feeling of volition." Thought and action exist in a relation of complementarity.

Shakespeare understood this well. In the central monologue Hamlet says:

> Thus conscience does make cowards of us all;
> And thus the native hue of resolution
> Is sicklied o'er with the pale cast of thought
> And enterprises of great pith and moment
> With this regard their currents turn awry
> And lose the name of action.

In this sense Hamlet expresses complementarity. Goethe, and Turgenev following him, perceived the tragedy of Hamlet precisely as a tragedy of complementarity—thought and reflection transform a person into a being devoid of will. The artistic expression of this idea is Turgenev's story "Hamlet of the Shchigrovskiĭ District." In the article "Hamlet and Don Quixote" Turgenev speaks in essence of the complementarity of these two great images of world literature: Hamlet embodies thought without action, Don Quixote action without thought.

However, all this is not so simple. Here the theme is not complementarity in principle, but only practical complementarity—this is not physics. Turgenev's concept is not true. Hamlet is an extremely active figure, but he controls his actions with thought. He tests the message of the ghost with a "mousetrap," he sends the informers Rosencrantz and Guildenstern to their deaths, he kills Polonius, thinking that he is killing the king, he does not kill the king while praying, so that he might go to hell rather than purgatory. At last, in the finale he still kills the king. The tragedy of Hamlet does not lie in lack of will, but in the situation of a man with a mind and a heart in a cruel, senseless environment.

Nevertheless Bohr is right on the whole—thought and action exist in a relation of practical complementarity—their unity is dialectical. Faust also understands this dialectic:

> "Tis written: 'In the beginning was the Word!'
> Here now I'm balked! Who will some help afford?
> ....
> The Spirit's helping me! I see now what I need
> And write assured: 'In the beginning was the *Deed*!' [2)]

It turns out that one can choose. Faust chooses action, the deed.

Complementarity also exists between thought and the words that express it:

> Thought uttered is a lie.
> (F. I. Tyutchev)

On the basis of the complementarity concept, Bohr examines the problem of free will. Complete determinism excludes such a freedom. However, "if we attempt to predict what another person will decide to do in a given situation, not only must we strive to know his whole background. . . , but we must realize that what we are ultimately aiming at is to put ourselves in his place. Of course, it is impossible to say whether a person wants to do something because he believes he can, or whether he can because he will . . . ." [10]

Bohr speaks of the complementarity of seriousness and facetiousness, and cursorily discusses the interrelation of science and art. In this regard we shall give a simple example: laughter is complementary to thought. We laugh while looking at a clown's tricks in the circus. But we only need think of why we are laughing that it is no longer funny to us. This pertains to the elementary reaction of laughter: if it is a question of true wit, then analysis can heighten the feeling of humor. This is true for esthetics. A widespread viewpoint is that analysis of the products of art annihilates its direct emotional perception. In othe words, complementarity holds sway. However, this is far from being always true. On a high level of understanding of art, analyzing its creations may not weaken but heighten esthetic emotions.

Complementarity is intrinsic to a certain degree to the change of styles in art. In his time, the eminent art critic H. Wölfflin revealed the fundamental features of the difference between the Renaissance and Baroque periods in painting, sculpture, and architecture.[11] In comparing creations similar in theme of the masters of these styles, Wölfflin pointed out their "complementary" features. They are presented in the following table:

Renaissance	**Baroque**
Linearity	Picturesque quality
Planar solution	Depth
Closed form	Open form
Multiplicity	Unity
Clarity	Unclarity

In fact, a picture cannot be simultaneously linear and picturesque, clear and unclear. This dialectic has its indirect expression also in the change in styles of science.[12]

The literary critic L. M. Lotman writes of the complementarity of two forms of information—specific (objective, complete, based on analysis) and nonspecific (perceived emotionally, directly, and subjectively).[13] These two forms of information enter the brain by different paths.[14,15]

The idea of complementarity in the broad sense of the word serves as the basis for understanding an entire complex of phenomena pertaining to humans, to their creativity, psychology, feeling, and thought. Here, as a rule, complementarity has no rigorous character in principle—this is practical complementarity.

NIELS BOHR ON BIOLOGY

Basing himself on the concept of complementarity, Bohr repeatedly discussed the problem of life and the possibility of physical study of it. In almost every article contained in the book, "Atomic Physics and Human Knowledge," Bohr speaks of this problem.[16] Since Bohr's views changed in line with the development of natural science, it is interesting to examine these articles chronologically—the book of Ref. 16 contains Bohr's lectures and articles published from 1932 to 1959.

The lecture "Light and Life" (1932) notes several fundamental views. First, "the recognition of the essential importance of atomistic features in the mechanism of living organisms is in no way sufficient for a comprehensive explanation of biological phenomena." Second, "the conditions in biological and physical research are not directly comparable, since the necessity of keeping the object of investigation alive imposes a restriction on the former which finds no counterpart in the latter." Third, "the complexity of the material systems with which we are concerned in biology is of a fundamental nature." This implies the fundamental conclusion: "... The very existence of life must in biology be considered as an elementary fact, just as in atomic physics the existence of the quantum of action must be taken as a basic fact that cannot be derived from ordinary mechanical physics."

The lecture "Biology and Atomic Physics" (1937) presents the same ideas in more distinct form. "... proper biological regularities represent laws of nature complementary to those appropriate to the account of the properties of inanimate bodies ... the existence of life itself should be considered, both as regards its definition and observation, as a basic postulate of biology, not susceptible of further analysis, in the same way as the existence of the quantum of action together with the ultimate atomicity of matter forms the elementary basis of atomic physics."

Further, Bohr stresses the incompatibility of his viewpoint with vitalism and mechanistics. He "rejects as irrational all such attempts at introducing some kind of special biological laws inconsistent with well-established physical and chemical regularities ... no result of biological investigation can be unambiguously described otherwise than in terms of physics and chemistry ... ."

As we shall see, these very important views, which Bohr was among the very first to formulate, have been repeatedly distorted. Before Bohr, L. S. Berg had expressed these same views: "There are no miracles in the world: nature works exclusively with the aid of the laws of physics and chemistry." [17,18] Berg was a biologist and his argumentation did not stem from a deep understanding of atomic physics, which was impossible in 1921 when he wrote "Nomogenesis."

In the lecture "The Unity of Knowledge" (1955) Bohr already was fully basing his work on the complementarity principle. "... Any experimental arrangement which would permit control of such functions (biological—M.V.) to the extent demanded for their well-defined description in physical terms would be prohibitive to the free display of life." Complementarity exists "... in which arguments based on the full resources of physical and chemical science, and concepts directly referring to the integrity of the organism transcending the scope of these sciences are practically used in biological research ... . Only by renouncing an explanation of life in the ordinary sense do we gain a possibility of taking into account its characteristics."

In the article "Physical Science and the Problem of Life" (1957), these ideas are developed further. Bohr speaks of the almost unlimited expansion of the applications of physical and chemical ideas in biology, but notes that "an account exhaustive in the sense of quantum physics of all the continually exchanged atoms in the organism not only is infeasible but would obviously require observational conditions incompatible with the display of life."

We note at once that such an "account" is hardly necessary for solving any scientific problem.

Before we relate the change in Bohr's views, let us take up the cited viewpoints.

They have been treated by many as arguments favoring the so-called irreducibility of biology to physics and chemistry. Heitler, one of the major physicists of the epoch, presents Bohr's views as follows.[19] We may enquire whether in a living organism the same laws of physics are valid or not which hold for dead matter. If the answer would be in the affirmative, then a living organism would differ in no essential point from inanimate matter, and no room would be left for the very concept of life.

Evidently Bohr said nothing of the kind. He set no limits on atomic-molecular physics in applications to biology and stressed that, besides physics and chemistry, there is no unequivocal description of biological experimentation. Heitler's conclusion is false. It does not follow in any way from the applicability of the general laws of physics to living organisms that a frog does not differ from the rock that it sits on, and that there is no place for the concept of life. The subsequent development of natural science has shown that the laws of physics operate in biology, but the manifestation or expression of these laws differs from nonliving nature proper.

Heitler further states that, according to Bohr, physical measurements performed on organisms by using x rays, etc., unavoidably kill the organisms—these measurements are incompatible with life. Let us point out in this regard that actually such measurements yield very rich information on life. The discovery of the double helix of DNA performed with x rays answered the biological questions of the reasons for the stability of genes, on the nature of the doubling of chromosomes in cell division, and on the nature of mutations. At present the method of nuclear magnetic resonance is being applied to study living cells and tissues. The number of such examples is unbounded.

In essence Heitler repeats the words of Mephistopheles in Goethe's "Faust" [20]:

Who'll know aught living and describe it well,
Seeks first the spirit to expel.
He then has the component parts in hand
But lacks, alas! the spirit's band.
Encheirisis naturae, Chemistry names it so,
Mocking herself but all unwitting though.[3)]

Encheirisis naturae is the custom of nature, its way of acting.[4)] I bring my own translation of this important excerpt, unfortunately rendered inexactly in the poetic translations of Kholodovskiĭ and Pasternak.

We note in passing that the solution of problems of poetic artistic translation also involve complementarity. An adequate translation preserving all the features of the original is impossible, since the languages differ. In conveying some features of poetry, those he deems most important, the translator unavoidably is imprecise in conveying other features.

Heitler asserts that Bohr spoke of strict complementarity of living and nonliving matter. The very fact of life is incompatible with a detailed knowledge of the atomic and molecular structure of the organism. In other words, a relation of complementarity exists, which can be written provisionally in the form

Atomic structure × Life $\sim$ A constant.

However, as we have seen, Bohr said nothing like this. In the same provisional notation, his statement consists in the following:

Atomic structure × Integrity of the organism $\sim$ Life.

Heitler's vulgarization of Bohr's views is characteristic of the attitude of a number of physicists toward the problem of the connection between physics and biology. It has seemed to many that physics and biology are incompatible. Wigner[21] and Elsasser[22] have declared the existence of specific "biotonic" laws in living nature that contradict quantum mechanics and statistical physics. If one perceives Bohr's views superficially they appear to support these ideas.

The incompatibility of physics and biology apart from any treatment of the principle of complementarity is stated even today by a number of biologists, including major theoreticians like Mayr.[23] These views are presented and criticized below. At the same time, certain philosophers strenuously threaten physicists and biologists with the bogey of the "irreducibility" of the more complex biological form of motion of matter to the simpler physical form. We shall also speak of this below.

At the same time (1944) another founder of quantum mechanics, Erwin Schrödinger, sharply formulated in his book "What is Life?"[24] a set of physical questions pertaining to life and was able to answer them in part. In contrast to Bohr's articles, Schrödinger's book was of pragmatic significance in exerting a direct influence on the development of biology.

THE CHANGE IN NIELS BOHR'S VIEWS

Grandiose events have occurred in the second half of the century in this development. The molecular nature of the gene was discovered, the nature of heredity. In its swift growth, molecular biology has decisively changed our views on fundamental biological phenomena, and this happened owing to the combination of genetics and biochemistry with physics and chemistry.

Bohr, who had attentively traced the development of natural science, understood before many others the need for reexamining his seemingly established views on the relationship between biology and physics.

In the last article of the collection of Ref. 16 entitled "Quantum Physics and Biology" (1959), Bohr's changing views are briefly characterized: "Quite different prospects of gradual elucidation of biological laws based on firmly established principles of atomic physics have arisen in recent years. This has happened owing to the discovery of strikingly stable structures of special function that bear genetic information, and also owing to the ever fuller penetration into processes to which this information is imparted."

The reference is to DNA—deoxyribonuclei acid, the substance of genes. Bohr again stresses the absence of any restrictions on the application of elementary physical and chemical concepts to analyzing biological phenomena. However, owing to the extreme complexity of biological systems, "concepts have found fruitful application in biology that pertain to the behavior of the organism as a whole and *as though* (author's italics) contradict the means of description of the properties of inanimate matter."

In closing Bohr points out that strict quantum-mechanical complementarity has already been taken into account in the applications of chemical kinetics in biology. A "complementary" approach in biology is required only because of the practically inexhaustible complexity of organisms.

Here this "as though" and the fact that Bohr puts the word "complementary" in quotes are characteristic.

I cite my correspondence with Bohr on this problem:

Dear Professor Bohr:

Allow me to ask you some questions in regard to your brilliant book "Atomic Physics and Human Knowledge," which has been recently published in Russian translation.

I am working in the field of molecular physics and polymer physics. In recent years I have been trying to develop some theoretical studies in molecular biophysics. I have employed the Ising model for ferromagnetism as the basis of a statistical-thermodynamic theory of replication of DNA. At present I am writing a book called "Molecules and Life. Introduction to Molecular Biophysics." Naturally it begins with discussing the philosophical question of the relationship between physics and biology. It would be very important to me to know your opinion on the following:

1. The principle of complementarity in quantum mechanics is based on the real properties of microparticles. Can we consider the extreme complexity of organisms as a sufficient basis for establishing a complementarity between biology and physics or between the integrity of an organism and its physicochemical structure? Does the understanding of such a complex system as a whole fall outside the bounds of physics and chemistry?

2. Does the current state of molecular biology indicate a need to consider life to be a primary postulate analogous to the quantum of action? Does the existence of life exclude an explanation of it in the ordinary sense of the word?

3. It seems that, while you spoke of complementarity in principle in biology in the articles written in 1932, 1937, and 1955, in your Bristol lecture in 1959 you had in mind only a practical complementarity devoid of any fundamental character.

4. Do you think that your concept is opposed to Schrödinger's concept ("What is Life?"), which views the already

known principles of physics as sufficient for understanding life? What do you think of Schrödinger's book?

5. Do you consider correct the "epigenetic" viewpoint proposed by Elsasser ("The Physical Foundation of Biology")?

I think that the fundamental qualitative difference between living and nonliving matter and the absence of intermediate cases does not imply any bounds on the physicochemical understanding of physics as a whole in the sense of the principle of complementarity. I cannot agree with Goethe, whose Mephistopheles says:

> Wer will was Lebendigs erkennen und beschreiben,
> Sucht erst den Geist herauszutreiben,
> Dann hat er die Teile in seiner Hand,
> Fehlt, leider! nur das geistige Band.
> *Encheiresin naturae* nennt's die Chemie,
> Spottet ihrer selbst, und weisz nicht wie.

(Translation above.)

At the same time, I quite agree with Barry Commoner, who stresses that one cannot view life simply as the chemistry of DNA and proteins.

I deeply regret that, being in Leningrad, I had no opportunity to meet with you during your recent visit to our country.

I would be very grateful if you could write to me briefly on these problems. Forgive me, please, for disturbing you for this reason.

With deepest respect and best wishes,
Sincerely yours,
M. Vol'kenshteĭn

Leningrad, 6 November 1961

Dear Professor Vol'kenshteĭn:

I wish to thank you for your kind letter of 6 November and beg pardon for not answering it earlier, owing to my absence from Copenhagen.

I have learned with great interest about your studies in molecular biology and your views on the epistemological problems that the existence of life poses. As you know, I have been reflecting on these problems for many years and I know well that certain of my earlier statements created an incorrect impression of my attitude toward them. A more current presentation of my views, which closely correspond to yours, insofar as I can judge, is given in a short lecture at the International Pharmacological Congress in Copenhagen in 1960, and I have attached a reprint.

At present I am working on a more complete presentation of the epistemological problems in physics and biology, and I shall send it to you as soon as it is finished. Of course, I shall be grateful for the information on the development of your studies and for sending any publications on them.

With greetings and best wishes,
Sincerely yours,
Niels Bohr

Copenhagen, 8 December 1961

The 1960 lecture was published in *Uspekhi Fizicheskikh Nauk* in 1962.[25] It speaks of the lack of any retrictions or violations of the principles of thermodynamics in living nature, and of the similarity between living organisms and automatons. At the same time it notes that resources of nature are manifested in life that are far richer than those applied in building machines. Evolution presents a "picture of the results of testing in nature of the vast possibilities of atomic interactions."

Further he says: "In biology the bases for a complementary description do not involve the problems of control over the interaction between the object and the measuring devices, . . . the need for complementarity of description is associated there with the practically inexhaustible complexity of the organism . . . . Thus, as long as the word "life" is retained (whether for reasons of practical or gnosiological order), the dual approach in biology will undoubtedly be retained."

Bohr's last speech, devoted to the relationship of physics and biology on 21 June 1962 at the Institute of Genetics in Cologne, was published posthumously under the title "Light and Life—Again." [26] In this lecture Bohr already does not speak at all of complementarity in biophysics. He stresses that the "formation of all macromolecular structures . . . amounts to substantially irreversible processes that determine the stability of the organism under the conditions imposed by nourishment and respiration." Bohr rejects the previously formulated views, noting that "the problem of biology cannot consist in accounting for the fate of each of the innumerable atoms that constantly or transiently are present in the organism" (cf. the preceding section). Amazement at life persists, but a shift has occurred—we acquire ever deeper understanding of the essence of the processes of vital activity. As examples Bohr cites the study of the structure of muscle, membrane transport in connection with neural activity, and the estimate of the dimensions of the gene based on the study of N. V. Timofeev-Resovskiĭ, Zimmer, and Delbrück.

Thus the complementarity of the atomic-molecular and integral descriptions of life that Bohr had previously asserted no longer exists for Bohr. Complementarity is mentioned only in connection with psychology—the complementarity of thought and feeling. But we as yet know very little about this.

The shift from theoretical to practical complementarity marks a decisive change in Bohr's views. This change happened, unmarked by many—far from everyone became acquainted with Bohr's last two lectures, while his earlier views, which he had repeatedly presented, were widely known. At the same time the incompatibility of biology and physics seems more convincing at first glance than the current views of the physical bases of life, which require special knowledge to understand.

One of the few scientists who has noted the evolution of Bohr's views on biology is V. L. Ginzburg.[27] He emphasizes that Bohr to his last days could change his opinions under the influence of new facts, such as the stated brilliant advances of molecular biology.

Niels Bohr was devoid of any dogmatism. He looked at the world broadly with open eyes and clearly understood all that happens in this world—both in the development of science and in the threats—first of fascism, and then of atomic war (see Ref. 28).

The concept of practical, rather than strict complementarity can arouse no objections.

Complementarity of this type is inherent in any open systems far from equilibrium. In these systems space and time structuring can occur as the result of microscopic fluctuations.

In studying the Bénard structures or the Belousov-Zhabotinskiĭ reaction, a practical complemenarity exists between the atomic-molecular description and the study of the integral system, just as in biology (in this regard see Refs. 29 and 30).

ON "IRREDUCIBILITY"

Statements often figure in the philosophical and parascientific literature in our country on the irreducibility in principle of the complex to the simple, in particular, the irreducibility of biology to physics. Irreducibility is opposed to reductionism—"the concept that asserts the possibility of complete reduction of higher phenomena to lower ones on which they are based.[31] Further it is stated that: "Reductionism is traced in mechanicism, in a tendency to treat psychological phenomena only as the result of physiological, informational, etc., processes, and in the biologicization of phenomena of social life." There is no mention of physics and biology here. The most recent edition of the Philosophical Dictionary does not contain the word "reductionism" at all, but contains the word "reduction." [32]

Without studying the problem as a whole, let us examine the relationship between biology and physics. To do this we must give a rigorous definition of the cited fields of natural science. Biology is the science of living nature. But what is physics?

Physics is the science of concrete forms of matter—substances and fields—and of the forms of existence of matter—space and time (see, e.g., Ref. 33). This definition, to which it is difficult to object, pertains equally to nonliving and living nature. Does this mean that biology is "reduced" to physics, that we have returned to the ancient concept of physics as the universal science (Aristotle)? In no way is this so. The cited definition means only that physics is the final, deep-lying theoretical basis for any field of natural science. The important problem in science consists in finding this basis, and correspondingly, not in "reducing" this field to physics, but in deriving it from physical bases. As applied to biology, such problems as a whole are still far from a solution, although intensified work is being performed along this path. In this regard biology is quite different from chemistry, in which the physical bases have already been established. There is no theoretical chemistry independent of quantum and statistical mechanics, of thermodynamics and kinetics. Evidently this belittles in no way the significance and independence of the great science of chemistry. On the contrary, chemistry has gained the deepest possible substantiation. And one cannot consider this to be reductionism, since physics as a whole is not at all simpler than chemistry, while chemical phenomena are not "higher" as compared with "lower" physical phenomena (cf. Ref. 34).

The relationship between physics and chemistry shows that the concept of irreducibility here has absolutely no content. It is purely speculative and declarative in character and in no way can facilitate the further development of chemistry. On the contrary, people of my generation remember that modern quantum chemistry was refected under the banner of antireductionism, and chemistry was artificially separated from physics (the discussion of electronic resonance in chemistry in 1951).

As I have already said, the situation in biology is completely different. This is natural, since biology deals with extremely complex nonequilibrium systems—with cells, organisms, biocenoses, and the biosphere. Therefore the physical foundations of theoretical biology are just beginning to take shape. We do not possess sufficient biological knowledge to formulate rigorously the corresponding physical problems. For biology this pertains mainly to the problems of evolution and individual development, not to speak of the higher nervous activity. Our knowledge of memory and thinking is far short of the construction of a quantitative physical theory.

Bohr's lectures and articles discussed above were composed in the period of the development of science when molecular biology was rising, whose laws are ultimately governed by atomic-molecular physics and chemistry. Bohr died in 1962 prior to the founding of a new field of physics devoted to the structure and properties of dissipative systems, i.e., open systems far from equilibrium. This field is alternatively called synergetics. Living organisms and associations of them, up to the biosphere as a whole, are dissipative systems. The foundations of the thermodynamics of living organisms were first formulated by E. S. Bauer[35] and analyzed by Schrödinger,[24] according to whose felicitous expression, "the organism feeds on negative entropy." Bauer wrote ". . . Living systems are never in equilibrium and perform continual work against equilibrium at the expense of their free energy." Following these phenomenological statements, the construction began of a general theory of dissipative systems, which we shall take up further.

These thermodynamic concepts and this theory are applicable to organisms precisely as to integral systems. This is physics. Thus Bohr's practical complementarity of studying the organism as an atomic-molecular and as an integral system does not at all imply complementarity of physics and biology. Actually we should consider the practical complementarity of two fields of physics.

Those who have attacked reductionism have repeatedly appealed to Bohr's early views, seeing in them an argument of the "irreducibility" of biology to physics. Here they ignored Bohr's words that "not one result of biological study can be described unambiguously in any other way than on the basis of concepts of physics and chemistry" (see the article "Biology and Atomic Physics" in Ref. 16).

Both Bohr's earlier and later views are completely opposed to vitalism. Bohr never set boundaries to the physical study of life. The subsequent development of science has shown that there are no such boundaries and that physical principles are fixed also in living nature, although their manifestations prove distinctive. Thus, for example, the template synthesis of DNA and RNA requires no new physics to understand it. In this sense the situation in theoretical biology and biophysics differs substantially from that existing at the beginning of the century. The new physics—quantum mechanics and the theory of relativity—arose because classical physics faced limits of applicability. We repeat that no such boundaries can be seen in biology and there is no need to create a new physics.

"Reductionism," physicalization, and mathematicization of biology are perceived by dogmatists as a pernicious heresy. Actually the concept of reductionism here is fully vacuous. The question is not of reductionism, but of integratism of natural science. Science studies the integral material world, its multileveled system. Different levels of study are presented in all fields of natural science. The deep level is always the physical one, and precisely this statement determines the richness of content and significance of the specific levels of study in chemistry and biology and the prospects of developing them further. What is usually called "reductionism" does not imply any "reduction." This is genuine science, beginning with the mechanical theory of circulation of the blood by Harvey and ending with the atomic-molecular theory of the gene that starts with the DNA model of Watson and Crick. On the contrary, the "antireductionist," vitalist approach has always been unconstructive and has hindered the development of science. Lysenko's views started with "antireductionism," although he stated that the ability of a sparrow to hop even in deep cold arose from atomic energy.

The advocates of the so-called irreducibility in natural science are actually deep pessimists who do not believe in the power of science and who gloat in its difficulties. The perception of the world as a set of phenomena separated from one another by impenetrable partitions arises form a highly dismal world outlook.

THEORETICIANS OF BIOLOGY AND PHYSICS

However, one cannot say that the bridges over the deep chasms that separate biology and physics have already been built. The appropriate studies have only begun. Many of the most eminent theoretical biologists who have effectively developed evolutionary biology consider physical approaches to biological problems inadequate and insufficient. In this sense the fundamental monograph of Ernst Mayr, one of the creators of modern evolutionism, in indicative.[23] Mayr's book is distinguised by extreme breadth and depth, and a translation into Russian is very desirable. Yet the views of Mayr and other evolutionists on the relationship between physics and biology require a critical analysis.

It is said at the very beginning of the book that "physical scientists tend to rate biologists on a scale of values depending on the extent to which each biologist has used "laws," measurements, experiments, and other aspects of scientific research that are rated highly in the physical sciences. As a result the judgments on fields of biology made by certain historians of the physical sciences that one may find in that literature are so ludicrous that one can only smile." (Ref. 23, p. 14). Further, Mayr cites the words of Rutherford, who considered that biology resembles a stamp collection (p. 33). In this regard we recall that, in speaking of the classification of spectral lines, certain physicists condescendingly called it zoology. The cited words only indicate that they belonged to physicists who actually had no concept of biology.

The second chapter of Mayr's work, "The place of biology in the sciences and its conceptual structure" is naturally devoted to the relationship between physics and biology. Mayr states that physics is not a suitable standard for science (p. 30). In his opinion, there are no laws at all in biology in the sense in which they figure in physics: "there is only one universal law in biology: All biological laws have exceptions" (p. 8). "When they say that proteins do not translate information back into nucleic acids, molecular biologists consider this a fact, rather than a law" (p. 37). At the same time, he says further, this "fact" finally refuted the inheritance of acquired traits (p. 572).

The discussion of fact and law is evidently unsound. With the same success one can say that conservation of energy in any isolated system is a fact, rather than a law. In essence, Mayr formulates precisely two laws having no exceptions:

Proteins do not translate information into nucleic acids.

Acquired traits are not inherited.

To these laws one can add a multitude of others, in particular, Mendel's laws.

Mayr writes: "The phenomena of life have a much broader scope than the relatively simple phenomena dealt with by physics and chemistry," (p. 52).

"It is just as impossible to include biology in physics as it is to include physics in geometry" (p. 53).

We note that the opposite happened—the theory of relativity included geometry into physics. Apparently Mayr doesn't know of this.

"Theory reduction is a fallacy because it confuses processes and concepts. (p. 62).

"The last twenty-five years have also seen the final emancipation of biology from the physical sciences (p. 131).

Mayr considers that physics and chemistry are useless for the theory of evolution. They are also useless for the theory of individual development:

"One cannot solve these problems without dissecting the systems into their components and yet the destruction of the systems during analysis makes it very difficult to understand the nature of all the interactions and control mechanisms within the systems" (p. 132).

"To a modern reader it is astonishing that such physical scientists as Haughton, Hopkins, and Jenkin thought that by applying the thinking of the physical sciences they could cope with such extra ordinarily complex phenomena unparalleled in the inanimate world, as the evolution of biological systems" (p. 514).

"It was Darwin more than anyone else who showed how greatly theory formation in biology differs in many respects from that of classical physics" (p. 521).

"Only since 1859 (the year of publication of "The Origin of Species"—M. V.) that the biological sciences have begun to emancipate themselves from the dominance of the physical sciences."

There are "many instances where physicalism has had a deleterious effect on developments in biology" (p. 846).

All these statements indicate that Mayr is not acquainted with modern physics. For him physics coincides with its understanding among a number of rather primitive thinkers of the 19th Century (Vogt, Büchner, Moleschott). Mayr quotes the words of Spencer (p. 386):

"Evolution is an integration of matter and concomitant dissipation of motion, during which the matter passes from an indefinite, incoherent homogeneity to a definite coherent heterogeneity . . . ,"

Mayr does not agree with this and considers that Spencer expressed an "inappropriate eigthteenth-century-type physicalistic interpretation of ultimate causations in biological systems, and has nothing to do with real biology."

However, in this dispute Spencer is more correct, as in essence he spoke of the origin of order from chaos, i.e., of processes that are now being studied by synergetics.

Mayr restricts physics and chemistry to the classical atomic-molecular theory. In his work little is said even of molecular biology. As regards the general thermodynamic bases of life (outflow of entropy, i.e., "feeding on negative entropy"; cf. the preceding section), Mayr does not know of them. He also does not know of the influence of the theory of evolution on physics. Boltzmann considered that the 19th Century should be called the century of Darwin. The further development of physics, starting with the second law and its statistical interpretation, led to the study of open systems far from equilibrium, and in recent years has enabled physics to turn to the fundamental views of biology on evolution and ontogenesis. Mayr mentions Schrödinger's book[24] only once, in pointing out that the author created a theory of the organism—an aperiodic crystal—without at all speaking of the true content of this book. At the same time, no theory in this sense exists. Schrödinger called the organism an aperiodic crystal desiring to note that the organism is a solid body devoid of periodicity in the arrangement of atoms and molecules. However, one can invest in these words a more interesting meaning, consisting in the idea that the organism contains a large volume of nonredundant, valuable information.

Thus, in the question of the relation between physics and biology Mayr stands on the ground of a rather primitive antireductionism based on ignorance of modern physics.

The words of Simpson,[36] another eminent evolutionist, are perhaps more interesting.

"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 considered as something nonphysical or nonmaterial. It is just that living things have been affected for upward of two billion years by historical processes . . . . The results of those processes are systems different in kind from any nonliving systems and almost incomparably more complicated . . . . *All* known material processes and explanatory principles apply to organisms, while only a limited number of them apply to nonliving systems . . . . Biology is the science that stands at the center of all science . . ."

The statement of the historicity of all organisms is absolutely correct. However, Simpson formulates two undoubtedly erroneous statements. First, historicity does not contradict physics in any way. Second, far from all known material processes figure in living nature. Organisms constitute fundamentally macroscopic systems (this had been shown already by Schrödinger[24]). Correspondingly, quantum-mechanical concepts are essential only for biologically functioning molecules, but not for organisms or cells as a whole. In biology, at least in darkness, there are no semiconductor phenomena, and all the more, no superconductivity—proteins and nuclein acids are genuine dielectrics. Life does not involve nuclear energy. As regards Simpson's biological patriotism, it is understandable. However, it is not clear what is the center of all sciences. But physics lies in the depth of biology.

Interestingly, neither Simpson nor Mayr has touched on Bohr's views, nor do they employ the concept of complementarity. These major biologists are very far from physics. Their views are presented here, since they are very indicative.

FROM BEING TO BECOMING

Biology differs from ordinary physics in historicity. A living organism traverses a path of individual development and carries a memory of preceding evolution. Any question directed to living nature has an evolutionary sense.

In ordinary physics there is no "memory." We study the structure and properties of the electron, the molecule, and the crystal independently of the history of their origin.

However, what we have said does not mean that there are no historical branches of the physics of nonliving nature. Thus, astrophysics and cosmology are a field ideationally very close to biophysics.

The reasons for the historic development of real systems consist in their nonequilibrium. The state of the system varies as a result of its instability. As we have already said, far from equilibrium microscopic fluctuations can grow to macroscopic magnitudes. A specific space-time order arises that differs from equilibrium. The phenomenological cause of such structuring is the efflux of entropy into the surrounding medium.

Historical physics, which studies the cooperative behavior of nonequilibrium, open systems and the processes of ordering in them, which have the character of phase transitions, constitutes the physics of dissipative systems (Prigogine) or synergetics (Haken). The development of this field marks the transition from studying being to studying becoming, from statics to dynamics. The corresponding approaches to phenomena of nature are universal—they are effective both in cosmology and in biology. It proves possible from unitary standpoints to study the formation of stars and galaxies, radiation from a laser, the onset of periodicity in cirrus clouds, periodic chemical reactions, and processes of biological development and evolution.

The fundamental idea of synergetics is the appearance of order from chaos. An idea of this sort first appeared in natural science in the hypothesis of Kant and Laplace on the origin of the solar system. The basis of theoretical biology—Darwin's theory of evolution—has the same character. An ordered, directed development of the biosphere arises from chaotic, random variability via natural selection.

This new stage of physics has been described now in a number of books and articles (see, in particular, Refs. 29, 30, and 37–41).

The fundamental problems of biology involving the properties and structure of integral biological systems have consequently become the object of studies conducted on the basis of theoretical physics. This pertains to the theory of evolution and to the theory of individual development—ontogenesis.

A view has become somewhat widespread among physicists far from biology that Darwinism is out of date, and that evolutionary theory is in no condition to explain the formation and variety of the biosphere. There would not have been sufficient material or time.

Here it is tacitly assumed that the material for evolution is created only as the result of mutations, whose frequency, i.e., the numbers of mutations per genome per generation are of the order of magnitude from 10^{-4} to 10^{-9}. In other words, these events are very rare. Thus the rate of evolution must be very small, and and it is really not understandable how the modern biosphere could arise in 3.5×10^9 years.

However, these arguments are in error. The number of mutant genotypes in a given population amounts to tens of percent, owing to the recombination of the parent genomes. Evolution does not occur by selection of all variants in each generation. Evolution is directed in the sense that the serious restrictions of the already developed organisms and accessible ways of changing them are imposed on the potentialities of natural selection. No evolution will create a terrestrial vertebrate with a number of extremities not equal to four.

The theory is not yet in a condition to give a quantitative estimate of the time for creating the biosphere, but it is qualitatively evident that there was enough time, given the stated directionality of evolution.

The physical approaches to biological evolution are presented in the book of Ref. 42 and in the articles of Refs. 43–46. In particular, it is shown that species formation can have the character of nonequilibrium phase transition of first or second order. This explains the important laws of the evolutionary process.

Individual development, including morphogenesis, i.e., the formation of a supermolecular cell, tissue, and organismic structure, also has a physical interpretation now (see Ref. 47). In these very complex processes interactions are realized of autocatalytic reactions with the diffusion of functional molecules, and, as is especially important, with mechanochemistry—direct transformations of the free energy of specific chemical reactions into mechanical work. Not so long ago we said that the cell consists of a nucleus and protoplasm. Later, owing to the electron microscope, a heterogeneity of the cellular content was discovered, with the presence in the cytoplasm of a number of complex organelles that perform different functions. The very important structural and dynamic role of the cytoskeleton—systems constructed of proteins resembling muscle proteins—has recently been established.

Owing to physical and chemical studies, we understand now that the organism or the cell amounts to complex "chemical machines" that operate on the basis of subtle diffusion and reaction gradients. In contrast to machines made by human hands, in living nature the transmission, transformation, and reception of signals are molecular and chemical in character. Correspondingly these "machines" contain considerable tolerances and gaps that enable these systems to adopt to changing conditions.

Of course, we are speaking only of general understanding. Facing biophysics, on all levels starting with the molecular, stretches an infinite unexplored territory.

Historical physics is practically complementary to atomic-molecular physics. The complementarity here in essence does not differ from the complementarity of any phenomenological and atomic-molecular aspects of physical phenomena. Of course, the study of one aspect creates no restrictions on studying the other.

Without zoology and botany biology could not exist. The variety of species is very great and their individual features are of direct interest. However the multitude of phenomena has a common fundamental nature. In all organisms the legislative power belongs to the nucleic acids, and the executive power to the proteins. The genetic code is single. To study various problems one can choose the most convenient organisms, but the conclusions drawn in working with them prove universal. Conditioned reflexes have been studied mainly on dogs, nerve-impulse transmission on the nerve fibers (axons) of the squid, muscular contraction of the gastronemius muscles of the frog, the laws of genetics on the fruit fly Drosophila, and then on the intestinal bacterium. I. P. Pavlov built a monument to the dog at Koltushi. With no less justification we could build a monument to the fly and the bacterium.

Physics and chemistry have played the determining role in the creation of molecular biology. The double helix of DNA was discovered in a physical study using x-ray structural analysis. The problem of the genetic code was first formulated by the theoretical physicist G. A. Gamow. The code itself was deciphered by chemical methods.

Correspondingly, in the first stage of development of molecular biology, a close collaboration of physicists and biologists arose, and led to many major advances.

Subsequently molecular biology became ever more "biologicized." It shifted from studying molecules and unicellular structures—bacteria—to supramolecular structures, cells and tissues of multicellular organisms. Genetic engineering and other branches of biotechnology arose. Seemingly physics was no longer needed in this field.

Consequently many biologists, in particular molecular biologists, now have lost interest in physics. Even earlier this interest was mainly platonic—it is harder for a biologist to enter the course of physical ideas than for a physicist to enter the course of biology. But now the gap between physics and biology has appreciably grown—in our country in any case.

At the same time, the further development of any fields of biology besides the purely descriptive ones is impossible without active interaction with physics, and of course, with chemistry. In the prewar period a synthetic theory of evolution arose owing to union of classical Darwinism with genetics. Now the need has become evident of incorporation into this theory of the views of molecular biology, synergetics, information theory, i.e., physics. Theoretical biology urgently needs physicomathematical modeling of the most important biological phenomena and processes—evolution, ontogenesis, cancerogenesis, and immunity. Intensified study is being conducted in all these fields and something has begun to become clear (see, in particular, Refs. 29, 30, nd 42).

The physical bases of theoretical biology were first formulated forty years ago by Schrödinger.[24] In a recent article Max Perutz, who won the Nobel prize for studying the structure of hemoglobin, showed that Schrödinger's ideas were stimulated by the work of the eminent biologist, N. V. Timofeev-Resovskiĭ performed jointly with Delbrück and Zimmer.[48] Perutz's article is titled "Physics and the Riddle of Life." Let us present an important point contained in this article:

"The apparent contradictions between life and the statistical laws of physics can be resolved by invoking a science largely ignored by Schrödinger. That science is chemistry. When Schrödinger wrote "The regular course of events governed by the laws of physics is never the consequence of one well-ordered configuration of atoms, not unless this configuration repeats itself many times," he failed to realize that this is exactly how chemical catalysts work. Given a source of free energy, a well-ordered configuration of atoms in a single molecule of an enzyme catalyst can direct the formation of an ordered sterospecific compound at a rate of 10^3–10^5 molecules per second, thus creating order from disorder at the ultimate expense of solar energy."

Lack of understanding of chemistry—the template catalytic replication of DNA—is characteristic of a later study by Wigner.[21]

The "biologicization" of molecular biology actually demands a further and deeper "physicalization" of it. Modern molecular biology is characterized by a shift from structure to the dynamics of the conformational transformations responsible both for enzymatic catalysis and for the biological functions of nucleic acids. Now a set of delicate physical experimental methods has been developed that enables obtaining the needed information. Broad theoretical studies are being conducted, but there is as yet no genuine physical theory of these phenomena.

Precisely the "physicalization" of molecular biology promises very important practical applications of it. Genetic engineering was created for the preparation of needed proteins by acting on the genome. Thus the intestinal bacterium proves capable of producing insulin and interferon. But studies of the physics of proteins, their evolution, their structure and dynamics must lead to the creation of new proteins that have not yet existed in nature.

Let us repeat in closing the fundamental conclusion from all that we have presented. Physics must be the basis of the future theoretical biology—physics in the broad sense of the words, including both the atomic-molecular treatment and the theory of integral, open systems far from equilibrium. There are no limits, nor are any foreseen, for physical studies of living nature.

1) Reworked and supplemented text of a paper given at the Symposium in Honor of N. Bohr, Pushchino, Moscow Province, October 1985.

2) *Translator's note*: The English translation of Goethe's *Faust* given here is from the translation by George Madison Priest, Covici Friede, New York 1932, lines 1224–1225.

3) See Footnote 2, lines 1236–1237.

4) *Translator's note*: The diverging interpretations of the Graeco-Latin phrase *encheiresin naturae* involve the word *εγχειρησισ* = taking in hand. Some translators have construed *nature* as the direct object of the implied verb *to take in hand*, to yield the translation *manipulation of nature*, as G. M. Priest does in a footnote. M. V. Vol'kenshteĭn (whose own Russian translation parallels Priest's quite closely) here prefers to treat *nature* as the subject of the verb, an interpretation apparently supported by a careful reading of the entire passage.

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[2] N. H. D. Bohr, *ibid.*, p. 393.

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