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Point of View

Over the last century, the theory of evolution has received several strong impulses, such as the transfer from the concept of a static universe to the concept of a developing universe, the development of genetics and the large amount of factual material accumulated by it, the widened knowledge in molecular chemistry and biochemistry, and so on. The most ambitious project is perhaps the creation of the universal theory of evolution. The fundamentals of the modern view on the global evolutionary process that unites the development of living and nonliving matter are presented. The author demonstrates how the systemic approach, the theory of the self-organization of complex systems, and the principle of systemic correspondence make it possible to explain various facts and to overcome ideas that for a long time disturbed scientists, particularly, the view on evolution as determined by incidental events and lacking an internal logic of development.

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The Principle of Systemic Correspondence in Evolutionary Processes

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At present, a new paradigm is developing; it is characterized by a systemic approach to the understanding of evolution and is based on the idea about the unity of matter. This idea rests on the fact that living and nonliving substances are subject to the same physical and chemical regularities [1, 2]. Such a universal understanding of matter and its development opens opportunities for a fundamental generalization of evolutionary processes, making it possible to single out common features and properties of seemingly unrelated phenomena, processes, and characteristics of the behavior of complex systems and offering hope for elaborating a holistic explanation of evolution [3]. Below are the results already obtained—a picture that we can construct using the current knowledge and the existing methodological approaches.

The initiating and organizing origin of evolutionary processes. Energy is a common quantitative measure of the motion and interaction of all forms of matter. Various energy flows integrate all phenomena in the universe and favor the nonequilibrium and irreversibility of numerous natural processes, including life [4]. Nonequilibrium and related irreversibility can be sources of order, correspondence, and an increase in the level of organization. The sensitivity of nonequilibrium states to external impacts can cause the spontaneous "adaptive organization" of a system, prompting its "adaptation" to changes in the environment [5]. It has become clear that energy should be defined as the main driving factor that initiates evolutionary processes.[1] The energy flow passing through a system is a mandatory condition to manifest its inherent capability of self-organization.

By the present day, significant amounts of data have been accumulated concerning self-organizing nonequilibrium systems of different complexity levels, starting from self-organization in inorganic chemical systems, where molecules are compositionally and structurally simple, up to the morphogenesis of living systems with their complex organic molecules [6–8]. Self-organization processes, such as the formation of formally and structurally freakish clouds, whirlwinds, tornadoes, and cyclones, as well as patterns that appear on glass at negative environmental temperatures, emerge under a system's significant departure from equilibrium [9]. The existing data show that, although matter has many degrees of freedom and the spontaneous capability of self-organization, only one of several possible options of the development of this system occurs in each individual situation. For example, at present, in the central part of the Sun, where temperature reaches 10–13 million Kelvin, there are conditions under which helium nuclei can be synthesized from hydrogen (the proton–proton cycle of nuclear reactions), while another cycle, the nitrogen–carbon (CNO cycle), requires higher temperatures close to 20 million Kelvin. Similarly, depending on the pressure and temperature, the same chemical ele-

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[1] It was J.-B. Lamarck, the creator of the first integrated evolutionary theory, who paid attention to the fundamental role of energy in the evolution of living matter. In a number of cases, he attributed complication in the organization of living systems to the action of fluids (for example, caloric and electricity). See Lamarckism, in *The Great Soviet Encyclopedia* (Moscow, 1973), vol. 14, pp. 377–379.

ments can be in different aggregate states: nitrogen under normal conditions is a gas but turns into a liquid at –147°C; oxygen liquefies at –182.9°C and forms crystals, i.e., transforms into the solid state, at –218.7°C.

These examples show that the emergence of new forms and states of matter is predetermined, on the one hand, by matter's spontaneous capability of self-organization and, on the other, by the conditions that play the role of "permissive" conditions for respective processes. Note that the system in which evolutionary processes take place carries the property of the organizing source, manifesting itself in the action of the systemic correspondence principle, which is not violated but is rather fulfilled in the form of prohibition, determining selection rules: a component contradicting the system's functioning principles will be rejected with time.

The principle of systemic correspondence holds in systems in nonequilibrium states. Since life cannot form and persist in the state of thermodynamic equilibrium, we are primarily interested in events occurring in systems in which all processes develop oppositely relative to the growth of entropy.

Living organisms evolve in ecosystems, an important property of which is the presence of branched feedback networks. Feedback can radically change the fate of a fluctuation—a departure from the preferred state. Essential for such influence is the nature of the feedback, whether positive or, vice versa, negative. In the former case, fluctuations grow, and the system can spontaneously transfer to another state. The result of changes under positive feedback can be different: either the baton is passed, and the gradual fixation of a new character, absent in the initial state, (property) occurs, after which the system stabilizes at a new level, or the system's behavior becomes chaotic. Under negative feedback, the system stabilizes [4]. The presence of a negative feedback explains, in particular, stabilization in the evolution of the structure of catalytically active domains in functionally important enzymes and the existence of a universal genetic code. Fluctuations in functionally important codons and their sequences lead to changes in the synthesis of proteins, which, therefore, can lose biological activity, and individuals with anomalous proteins die, suffering the action of the systemic correspondence principle.

The necessity to preserve correspondence to the conditions of an ecosystem is indicated by the fact that a complicated system of control over violations in the DNA structure and function is present in the cell, control taking place at the level of replication. Errors in the course of DNA replications are very rare, the maximal probability of errors in this process being less than 10^{-8} and the real frequency of errors being about 10^{-10}. The high accuracy of information replication is ensured by the DNA-polymerase enzyme complex. The enzymes participating in DNA replication can edit and correct errors. All DNA inaccuracies and defects are subject to reparation; if it is impossible to correct an error, the cell is killed [10]. The above-described control over violations in the DNA structure during replication protects the genome from incidental changes and preserves the correspondence of the biological object to the ecosystem. This mechanism of evolutionary changes makes it possible to explain the coexistence of organisms of different levels of organization in ecosystems, particularly, the presence of crocodiles—the descendants of archosaurs extinct 200 million years ago—in some ecosystems; the 220-million-year persistence of the tuatara, a representative of the very ancient order *Rhynchocephalia*; the presence of the crossopterygian *Latimeria chalumnae* in certain habitats, whose ancestors used to live on our planet 380 million years ago; and, finally, the very widespread *Cyanophyta*, which are prokaryotes often present in deposits the age of which is about 3–3.2 billion years [11, 12]. The presence of 40 similar genes in eukaryotes and eubacteria and 15 similar genes in eukaryotes and archaebacteria [13] is an amazing example of the long existence of functionally universal blocks of genetic systems. We can say that, depending on the systemic "permission," different groups of living organisms evolve according to different clocks, each of which keeps its own time at its own tempo [14].

In studying processes that determine the formation of new forms and states of a system component, it is exceptionally important to account for the environmental factor. It is also necessary to understand that evolutionary changes in matter occur successively: each new state of matter is determined by information contained in the preceding state. Such a "relay-type" character, typical of the process of matter organization complication, reflects the time and direction of evolutionary processes [15] under the decisive role of the presence or absence of correspondence in a system [16].

Independent (parallel) development of similar or identical forms and states of matter. Ultimately, all living systems consist of "nonliving" chemical elements; hence, the formation of chemical elements in the universe can be viewed as the first condition that made the emergence of life possible ("permitted" it). According to the theory of the "hot" universe, created by G. Gamow in the second half of the 1940s, the synthesis of chemical elements was initiated by the Big Bang. At the first stage of its evolution, the universe was filled with hot radiation and matter and was quickly expanding. Since the expansion of the universe, especially at the initial stages, was very fast, the high density and temperature could persist for a very short time. Nucleosynthesis begins at 1 billion degrees Celsius. The subsequent transformations (over ~1–200 s) result in primary nucleosynthesis, leading to a mixture of light nuclei, which, to all appearances, is comprised of two-thirds hydrogen and one-third helium. As the temperature and density of matter decreases, the active phase of nucleosynthesis comes to an end, and the formed hydrogen and helium continue to exist for billions of years while large-scale structures—stars and clusters—are formed. In supernovas, the temperature and density of matter reach values that make possible the formation of heavier nuclei from hydrogen and helium. In the course of thermonuclear synthesis, heavy chemical elements appear (carbon, oxygen, sodium, magnesium, calcium, potassium, and so on), comprising about 2% of the mass of stars and interstellar gas, and this becomes the next permissive condition for the formation of life [17–19].

The same atoms are formed independently at different times and in different parts of the universe. The isotropy of time and space makes events separated from one another by billions of years in time and thousands of megaparsecs in space essentially similar. The homogeneity principle states that the laws of nature do not change with time, and, under similar conditions, we will observe phenomena and processes behaving in an analogous way. Hence, similar or identical forms of matter appear independently of one another everywhere where there exist permissive conditions [4]. This also explains parallel evolution in living nature. In the first half of the 20th century, A.A. Zavarzin discovered the parallel evolution of the same tissues in arthropods and vertebrates [20]. The organ of vision, the eye, emerged independently in different groups of organisms: cnidarians, different types of worms, mollusks, arthropods, and vertebrates. Convincing evidence of the independent formation of the same skeleton can be traced by the example of the structure of shells in protozoa—foraminifera (*Foraminifera*) and cephalopods (*Nautiloida*), as well as in bivalves (*Bivalvia*) and ostracods (*Ostracoda*). Analyzing the structure of genes and the use of synonymous codons shows that cryoprotective proteins formed independently in cods (*Gadidae*), living in the Arctic waters, and in nothothens (*Nototheniidae*), living in the Antarctic [21]. Note that the cryoprotective protein of nothothens was initially a trypsinogen, the precursor of proteases. Other striking examples include the following:

• the radial form of the crown of large plants with a vertical trunk, common for various ecosystems, because it is “permitted” by gravitation, and the torpedo-shaped body of the majority of actively mobile aquatic organisms, which emerged owing to the laws of hydrodynamics;

• the arthropod level of organization, reached independently by a number of unrelated groups of organisms [22];

• the asynchronous and independent formation of reptilian characters in different groups of amphibians and the independent and different formation, in terms of rates, of mammal features in different groups of theriodonts [23];

• the same set of types of phyllotaxis and leaf dissection in various groups of plants, from ferns to higher flowering plants [24]; and

• the structural differentiation of nuclei located in a common cytoplasm, or nuclear dualism, which emerged independently in different protozoa (*Ciliophora* and some groups of *Foraminifera*).

Energy processes in biological systems. The main energy source that hinders the growth of entropy in processes associated with life activity is the flow of solar radiation. Living systems are a type of open stationary-state systems, when the velocity of the substance and energy outflow to the external environment corresponds to the velocity of the substance and energy inflow from the external environment. These processes in biological systems agree with the laws of nonequilibrium thermodynamics, and the stationary state is considered as the most ordered state of an open system, under which the velocity of entropy growth is minimal [5]. A critical factor in ecosystems is the interdependence between different biological species participating in the same or related processes. A classical example of this interdependence is the cycle of carbon and the cycle of oxygen in the biosphere (almost all oxygen participating in it is of biogenic origin).

In communities of heterogeneous organisms, observable are processes of matter, energy, and information exchange, as well as the regeneration of initial substances from exchange products; this is why an individual species cannot exist outside of a community. Note that only fit molecules perform metabolic transformations. Out of many purine and pyrimidine derivatives, only the purines adenine and guanidine and the pyrimidines cytosine and thymine are used as the main structural blocks for DNA. Only 20 out of the 150 amino acids identified in living organisms participate in the creation of proteins. Amino acids are not only structural blocks of protein molecules but also precursors of hormones, alkaloids, porphyrins, pigments, and many other biomolecules. Mononucleotides are used as structural blocks of nucleic acids and as coenzymes and substances responsible for energy accumulation. Being not only structural blocks for biopolymers but also performing simultaneously several functions in living organisms, the few amino acids and mononucleotides determine the universality of metabolic processes in all biological systems [1, 3]. The universality of biochemical processes in biological systems is explained not so much by phylogenetic kinship as by the commonness of trophic levels in ecosystems and correlates with energy purposefulness.

Energy exchange inside a biological system is organized in such a way that not only possible but also thermodynamically impossible reactions take place in it. The permissive conditions in this case are energy-matching processes, when thermodynamically possible reactions give previously accumulated energy to a thermodynamically impossible reaction through a common component. For example, chlorophylls, by catching solar radiation energy and transforming it into chemical energy, accumulate it, becoming biological "creditors," constantly giving energy "loans" for the growth and development of biological systems.

The complication and the threshold nature of the self-organization of biological systems. There are processes in nature that proceed in one direction under any changes. They include complication, the source of which is perhaps nonequilibrium inherent in the universe. The property of living matter to complicate and improve, as well as that of nonliving matter, rests on the transformation of energy flows and obeys the laws of thermodynamics. The vector of evolution is largely determined by the energetically most likely processes, while energy purposefulness requires improving the processes of the transformation of energy input into work, which leads to the formation of complex self-organizing systems. Let us consider how this happens by the example of the extraction of chemical energy from glucose by cells.

Since the atmosphere of the early Earth lacked free oxygen, anaerobic digestion, primarily glycolysis, should be assessed as the simplest form of the biological mechanism that ensures getting energy from nutrients. Meanwhile, only a small part of chemical energy that can potentially be obtained from the glucose molecule is released in the process of glycolysis. The appearance of molecular oxygen in the Earth's atmosphere made it possible to increase the share of energy extracted from glucose at the expense of respiration—a process more complicated than glycolysis: under respiration, glucose can fully be oxidized to CO_2 and H_2O with a much higher release of energy [1].

An important characteristic of the structure of matter and processes of its development is discreteness. The surrounding world consists of discrete objects: many millions of galaxies and many billions of stars at the level of the megaworld; the diversity of elementary particles of the microworld; and molecules and atoms, which constitute objects of the macroworld. Many changes are discrete, leading to the absence of a limiting real stabilization of the system in which various processes are characterized by discontinuity and having positive and negative feedback [4]. At each stage of the self-complication and self-improvement of living systems, a certain critical point may be reached, when even insignificant events can cause a spasmodic transition of a system to a new state. The most complicated systems turn out to be the most dependent in this situation because it is impossible to perform a spasmodic adjustment of a complex component to new, discretely (from event to event) occurring changes in the ecosystem. This explains the threshold nature of self-organization in living systems—one of the factors that has predetermined the extinction of various species of organisms during the history of the Earth.

Are evolutionary changes random or regular? If we present the evolution of matter as the formation of an hierarchical system, where the properties of a subsequent form are predetermined by those of the previous ones and the processes of development obey the same laws, we can consider the evolution of the living and nonliving as a continual succession of changes [25].

The scheme of evolution that explains the formation of new biological species as a probabilistic process has been reviewed in recent years. The colossal amount of data accumulated by natural science thus far has opened prospects for studying processes that predetermine the emergence of new forms of life. The analysis of the results of modern genetic studies [26] shows the ability of an organism to change or, vice versa, to preserve its genome practically unchanged depending on the state of the environment. The mechanisms underlying these processes include the following:

• the epigenetic variability, i.e., the ability of the cell to switch purposefully from one inheritable program of functioning to another under the influence of the metabolic situation;

• the presence of a complex system in the cell, controlling violations in the structure, which occurs at the level of the replication of the DNA function;

• the ability of genetic elements of multiplication inside the genome, owing to which it can change qualitatively;

• the amplification restructurings of the genome, during which additional genome copies are formed, the gene amplifying not in isolation but rather within chromosome segments that sometimes include several million DNA bases (the amplified portions can remain in the initial chromosome or form minichromosomes and extranuclear cytoplasmic plasmids, which, in turn, can embed again into the initial or other chromosomes);

• mobile genetic elements, emerging in a number of cases simultaneously in many individuals and creating new constructions, which initiate the reorganization of the genome and play a special role in evolution, affect the diversity of organisms;

• transduction (horizontal gene transfer), which, under natural conditions, causes the transformation of the genome and is widely used in genetic engineering;

• symbiogenesis, i.e., the origin of mitochondria and chloroplasts in eukaryotes; and

• the modularity of genome organization, which makes it possible to obtain quickly new constructions, creating colossal possibilities to regulate gene ensembles.

A functioning genome is a complex of matrix systems in which the information flows in two directions: from nucleic acids to proteins and from proteins to nucleic acids. Change in conditions initiates genome self-organization. Self-organizing systems can correct their behavior proceeding from the previous experience [6, 7]. These processes cannot be attributed to random events, just like any other observable process, because, recognizing the possibility of pure chance, we cannot formulate laws and form generalizations about its character or verify experimentally conclusions and assumptions. At the same time, an accidental event and a statistically random event are two perfectly different notions. The evolutionary continuity of prebiotic (chemical) and biotic evolution cannot be implemented through a series of random events: such an idea is beyond both mathematical and philosophical criticism. Physical and chemical laws also require calling the sequence executing the evolutionary continuity principle only a sequence of probable events. The problem of the absurdly small probability of the emergence of new species, which manifests itself if evolutionary variations are determined by a series of random events, is overcome when we recognize that self-organization plays the role of a fundamental property of the universe and a leading factor in the evolution of matter. The explanation of the emergence of new biological forms, based on probabilistic processes, becomes unobvious.

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Living organisms and nonliving nature obey the same conceptual laws of physics and chemistry, and none of the regularities established in these areas bans the development of living systems. The modern picture of the world, based on nonequilibrium, nonlinearity, and the existence of irreversible processes and feedbacks, makes it possible to describe uniformly the living and nonliving and to create an integrated theory of evolution. The formation of life is a natural stage in the development of nature, which comes after the stages of the formation of the first elementary particles and then the atoms of hydrogen, helium, carbon, oxygen, and so on. Hence, the emergence of life on Earth should not be viewed as a unique event [27].

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