

## On the Possibility of Physical Self-Organization of Biological and Ecological Systems

V. G. Gorshkov and A. M. Makar'eva

Presented by Academician K. Ya. Kondrat'ev August 1, 2000

Received September 18, 2000

It is well known that closed systems tend to attain a stable state with the minimum degree of orderliness (maximum entropy, which is the measure of the disorder or randomness of the system). According to the second law of thermodynamics, entropy increases during a spontaneous irreversible process. Therefore, the processes of spontaneous ordering (entropy decrease) are prohibited in closed systems. In contrast to closed systems, open systems exposed to flows of external energy are able to increase their orderliness. These processes are called physical self-organization.

The nonequilibrium states of physical systems with stored potential energy are capable of generating intense avalanche-like ordered processes, which are induced by the systems' tendency toward an equilibrium state. In addition to true avalanches (i.e., landslide movement of large mass of rock debris or snow) formed as a result of accumulation of gravitational energy in mountains, these processes also include cyclones, tornadoes, earthquakes, etc. The power of cyclones and tornadoes is determined by the condensation energy of water vapors accumulated in the preceding processes of long-term evaporation of water. Earthquakes are caused by the sudden release of the deformation strain energy stored within some limited region of the rocks of the Earth. The nonequilibrium states of some physical systems with stored potential energy are collectively known as states with self-organized criticality [1, 2].

Strict coordination of the newly formed level of orderliness with the magnitude and pattern of the external flow of energy is a typical feature of the state of physical self-organization. If a system with physical self-organization is exposed to external flows of energy, this gives rise to a rigorously defined distribution over the possible states of physical self-organization. For example, the number and size of vortices (whirlpools) in rivers with turbulent water flow are determined by the power of the water flow. Moreover, the character,

probability of implementation, and specific features of the ordered states generated as a result of decay of an initial physical state with self-organized criticality are entirely determined by the character and specific features of the potential energy of the initial state.

All newly appearing ordered physical states in self-organized physical systems undergo continuous decay, with the energy of their orderliness being dissipated. To conserve the ordered physical states in a given external energy flow, new ordered structures should be continuously generated in place of the decayed ones. Once the energy supply has been ceased (or the accumulated potential energy has been dissipated), the self-organized states decay. As a result, the system gradually turns into the state with the maximum disorder. In this case, the term "self-organization" is inadequate to the processes in the physical systems. Indeed, the organization of these systems is determined by the character and magnitude of external flows of energy, rather than by the processes of self-organization.

The processes of physical self-organization and decay of states with self-organized criticality are described by nonlinear equations of physical kinetics [2, 3]. Many researchers believe that similar approach can be applied to the mathematical description of biological evolution and many characteristics of ecological and biological systems [4–6]. The goal of this work was to determine whether there are features of fundamental difference between organization of physical systems and biological (ecological) systems.

The degree of orderliness of all physical systems in natural external flows of energy is characterized by macroscopic degrees of freedom (e.g., the number of vortices in a turbulent flow of liquid or air). Each degree of freedom is described by a discrete measurable parameter (e.g., the size of turbulent vortex, the speed of rotation, etc.). Given that the resolving power of any measurement is finite, the number of all possible values of any degree of freedom is limited.

The degree of orderliness (information content) of a system is proportional to the number of the degrees of freedom of the system, the measurable characteristics of the degrees of freedom being determined uniquely. Thus, the maximum possible degree of orderliness

(information) with a logarithmic accuracy can be determined by the number of the degrees of freedom of the system (number of information memory cells) [7]. It should be noted that the total number of the possible states of a system with  $N$  degrees of freedom and  $k$  possible values of the measurable characteristics of each degree of freedom can be calculated as  $k^N = 2^{N \log_2 k}$ . Therefore, the information content of the system in which the measurable characteristics are known for each degree of freedom is calculated as  $N \log_2 k$  if all values of the measurable characteristic are equiprobable and as  $-N \sum_{i=1}^k \omega_i \log_2 \omega_i$  provided that the probabilities  $\omega_i$  of the  $k$  values are different.

It should also be noted that appearance of macroscopic degrees of freedom in flows of external energy gives rise to two possible effects. First, the system may be subjected to temporary *stochastization* against the background of a relatively equiprobable distribution of the general state of the system over all possible physical states in each newly emerging degree of freedom. Second, the system undergoes *organization*, if the distribution over certain degrees of freedom is the most probable. Once the flow of external energy has been ceased, the macroscopic memory cells of the physical system disappear, together with the opportunities of stochastization and organization of the system. Similarly, thermodynamic entropy tends to zero as temperature approaches absolute zero. The physical system in this case changes into the ground state, which contains the sole memory cell and the only physical state of the cell. Therefore, the information content of the system is zero [7].

In the presence of maximum flows of external energy, the degrees of freedom of the self-organized physical state are macroscopic and their density per unit macroscopic volume is limited.

This can be illustrated by a relatively simple example of a system with a turbulent flow of liquid or gas remote from the solid walls of the system. The number of degrees of freedom (memory cells) of the system is determined by the number of vortices, in which the energy of matter rotation is dissipated [8, 9]. The dependence of the density of the number of the degrees of freedom ( $n$ ) on the energy power density ( $\epsilon$ ) per air mass unit can be derived from the Kholmogorov–Obukhov law [8] as

$$\ln \frac{n}{n_0} = \frac{3}{4} \ln \frac{\epsilon}{\epsilon_{cr}}, \quad (1)$$

where  $n_0 = 1 \text{ m}^{-3}$ ;  $\epsilon_{cr} = 10^{-3} \text{ W/kg}$  is the critical energy density corresponding to the appearance of flow turbulence (figure).

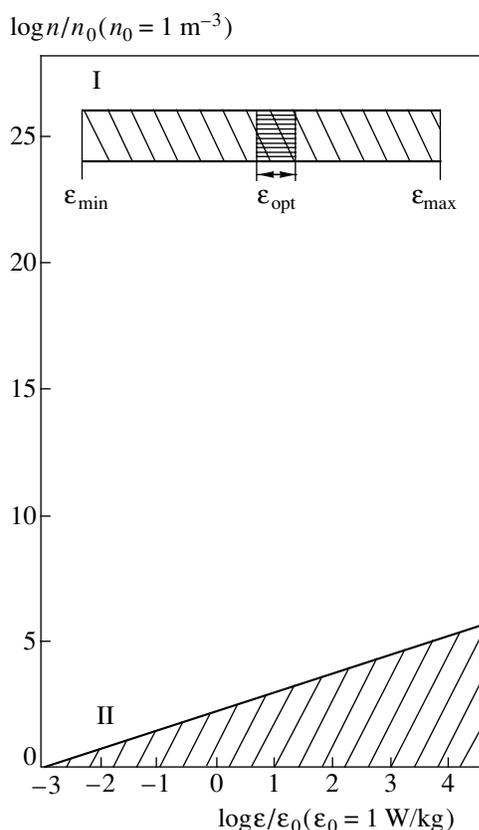
It was assumed that turbulence was absent at air flow rates below 1 m/s (in a boundary atmosphere layer  $l \sim 1 \text{ km}$ , this corresponds to the Reynolds number

$Re \leq 10^4$  [8]). Movement of natural bulk air, like any other ordered process in natural environment, is characterized by lower rates. Therefore, the number of the degrees of freedom in these systems is several orders of magnitude smaller.

In contrast to physical ordered systems, ordering of biological systems is characterized by molecular rather than macroscopic degrees of freedom (memory cells). The number of molecular degrees of freedom is determined by the number of nucleotide pairs ( $np$ ) in the DNA molecules encoding the living-cell functions. The density of the molecular degrees of freedom is higher than  $10^{24}/\text{m}^3$ , because the average value of  $np$  in the DNA molecules of one procaryotic or eucaryotic cell is  $10^6$  or  $10^9$ – $10^{11}$ , respectively [10], whereas the number of cells per  $1 \text{ m}^3$  of metabolically active biomass of procaryotic or eucaryotic organisms is  $10^{18}$  or  $10^{15}$ , respectively [11]. Therefore, there is an enormous gap between the quantitative characteristics of organization of physical and biological (ecological) systems (figure). Quantitatively, this gap is larger than  $10^{20}$ . Therefore, none of environmental factors or changes in physical flows is able to increase the existent degree of biological and ecological ordering.

It has been known since the Pasteur time that spontaneous generation, i.e., the hypothetical process by which living organisms develop from nonliving matter (abiogenesis) is impossible under any conditions. Experimental studies on spontaneous generation have been given up at about the same time as the attempts to invent a perpetual motion machine have been completely abandoned. The orderliness of an organism of any species is maintained throughout the entire period of its existence (millions of years). This orderliness is supported at the expense of internal processes of competitive interaction between individual species in population and elimination of noncompetitive specimens in the course of natural selection. The progeny of the specimens with high orderliness (competitive specimens) fills the resulting population vacancies.

Competitive interaction, stabilizing selection, and reproduction of normal specimens are energy-consuming processes. Therefore, living systems take up energy from the environment. However, the energy uptake by living systems differs fundamentally from the energy uptake by ordered physical systems. Ordering of physical self-organized systems is determined by the characteristics of dissipated energy flows. This orderliness is generated and supported only if energy is supplied to the system. Once the energy supply is ceased, the system immediately becomes disordered. In contrast to physical orderliness, genetic orderliness of organisms of any species decays in the absence of competitive interaction and stabilizing selection even if the energy supply (food flow) is available and specimens continue to reproduce. Besides, in contrast to stabilization of self-organized physical states, the processes of competitive interaction, selection, and reproduction of speci-



Dependence of organization of physical and living systems on the density of energy absorbed by the system. Ordinate is the common logarithm of density of memory cells (degrees of freedom) per unit volume ( $\text{m}^3$ ) of physical systems (II) and unit of metabolically active volume ( $\text{m}^3$ ) of biological (ecological) systems (I). Abscissa is the common logarithm of the external energy power  $\epsilon$  consumed by the unit mass of the system ( $\text{W/kg} = \text{m}^2/\text{s}^3$ ). Areas corresponding to physical (II) and biological (I) organized systems are hatched.  $\epsilon_{\min}$  is the observed minimum of metabolic power;  $\epsilon_{\max}$  is the observed maximum of metabolic power.

mens in biological populations are independent on the characteristics of external energy flows (food). The level of organization of living systems themselves determines these processes. For example, the range of metabolic power of energy consumption is about the same in all living systems (from  $5 \times 10^{-3}$  to  $7 \times 10^3$   $\text{W/kg}$  [12]) regardless of the amount of genetic information (genome size) (figure). Therefore, the level of genetic orderliness of organisms does not depend on the food consumption by the organisms.

The slanting line in the figure shows the dependence of the density of the number of turbulent degrees of freedom (turbulent vortices) of bulk air on the energy power density per unit air mass  $\epsilon$  (Eq. (1)). According to our estimates, characteristics of other natural physical self-organized processes in natural environment fall within the hatched triangle shown in the figure. Noted that, if we continue the slanting line of physical self-organization to the right, it will reach the orderliness

values typical of living systems only at the energy densities larger than  $10^{32}$   $\text{W/kg}$ . It is obvious that none of molecular structures required for the origin of life is able to withstand such a large energy density.

The processes of evolution are based on genetic mutations and natural selection of specimens in populations of biological and ecological systems. These are true processes of self-organization, which do not depend on external flows of energy. Therefore, the non-linear equations of physical self-organization considered above fail to describe true biological self-organization (i.e., evolution). These equations also fail to describe the existing organization of biological and ecological systems (i.e., the organization that has emerged during biological evolution). These statements are true for any level of organization of living objects (from cells to multicellular organisms and ecological communities).

The changes in the state of physical systems associated with changes in the probability of distribution between the finite physically ordered states are fully determined by the characteristics of the effects induced in the system by external energy. In contrast, changes in biological orderliness are induced by spontaneous mutations. Therefore, these changes are random and independent on changes in flows of food. Decay of states of the physical self-organized criticality gives rise to the processes similar to those observed as a result of degeneration (pathology) of states of biological self-organization. However, the *degeneration* processes are unrelated to the increase in the level of organization of biological systems.

The life on Earth is exposed to an external flow of solar energy and consumes this energy. Although this energy supports metabolism of all living organisms, the level of orderliness of life is independent of the amount or the character of the consumed energy. The level of organization (information content) of living systems is more than 20 orders of magnitude higher than the level of organization of all possible ordered physical states generated in the environment by solar energy or any other source of external energy.

In this context, all individual self-reproducing living organisms outside their populations behave like closed physical system. Beyond the population control (i.e., in the absence of competitive interaction and selection), both individual specimens and their progeny may lose their level of orderliness. Therefore, the properties of the biological systems are described by the law very similar to the second law of thermodynamics for closed physical systems.

#### ACKNOWLEDGMENTS

We are grateful to M.V. Filatov for stimulating discussion. This study was supported by the State Committee for Ecology of Russian Federation and the International Science Foundation (Open Society Research

Support program, project no. 800/2000; the grant was awarded to A.M. Makar'eva).

## REFERENCES

1. Bak, P., Tang, C., and Wiesenfeld, K., *Phys. Rev. Lett.*, 1987, vol. 59, pp. 381–384.
2. Cross, M.C. and Hohenberg, P.C., *Rev. Mod. Phys.*, 1993, vol. 65(II), pp. 851–1111.
3. Eckmann, J.-P. and Ruelle, D., *Rev. Mod. Phys.*, 1985, vol. 57(I), pp. 617–656.
4. Kauffman, S.A., *The Origins of Order*, Oxford: Oxford Univ. Press, 1993.
5. Boer, J., Derrida, B., Flyvbjerg, H., *et al.*, *Phys. Rev. Lett.*, 1994, vol. 73, pp. 906–909.
6. Sneppen, K., Bak, P., Flyvbjerg, H., and Jensen, M.H., *Proc. Natl. Acad. Sci. USA*, 1995, vol. 92, pp. 5209–5213.
7. Brillouin, L., *Nauka i teoriya informatsii* (Science and Information Theory), Moscow: Fizmatgiz, 1960.
8. Landau, L.D. and Lifshits, E.M., *Mekhanika sploshnykh sred* (Mechanics of Continuum), Moscow: Gostekhizdat, 1954.
9. Monin, A.S., *Usp. Fiz. Nauk*, 1986, vol. 150, pp. 61–105.
10. Hinegardner, R., in *Molecular Evolution*, Sunderland (Mass.): Sinauer Associates, 1976, pp. 179–199.
11. Gorshkov, V.G., Gorshkov, V.V., and Makarieva, A.M., *Biotic Regulation of the Environment: Key Issue of Global Change*, Chichester: Springer, 2000.
12. Gorshkov, V.G., *Zh. Obshch. Biol.*, 1981, vol. 42, pp. 417–429.