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Information in the Animate and Inanimate Worlds

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Abstract—Closed systems are governed by the second law of thermodynamics and cannot spontaneously become more ordered. In open physical systems exposed to external energy flows, additional macroscopic degrees of freedom ("memory cells") emerge, their number increasing with an increase in the flow and orderliness of the external energy. Biological systems are characterized by molecular degrees of freedom, the density of which is more than twenty orders of magnitude higher than that of macroscopic degrees of freedom in any open physical system exposed to the same external energy flow. This indicates that the self-organization of physical systems in external energy flows and the self-organization and evolution of living systems are fundamentally different. Thus, although life is an open system, the energy (food) flows that it consumes and all other external factors affecting life are so poorly ordered, compared to life itself, that they cannot increase the degree of order in the latter. Therefore, living systems obey an analogue of the second law of thermodynamics: within periods of time considerably shorter than the duration of evolutionary changes, living systems can only lose the accumulated information (i.e., the entropy can only increase), even if the systems consume external energy–food flows.

Key words: biosphere, information, closed and open systems.

CLOSED AND OPEN SYSTEMS

Physical systems are generally divided into closed and open ones. Nothing occurs in closed systems that are in thermal equilibrium. They are in the state of the maximum possible chaos. No observable processes can spontaneously occur there. This property of closed systems has been verified empirically and is called the second law of thermodynamics. In open physical systems, which receive energy from outside, various processes may be detected and the so-called physical self-organization may occur. A well-known example of this self-organization is generation of rotational flows (rifts) in a river with strong current and many rapids. However, organized processes do not occur in all open physical systems. This only takes place in the systems that receive information flows from outside. Let us consider this phenomenon in more detail.

Memory cells are necessary for information to emerge. In a written text, the positions (locations) of letters and spaces serve as memory cells. If all positions are occupied by definite letters forming words and phrases, then a sensible text bearing certain information appears. The amount of information is limited by the total number of memory cells (i.e., the number of characters or the "length" of the text) and the number of letters in the alphabet used (more precisely, their frequencies in the words of the text). The amount of information is maximum if each position in the text is occupied by a certain letter corresponding to a sensible word, phrase, paragraph, etc. If a letter, word or phrase of such a text is replaced by that chosen at random, then information, generally speaking, will be partially or completely lost (this loss does not occur in the case of specially coded texts that contain redundant information as a safeguard against noise). Information will be entirely absent if a letter chosen at random is placed at each position in a text of a given length. This state of the text is equivalent to the maximum chaos characterizing a closed physical system.

The text length, i.e., the total number of positions in it (taking into account the number of values that a character at each position may assume) is the system's information capacity. Literal information may be converted into digital information used in modern computers and video cameras. In these devices, memory cells are macroscopic elements of various physical nature. An increase in the number of memory cells increases the resolution of television screens and the total memory capacity of computers.

INFORMATION OF SOLAR RADIATION

Molecules of environmental substances, which interact with solar radiation, are natural memory cells on Earth. If there were no solar radiation, the environment would come to a state approaching the thermal equilibrium characteristic of closed physical systems in which no processes occur. Solar radiation causes the transition of environmental molecules into the excited state with an energy exceeding the thermal (chaotic) energy of the molecules. Decomposition of these excited states is responsible for generation of all natural processes observed in the environment, such as the water cycle, wind, and global circulation in the atmosphere and ocean.

The transition of environmental molecules excited by solar radiation to a higher energy level, compared to the thermal noise, means that Earth receives from the Sun an energy flow rich in information, rather than a mere heat flow. The amount of solar energy received by the Earth is equal to the amount of thermal energy radiated by the Earth back into space. Otherwise, the Earth would permanently have been heated or cooled, which is not the case. (According to recent paleontological data, life has existed on Earth for the past 3.85 billion years. According to other independent data, the global average temperature of the Earth's surface varied insignificantly and remained within the interval from 10 to 20°C, which is optimal for life.)

However, the energy that the Earth receives and the energy that it sends back substantially differ in their information characteristics. The Earth receives shortwave visible light from the Sun and emits long-wave heat radiation back into space. In the 20th century, it was discovered that radiation consists of discrete particles, photons. The absolute temperature of the solar surface is about 6000 K; and that of the Earth's surface, 300 K, i.e., 20 times lower. Therefore, an average solar photon contains 20 times more energy than an average photon of the Earth's thermal radiation. The flows of energy that are absorbed and radiated by the Earth are equal; hence, each solar photon breaks down into 20 thermal photons. The transfer of information to the environmental molecular memory cells, i.e., generation of all ordered processes observed on the Earth's surface, occurs during the cascade of this breakdown. (Ordered geothermal energy, such as that of volcanoes and geysers, accounts for several millionths of the solar energy received by the Earth's surface. Therefore, we may postulate with a high degree of accuracy that *all* ordered processes in the environment are generated by solar radiation.)

It is possible to estimate the amount of the molecular memory cells that interact with solar radiation throughout the Earth's surface, thereby estimating the information flow sent to the Earth by the Sun. One solar photon can excite as many as 20 molecules, and each of them will emit a thermal photon. Therefore, the number of molecular memory cells excited by solar radiation is of the same order of magnitude as the number of thermal photons emitted by the Earth back into space. This number (S) is equal to the known energy flow of solar radiation absorbed by the Earth's surface ($Q = 10^{17}$ W; Gorshkov, 1996) divided by the average energy of a thermal photon emitted by one molecule. This energy is $k_B T \sim 10^{-21}$ J, where k_B is the Boltzmann constant, which is proportional to the inverse value of the Avogadro number (6×10^{23}), and $T = 300$ K is the temperature of the Earth's surface. Thus, $S = Q/(k_B T) = 10^{38}$ molecules per second. Let us assume that, approximately, one molecular state is excited above the level of thermal noise; hence, the molecular memory cell contains two states, excited and basic. In this case, the dimension *molecule* may be substituted by a *bit*; thus, the information flux received by the Earth from the Sun is in the order of 10^{38} bit/s.

The information flow received by the Earth (in the form of the solar-energy flow) is connected with the transition of molecules to quantum states excited above the thermal noise and characterized by a definite amount of energy. In other words, the information flow is inevitably related to an energy flow that can cause molecular excitation. The information flow increases with an increase in this energy flow.

As noted above, energy does not necessarily cause molecular excitation above the thermal noise. In theory, there might be a situation where the Earth would receive a constant energy flow from the Sun, and the temperature of the Sun's surface would gradually decrease to the temperature of the Earth's surface. In this case, the Earth's surface would always remain warm, and the information flow from the Sun to the Earth would decrease until the temperatures of the Sun's and Earth's surfaces became equal and the information flow, zero. After this, all ordered processes on the Earth's surface, such as the water cycle (evaporation, precipitation, river flow), cyclones, thunderstorms, winds, and hurricanes, would cease. The Earth's surface would come to heat equilibrium with the Sun's surface, thus becoming a subsystem of the latter.

The energy of all ordered processes generated by solar radiation on the Earth's surface is gradually dissipated to be transformed into heat, which is emitted into space in the form of thermal photons. Then, the information contained in all molecular memory cells is erased. The number of molecular memory cells containing information, i.e., the cells that are in a definite state, approximately determines the amount of information expressed in bits (assuming that the molecular memory cells are binary, i.e., can only exist in one of two states). The amount of molecular memory cells that do not contain information (those that are in an indefinite state) is a measure of chaos; in physics, this value is termed entropy. The total number of memory cells is the information capacity of the system. Thus, the sum of the amount of information and the entropy is the system's information capacity.

Therefore, the maximum possible amounts of both information and entropy are also equal to the information capacity of the system. If solar radiation activated all molecular memory cells of the environment (the entire information capacity of the system), then solar radiation would bring to Earth a pure information flow and no entropy. Earth's thermal radiation appears after information is erased from all memory cells. Therefore, Earth radiates a pure entropy flow and no information into space. Thus, the information flow that comes to Earth ($Q/k_B T$) is equal to the backward entropy flow. In physics, the entropy flow is known to be determined by the ratio Q/T and coincides, to an accuracy of the constant k_B (i.e., to the accuracy of the choice of units of measure), with the information flow defined above. The above considerations clarify the meaning of this ratio: it is proportional to the amount of molecular memory cells that have received and then completely lost information from solar radiation.

INFORMATION OF PHYSICAL PROCESSES ON THE EARTH'S SURFACE

Physical processes induced by solar radiation on the Earth's surface have been termed physical self-organization. Most molecular excitations undergo rapid dissipation and are converted into heat without causing any significant chemical reactions. However, the conversion of solar radiation into heat is unevenly distributed over the Earth's surface, which leads to the appearance of temperature and pressure gradients and heterogeneity of the water cycle (water evaporation, river flows, etc.). This heterogeneity results in the well-known large-scale processes such as winds, storms, hurricanes, cyclones, thunderstorms, and tornadoes. Some of these processes, e.g., water evaporation from the surface of water bodies into the atmosphere, are directly caused by solar irradiation. Other processes—e.g., hurricanes, tornadoes, and avalanching—occur after the accumulated potential energy has reached a certain critical level: latent heat of evaporation should be accumulated in the atmosphere before hurricanes and tornadoes are generated, the gravitational energy of snow precipitation should be accumulated in the mountains before avalanching, and the gravitational energy of sand should be accumulated in sand dunes before their destruction.

When the accumulated potential energy has reached the critical level, the potential energy is converted into the kinetic energy of the breakdown of the given state. Energy accumulation is strictly limited by this critical level, so that the amount of energy cannot exceed it. The physical processes triggered by reaching the critical level of energy accumulation have been termed self-organized criticality processes (Bak *et al.*, 1987).

Information on all these physical processes is recorded in macroscopic, rather than molecular, memory cells, which are often called the degrees of freedom of a certain process. For example, the degrees of freedom of a rotational (vortical) water flow in rivers are the numbers of possible vortices of different sizes. The total number of vortices is determined by the number of the smallest vortices, in which the vortical energy is dissipated to be converted into heat; their number increases with an increase in the energy of the flow (Landau and Lifshitz, 1954). The number of macroscopic memory cells is always greater than the number of molecular memory cells in the environment and exceeds the latter by many orders of magnitude. Correspondingly, the information flows that characterize the physical self-organization processes caused by solar radiation are many orders of magnitude weaker than the information flows carried to Earth by solar radiation, and the efficiency (performance coefficient) of the conversion of solar energy into the energy of macroscopic physical self-organization processes in the environment never exceeds 1% (Gorshkov *et al.*, 2000). As the external energy flow increases, the physical self-organization energy generated by this flow increases as well. For example, the number of vortical flows on rapids increases with an increase in the drop of the river.

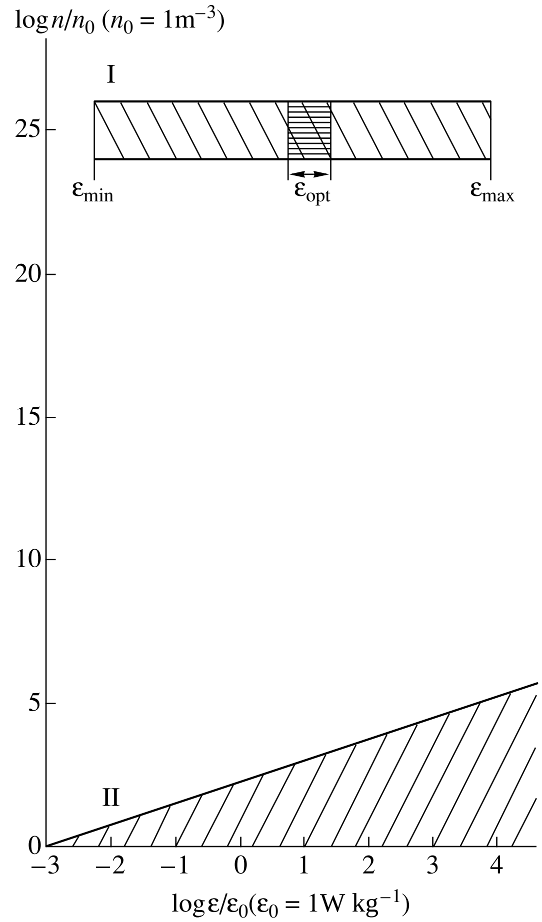

Fig. 1. Organization of physical and living systems as related to the density of energy absorbed by the system.

In the inanimate world, information is virtually never recorded in molecular memory cells. Information recorded in molecular memory cells—namely, genetic information—is accumulated and used only in the animate world (Earth's biota) (Fig. 1). Therefore, the amounts of information and the rates of its flow in the animate and inanimate worlds differ by more than 20 orders of magnitude. This results in fundamental differences between self-organization processes in the animate and inanimate worlds, which has not been properly taken into account thus far.

Figure 1 shows the differences in the characteristics of organization of physical and living systems as related to the density of energy absorbed by them. The ordinate shows the common logarithm of the number of memory cells (degrees of freedom) per unit volume (1 m^3) of physical systems (II) and per unit metabolically active volume (1 m^3) of biological (ecological) systems (I); the abscissa shows the common logarithm of the power of external energy (ε) consumed by unit weight of the system (W $kg^{-1} = m^2 s^{-3}$). The areas occupied by physical (II) and biological (I) organized systems are hatched; ε_{min} is the observed minimum of metabolic power; ε_{max} is the observed maximum of metabolic power (the highest proliferation rate of bacteria, record-setting jumps of animals, etc.). Powers (ε) that fall within the interval $\varepsilon_{min} \leq \varepsilon \leq \varepsilon_{max}$ are observed in species with practically all known sizes of genomes, from 10^6 bp in bacteria to 10^9–10^{11} bp in plants and animals; ε_{opt} is the area of optimal metabolic power of life (hatched in Fig. 1), which is used by more than 90% of species inhabiting the biosphere, irrespective of the sizes of their genomes (Gorshkov *et al.*, 2000). The sloping line shows the density of the number of vortical degrees of freedom (vortices) of air masses as dependent on the density of energy power per unit air mass (ε) according to the Kolmogorov–Obukhov law (Landau and Lifshitz, 1954). According to our estimations, the characteristics of all other natural self-organized physical processes in the environment are within the hatched triangle. Note that, if we continue the sloping line of physical self-organization to the right, the latter will reach the amounts of order characteristic of living systems when the energy density becomes higher than 10^{32} W kg^{-1}. Obviously, stable molecular structures that are necessary for the origin of life cannot form at these energy densities.

The mechanisms and dynamics of all physical self-organization processes are entirely determined by the external energy flow supplied to the system (in the given case, by solar radiation) and the characteristics of the environment where these processes occur. The cessation or change of the external energy flows lead to the cessation or corresponding change of the physical self-organization processes. After the external energy flow has resumed, physical self-organization processes also resume in the same form characteristic of the specified external energy flow. Similarly, self-organized criticality processes are entirely determined by the nature and critical level of the accumulated potential energy. If the patterns of external energy flows and accumulated potential energy remain unchanged, there are no evolutionary changes in physical self-organization and self-organized criticality processes. In this respect, the term self-organization does not properly characterize the processes and states in physical systems: they are organized by the rates and nature of the external energy flows or accumulated potential energy and the environment, rather than self-organized. Hence, the environment, which is exposed to external energy flows, determines and controls all physical "self-organization" processes; therefore, these processes can neither change the environment directionally nor control it (cf. below).

INFORMATION OF BIOLOGICAL SYSTEMS

Biological systems (living organisms and their communities), which accumulate information in molecular memory cells (DNA macromolecules), have no limit for accumulating this information; anyway, modern science cannot predict such a limit. Living systems have accumulated so much information during their evolution that the highly organized life processes that are determined by this information can neither start spontaneously nor be maintained by any external energy flows. This has been known since Pasteur's studies that demonstrated the impossibility of spontaneous generation of life under any conditions. This is also evidenced by the fact that extinct species never reappear. Therefore, the evolution of living organisms is the only true self-organization.

The preservation of genetic information and the maintenance of stable biological systems (species and communities) are based on a new fundamental mechanism, which is absent in physical self-organization systems. This mechanism involves the formation of a population of individuals belonging to similar biological systems, competition between individuals, and culling of defective individuals which have lost part of the genetic information. The capacity of normal individuals for reproduction makes it possible to fill the resultant vacancies and maintain a stable population size.

The organizational levels of living systems do not depend on the external energy flows that the systems consume (Fig. 1). Therefore, life itself can control environmental conditions, i.e., change them so that they remain stable and optimal for life. Life needs energy consumption (nutrition) to replenish the energy that has been spent on competition, reproduction, and control of the environment (Gorshkov *et al.*, 1999).

It is conceivable that the animate world separated from the inanimate world when "prelife" had accumulated the amount of genetic information that was sufficient for generating the processes whose complexity depended no more on the environment or nutrition, i.e., it could not be increased on their expense. On the other hand, life can withstand unfavorable environmental

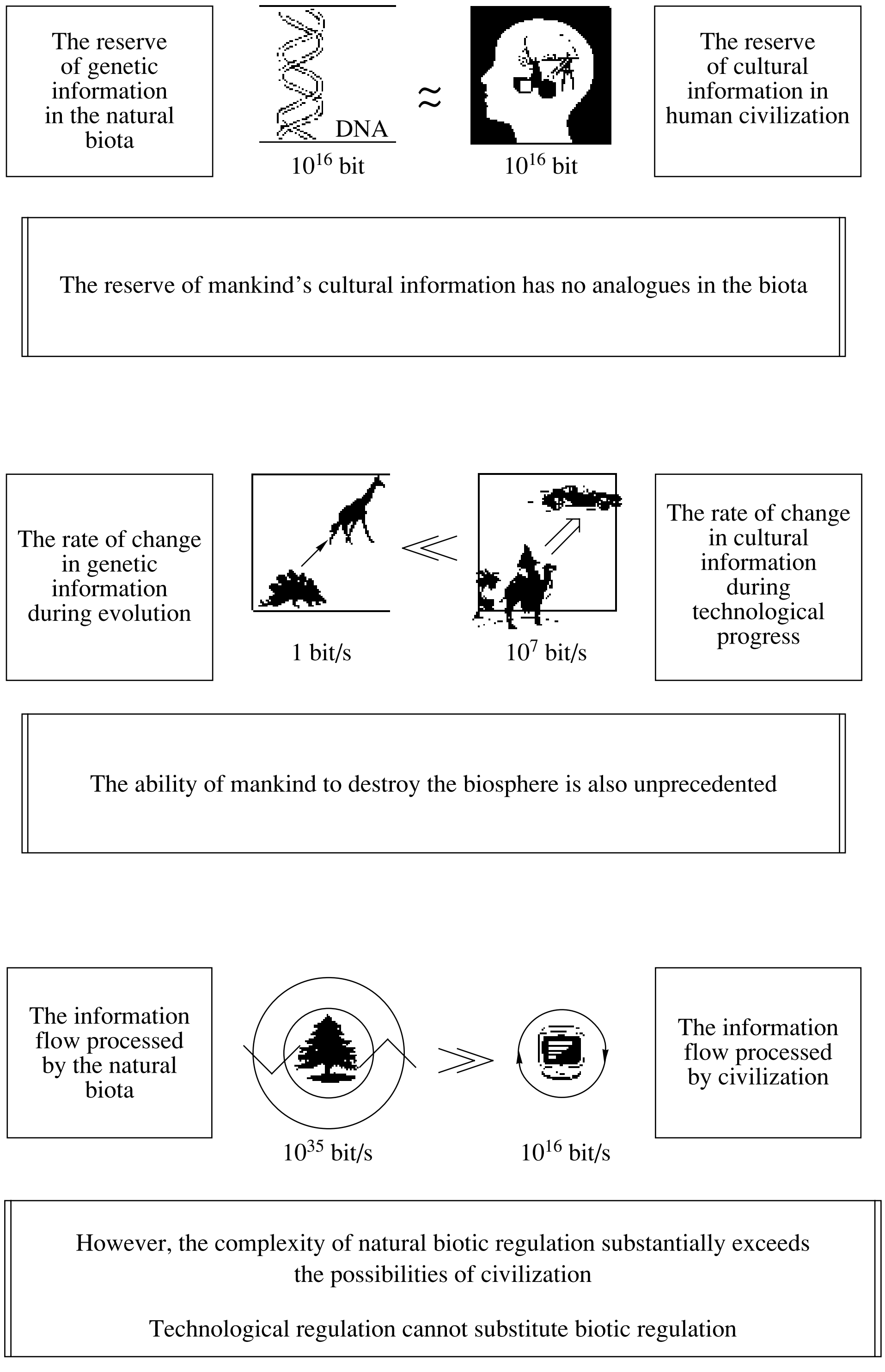

Fig. 2. Basic informational characteristics of the biota and modern civilization.

changes by returning the environment into the optimal state. Obviously, the effects of life on the environment, which are based on information recorded in the genome and accumulated in the memory of organisms, cannot be described by the same equations as those pertaining to physical self-organization and self-organized criticality, because the entire information on the latter processes is contained in the environment and external energy flows. These equations are even less applicable to the evolution of life, which is related to the accumulation of genetic information and further changes in it.

Note that the amount of information accumulated in the biota has exceeded the amounts of information that are brought to the biota by food flows to so high a degree that the latter do not affect the former. For the periods of time that are shorter than the duration of evolutionary changes, the information of the biota remains unchanged due to stabilizing selection and may only decay (be erased) in the absence of natural selection. In this regard, the behavior of life is similar to that of a physically closed system. Although life is an open system, the flows of energy (food) that it consumes, as well as all other environmental effects, are so low-organized compared to life that they cannot increase the amount of order (i.e., information content) of life. Therefore, living systems obey an analogue of the second law of thermodynamics: during time intervals substantially shorter than the duration of evolutionary changes, only the loss of accumulated information—i.e., an increase in entropy—can occur in living systems, notwithstanding the consumption of external energy–food flows.

Fluctuations that are termed noise occur in all systems. They also occur in genetic systems, which is related to the impossibility of precisely determining the genetic norm (a normal genome) in the course of competition: the loss of a small portion of the species' genetic information does not lead to a decrease in individual competitiveness. The term "white noise" refers to fluctuations that are evenly, randomly distributed over all characteristics of the system, by analogy with white light, in which all colors of the spectrum are homogeneously mixed. White noise emerges in absolutely closed systems that are not exposed to external factors capable of causing heterogeneity in the distribution of fluctuations. In the inanimate world, it is very difficult to create conditions excluding the external effects; therefore, white noise is practically never observed in physical systems. Genetic systems are ideal models for studying white noise, because, as determined to a high accuracy, external factors have no effect on the degree of order in them.

INFORMATION OF THE BIOTA AND CIVILIZATION

Environmental management is a characteristic feature of all human civilizations. When colonizing new territories, people aimed at bringing the environment into the state that was optimal for their activities. They felled forests to convert the cleared area into arable lands and pastures, drained bogs, and built dams on rivers. In this course, people destroyed the natural communities of various living species constituting the Earth's biota, whose functioning ensures the stability of the existing global climate, as is gradually becoming evident (Gorshkov *et al.*, 2000).

Destruction of the biota by man may undermine the global climate stability. Life has existed for many billions of years, and, throughout this period, the global average temperature of the near-surface atmosphere has varied from 10 to 20°C, and the greater part of the hydrosphere has been in a liquid state and concentrated in the ocean. The observed stability of Earth's climate indicates that the undisturbed biota could ensure the climatic stability for a practically infinite time (billions of years).

Rapid development of modern civilization, amazing advances in computer technologies and worldwide informational networking, and the obvious ability of people to completely destroy the global biota suggest that human powers are unlimited and exceed those of the undisturbed biota in all respects. This creates the impression that, if people realize the necessity of environmental and climate management, they will meet no difficulties in using the means provided by civilization for substituting the biota in its regulatory functions. To answer the question as to whether or not this is so, we should perform quantitative analysis of the resources and flows of information in the biota and civilization (Fig. 2).

The genetic information resource of the global biota may be estimated from the known number of species (about $\sim 10^7$) and the mean number of molecular memory cells (nucleotide pairs, bp) in a species' genome (about $\sim 10^9$, bp). Therefore, the information reserve of the biota is about 10^{16} bit. The information reserve of modern civilization is about the same order of magnitude. This may be demonstrated if we assume that the entire information of the modern civilization may be stored in the memory of modern computers and use the known data on the memory capacity and the total number of these computers in the world. The rates of changes in the information reserves during the biological evolution of the global biota and the progress of civilization differ from each other by seven orders of magnitude. This difference in the rate of accumulation of information allows man to master the animate world and displace the undisturbed biota from the face of the Earth.

However, the information flows in the biota that determine its environment-controlling potential are 20 orders of magnitude greater than the information flows in human civilization (Fig. 2). This is related to the fact that the biota uses molecular memory cells in every living cell, and each cell processes information flows of the same order as modern personal computers do. It may be calculated that there is about 10^{28} cells in the biosphere and no more than 10^8 computers in civilization (no more than one personal computer per 10–50 people). This fantastic difference between information *flows* in the biota and civilization will probably not be eliminated, however dramatic future progress of civilization will be

(Gorshkov *et al.*, 2000). Therefore, people will inevitably face the necessity of restoring the disturbed biota and preserving the undisturbed biota to an extent that will ensure, as before, the maintenance of the global environment and climate in the state suitable for human life.

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