Makarieva A.M. (2008) **Cybernetics.** In Sven Erik Jørgensen and Brian D. Fath (Editor-in-Chief), Systems Ecology. Vol. 1 of Encyclopedia of Ecology, 5 vols, pp. 806-812. Oxford: Elsevier.

Systems ecology: Cybernetics

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Introduction

The word "cybernetics" originates from the Greek word "steersman". Cybernetics can be broadly defined as a field of knowledge seeking to offer a general mathematical approach to the study of complex systems irrespective of their nature (e.g., artificial or living). In this context under complex systems one understands the systems composed of elements exchanging energy, matter and information with one another and with the environment, i.e. systems where various control (feedback) processes operate, Fig. 1.

To give a simple example, stability of a system quantity x over time t can be described as $dx/dt = -kx$, where parameter k can, in general, depend on both x and t. If the value of k is positive, any disturbance $\Delta x = x - x_0$ of the initial value x_0 of this parameter will exponentially diminish with time, returning the system to the initial state, $\Delta x = \exp(-kt)$. At negative k, any slight perturbation will exponentially amplify destabilising the system. Such formal description does not depend on the nature of either parameter x or the positive or negative feedback processes in the system that are responsible, respectively, for the system's instability or stability (homeostasis).

Established in the 1940-50s with works of Norbert Wiener, William Ashby and others, the notion of cybernetics became well-known in the 70s-80s of the 20th century, the time marked with intensive research and large expectations associated with the idea of creating artificial intelligence. Cybernetics studies in life sciences can be exemplified by the models of organic evolution like the Eigen's hypercycle; there is much modelling research in the fields of neurophysiology and sociobiology.

While generality of a scientific approach is obviously an important scientific merit, the overall success of the approach is determined by its concrete applications within particular fields. Ecology, the science of interactions among organisms and between the organisms and their environment, features high complexity and has the problem of homeostasis versus change at its very heart. To apply the cybernetics approach in ecology, it is important to establish the correspondence between the major notions of cybernetics like information exchange, communication, control processes etc. and measurable characteristics of the organism, ecosystem, and biosphere. This article describes the essential aspects of ecological cybernetics. The first section discusses the origin of information fluxes in the biosphere. In the second section information stores and exchange fluxes within the biosphere, on the one hand, and within the modern civilization, on the other, are described and compared. The third section discusses control processes operating at the biota-environment interface, which allow life to persist on Earth for practically infinite time periods of the order of billion years, thus maintaining homeostasis of the living matter.

Solar energy and information

According to the second law of thermodynamics, closed systems ultimately reach the state of maximum entropy. The apparent high degree of orderliness of ecological systems and the persistence of this orderliness through time indicates that there is a continuous external input of order (information) into ecological systems. The source of this information is the solar energy, the primary source of energy for life on Earth. Both solar radiation and thermal radiation of Earth consist of particles — photons. Mean energy of one photon is proportional to absolute temperature measured in degrees Kelvin. Absolute temperature of Sun is about T_S = 6000 K. Absolute global mean surface temperature of Earth is about T_E = 288 K (i.e. about 15 °C). Mean energy of one solar photon is about $T_S / T_E = 6000/288 \approx 20$ times larger than the mean energy of one thermal photon of Earth. According to the law of energy conservation, the cumulative energy of all solar photons coming to Earth is equal to the cumulative energy of thermal photons emitted by the Earth into space. It means that the number of thermal photons emitted by Earth into space is about 20 times larger than the number of solar photons reaching Earth surface. Consequently, one solar photon decays on average into 20 thermal photons. Decay of solar photons gives rise to all ordered, information-rich processes on Earth, of which life is most powerful, Table 1.

Information capacity of a system is characterized by the available number N of memory cells. If a cell's memory can be characterized by only two possible values of a certain variable, the total number of possible combinations of these values in all memory cells is 2^N. The system possesses the maximum possible amount of information equal to N bits when the values of the measured variable are defined in all N memory cells. If states of N_1 cells remains unknown, the amount of information reduces to $N - N_1$. If the measured variable remains undefined in all memory cells, the information becomes zero while the entropy of the system reaches its maximum.

Solar photons interact with molecules of vegetation covering the Earth's surface. These molecules can be viewed as elementary memory cells of the ecosystem. Solar photons can excite molecules, i.e. impart a certain amount of energy to molecules and increase their energy above the average thermal level. A good approximation is to assume that molecular memory cells are characterized by two states — excited (a definite state) and non-excited (indefinite state) compared to the average chaotic thermal level. During the process of decay, solar photons are able to excite molecules until their own energy becomes equal to the average energy of thermal photons of the Earth’s surface. Each solar photon possesses an amount of energy equal to that of about 20 thermal photons of Earth. Consequently, one solar photon can excite about 20 molecules, i.e. impart information to about 20 molecular memory cells. Such consideration makes it possible to estimate the amount of information (in bit s^{-1}) coming from Sun to Earth per unit time. It is roughly equal to the number of thermal photons emitted from the Earth to space, because each thermal photon is emitted from an excited molecule, which represents a memory cell containing one bit of information. The number of Earth’s thermal photons emitted to space in a unit of time is equal to the power Q ($Q \approx 2 \times 10^{17}$ W) of solar radiation reaching the Earth divided by the energy ε of one thermal photon, which is determined by the Earth’s temperature T_E, $\varepsilon = k_B T_E$, where $T_E \approx 288$ K, k_B is Boltzmann constant, which is proportional to the reverse Avogadro number ($k_B = 1.4 \times 10^{-23}$ J K^{-1} $molecule^{-1}$). As far as one molecule represents a memory cell with two possible states, dimension molecule^{-1} in Boltzmann constant corresponds to bit^{-1}. The information flux F coming from Sun to Earth is $F = Q/(k_B T_E) \approx 10^{38}$ bit s^{-1}.

If one solar photon possesses energy equal to that of $T_S / T_E \approx 20$ thermal photons, the maximum number of molecules it can excite is $T_S / T_E - 1 \approx 19$, because after 19 acts of excitation its energy becomes equal to that of one thermal photon. After that it cannot impart any additional energy to molecules, and, therefore, cannot excite them. So, only $(T_S / T_E - 1)/(T_S / T_E) \times 100\% = (T_S - T_E) / T_S \times 100\% \approx 95\%$ of Earth's thermal photons come from excited molecules and characterize information flux coming from Sun to Earth. The ratio $(T_S - T_E)/T_S$ describes the well-known Carnot efficiency of the solar radiation on Earth. If the sun's temperature were equal to that of Earth, solar photons would have the same energy as thermal photons of Earth and could not excite any molecules on the Earth's surface. In such a case the information flux from Sun to Earth would be equal to zero.

Stores and fluxes of information in the natural biota and civilization

Stores of information

The maximum rate of information processing by the human brain does not exceed 100 bit s^{-1}. Information is acquired most actively during the first 20 years of life of the individual, i.e., during about 6×10^8 s. The amount of information acquired later in life does not change the order of magnitude of the total store. The amount of information stored in memory of an adult human can be estimated at about 6×10^9 bit.

An upper estimate of the total amount of cultural information of the modern civilization can be obtained multiplying the current population number of Earth ($\sim6\times10^9$ people) by the average individual memory store of information ($\sim6\times10^9$ bit), which gives a value of about 10^{19} bit. This is a gross overestimate of the real value, because most part of memory information is the same in all contemporary people. The unique non-overlapping information of the civilization is stored in memories of specialists (professionals) — scientists, craftsmen, writers, musicians, artists. Working specialists constitute not more than about 10% of the whole population (multiplier 10^{-1}). Each field of knowledge can normally exist with no less than 100 specialists working in this field and sharing the same memory information (multiplier 10^{-2}). The real value of information store of the modern civilization can be obtained multiplying the upper estimate by 10^{-3}, which gives about 10^{16} bit.

Genetic information of most species of the biosphere is written in polymer double-strand molecules of DNA, which represent various sequences of the existing four different monomer units — nucleotide base pairs (bp). Human genome contains $G = 3\times10^9$ bp, i.e., 3×10^9 memory cells each of which can be characterized by one of the four different values. The store of genetic information in the human genome is equal to $\log_2 4^G = 2G = 6\times10^9$ bit. The stores of genetic and non-genetic (memory) information in humans are of the same order of magnitude.

To quantify the store of the genetic information of the natural biota as a whole it is necessary to multiply the information content of an average genome by the total number of species in the biosphere, which is equal to about 10^7 species. The average genome size can be taken equal to 10^9 bp, which is the average genome size of insects that constitute the majority of species in the biosphere. The total amount of genetic information stored in the natural biota is of the order of 10^{16} bit and coincides in the order of magnitude with the information store of the modern civilization, Fig. 2a.

The amount of information that can be stored in a modern PC is of the order of 10^{11} bit, i.e., it greatly exceeds the amounts of genetic and individual memory information of one person. The cumulative memory capacity of modern computer technologies is large enough to store both the cultural information of the modern civilization and the genetic information of the natural biota.

Fluxes of information exchange

Species composition of the natural biota changes with evolutionary transitions of old species to new related ones. The genetic information of the biosphere changes in the course of evolution. Closely related species differ from each other in about 1% of their genetic information. The average species life span is about three million years. Thus, 1% of the genetic information changes in a single act of speciation approximately every 3×10^6 years. A complete turnover of the genetic information of the natural biota, 10^{16} bit, Fig. 2a, takes about 3×10^8 years, i.e. about 10^{16} s. The rate of evolution (i.e., the rate of change of genetic information of the natural biota in the course of evolution) is approximately equal to 10^{16} bit / 10^{16} s = 1 bit s^{-1}, Fig. 2b. This extremely low rate of information change has been sufficient to ensure sustainable development of the biosphere, that is, to support evolution of the natural biota in such a manner that the latter has been able to compensate directional adverse environmental changes of cosmic and geophysical nature during the whole period of life existence, i.e., during nearly four billion years.

The rate of information change during technological progress of the civilization is determined by the ability of people to generate and assimilate new cultural information. The present-day population of Earth can assimilate no more than $6\times10^9 \times 10$ bit s^{-1} = 6×10^{10} bit s^{-1}. The present-day rate of technological progress depends on the average time of renewal of modern technological systems, which is of the order of 10 years, i.e., about 3×10^8 s. Given that the store of information of the modern civilization is of the order of 10^{16} bit, the modern rate of civilization progress is about 10^{16} bit / 3×10^8 s $\approx 3\times10^7$ bit s^{-1}. (This estimate is obtained under the reasonable assumption that the most part of cultural information of the modern civilization is represented by information stored in memory of specialists dealing with modern technologies.) The ratio of the amount of newly-generated information to the amount of assimilated information for modern people does not exceed $3\times10^7 / 6\times10^{10} \approx 10^{-3}$.

The information rate of the progress of the modern civilization, 3×10^7 bit s^{-1}, exceeds the information rate of evolution, 1 bit s^{-1}, by more than seven orders of magnitude, Fig. 2b. This provides an explanation for the unprecedented (as compared to all other extant and extinct species) potential of *Homo sapiens* to destroy the natural environment.

An estimate of the total information flux going through all modern computers can be obtained multiplying the average information flux in one PC, $\sim 10^8$ bit s^{-1}, by the total number of people owning computers. Assuming that at present there is one PC for every hundred of people we obtain that the total flux of information in computers of the modern civilization is of the order of 10^{16} bit s^{-1}. This figure will hardly ever increase by more than six orders of magnitude (by providing computers for all people on the planet and ensuring a four orders of magnitude's increase of information flux in each PC), i.e. up to 10^{22} bit s^{-1}.

Even the present-day global computer information flux, 10^{16} bit s^{-1}, exceeds the assimilation capacity of the brain of modern people, 10^{10} bit s^{-1}, by a factor of million. Computers work on the basis of programs designed by people and speed up significantly processing of information. But this only makes sense while people are still able to check and control the outgoing flux of information. All the information that is generated by computers and other mass-media devices (TV, cinema, video, theatre, music etc.) above that threshold represents informational pollution of the environment. Informational pollution affects all the five organs of sense of people, and, among various types of pollution, presents the most dangerous threat to the mental health of humans.

In humans, metabolic power of existence in adults is equal to q = 140 W. The body temperature of humans is approximately equal to $T_b \approx 37°C = 310$ K. The average thermal energy of molecules in the human body is equal to $k_B T_b$, where k_B is the Boltzmann constant ($k_B = 1.4\times10^{23}$ J K^{-1}). Thus, $k_B T_b$ gives the order of the average amount of energy necessary to excite a molecule, i.e., the additional energy committed to a molecule as compared to the average thermal level. Assuming that one molecule corresponds to one memory cell with two possible states (excited and non-excited), i.e. 1 molecule ≈ 1 bit, we obtain that the information flux going through all living cells of the human body is equal to $q/k_B T_b \approx 3\times10^{22}$ bit s^{-1}. This value exceeds the asymptotic information power of possible future computers and by more than 12 orders of magnitude exceeds the assimilation capacity of the modern humanity.

Human body contains about 10^{14} living cells. Thus, every living cell processes on average about $3\times10^{22} / 10^{14} \approx 10^8$ bit s^{-1}, which is equal to information flux realized in a modern PC. The biosphere contains about 10^{28} living cells. Thus, the natural biota of Earth as a whole processes about $10^8\times10^{27\cdot} = 10^{35}$ bit s^{-1}, which is about twenty orders of magnitude more than the information flux of all computers of the modern civilization. Unlike in computers, molecular memory cells of living cells are directly coupled with the environment. Thus, the whole flux of information processed by the biota is used for correct interaction with the environment in control processes aimed at environmental and ecological homeostasis.

Energy consumption of the modern humankind is equal to 10^{13} W, which is only an order of magnitude less than the photosynthetic power of the natural biota, Table 1. But, due to the huge difference in the rates of information processing between the natural biota and civilization, any kind of anthropogenic energy use is inevitably characterized by a remarkably low efficiency, i.e. low information content of most processes generated by the humankind with help of energy use.

The humankind spends a large portion of its energy on transport, i.e. moving macroscopic objects — cars, trains, people etc. Motion of a macroscopic object is totally determined by only four variables — its mass and three co-ordinates of the velocity vector. Motion of macroscopic objects can be fully described by a very small amount of information coded in corresponding macroscopic memory cells. It is in principle possible to efficiently convert the kinetic energy of moving macroscopic objects to gravitational or electric energy that could be further used for generation of complex correlated molecular processes similar to those taking place in a living cell. But the kinetic energy of transported objects does not generate any ordered, information-rich processes. It is spent on friction, and finally dissipates converting to heat.

Macroscopic motion can be found in natural ecosystems as well (e.g. locomotive animals). However, in stable ecosystems the amount of energy allocated by the natural biota to this low-efficient channel of energy use does not exceed 1% of the total biotic energy consumption. Meanwhile humans spend on transport more than one third of the consumed energy. The remaining part of anthropogenically utilized energy is spent even more wastefully with respect to the information content of the generated processes (e.g., heating of buildings).

The total amount of energy consumed by the humankind, Table 1, does not characterize the amount of work that can be done by humans in order to stabilize the environment. Of critical importance is the total flux of information that can be processed by the modern civilization. And, as far as information fluxes are concerned, the modern civilization is inferior to the natural biota, Fig. 2c, which uses this flux to maintain ecological and environmental homeostasis.

Control processes in ecological systems

Life is based on biochemical reactions that convert inorganic substances stored in the environment into organic ones and back. The existing power of the biochemical fluxes of synthesis and decomposition of organic substances is such that, were not these feedback processes rigidly correlated, the environment could change completely in time periods of several tens of years, reaching a state where life would be impossible.

For example, the global amount of atmospheric CO_2 is of the order of $M^- \sim 10^3$ Gt C (1 Gt = 10^9 t). The mean global rates of biochemical synthesis P^+ and decomposition P^- are of the order of $P^+ \sim P^- \sim 10^2$ Gt C year^{-1}. If the rates of synthesis and decomposition were not correlated, i.e. if they coincided by the order of magnitude only, their relative difference would be of the order of unity, $|P^+ - P^-|/P^\pm \sim 1$. In such a case, if synthesis exceeded decomposition, $P^+ > P^-$, the global biota would use up the entire store of atmospheric carbon on a time scale of $M^- / P^- \sim 10$ years. This would render further photosynthesis and existence of life impossible. The amount of organic carbon in the biosphere (living biomass, humus, and oceanic dissolved organic carbon) is of the same order of magnitude, $M^+ \sim 10^3$ Gt C. If the rate of decomposition exceeded the rate of synthesis, the global biota would be able to destroy itself completely in equally short periods of time.

The fluxes of synthesis and decomposition cannot be correlated with each other directly. Synthesis and decomposition of organic matter represent independent biochemical processes that are generally performed by different species under different environmental conditions (temperature, humidity etc.). While primary productivity is limited by the incoming solar radiation, there are no physical limitations on the rate of decomposition, since the latter is ultimately dictated by the population numbers of heterotrophic organisms. Characteristic ecosystem values of P^+ and P^- are determined by the individual design of every species, population abundance and overall numbers of autotrophic and heterotrophic species inhabiting Earth. The values of P^+ and P^- cannot coincide with an infinite precision a priori.

For example, even if the mean global rates of synthesis and decomposition coincided, say, with a high accuracy of 1%, $\alpha \equiv |P^+ - P^-|/P^+ \sim 0.01$, such a biota would completely destroy its environment (or self-destroy) in $M^\pm/|P^+ - P^-| = M^\pm/(\alpha P^+) \sim 10^3$ years, i.e. nearly instantaneously on a geological scale. The life span of the biota is short for any realistic accuracy of the coincidence of P^+ and P^-. To extend the biotic life span to the documented several billion years of life existence, $T \sim 10^9$ years, one has to demand that the living organisms and their ecological communities are designed such that the mean rates of synthesis and decomposition performed by them coincide to the accuracy of $M^\pm/(P^+T) \sim 10^{-8}$, which is improbable.

Correlation of the ecological fluxes of synthesis and decomposition of the organic matter is achieved indirectly, via continuous sensing of information about the current state of the environment that is performed by living organisms. The biota reacts to any environmental change as soon as its relative magnitude reaches some critical value, biotic sensitivity ε_b. As long as the magnitude of the environmental change remains lower than biotic sensitivity, synthesis and decomposition of organic matter by the biota may proceed in a non-correlated manner at different rates. As soon as some environmental parameter changes by ε_b, the biota initiates compensating negative feed back processes and keeps them going until the disturbance is diminished to a level below ε_b, when the biota no longer notices it. The optimal state to which the ecosystem ultimately returns (the state of ecological homeostasis) is thus defined to an accuracy of ε_b. For example, if the amount of inorganic carbon in the atmosphere changes by $\varepsilon_b \sim 1\%$ (e.g. increases), the biota can enhance the rate of biochemical synthesis (that takes away CO_2 from the atmosphere) or reduce the rate of biochemical decomposition (that would further add to the atmospheric CO_2 amount) until the perturbed concentration relaxes to its optimal value. The same principle can be used to control temperature, humidity and all other environmental parameters.

The huge information fluxes processed by the natural biota, Fig. 2c, are necessary for sensing the environment, reading the data about its state and ensuring regulatory ecological processes aimed at compensation of possible environmental disturbances. This biotic regulation of the environment is equivalent to an operating system where the characteristic rate of information processing exceeds the maximum possible rate of automatic control provided by all computers of the modern civilization by 20 orders of magnitude. Biotic regulation is based on genetic programs of biological species of the biosphere. It can be viewed as an automatically-controlled operating system where the program of automatic control has been tested for reliability in an experiment lasting for several billion of years (during the whole period of life existence).

The relative degree of unsteadiness in the work of a computer is defined as the ratio of the rate of human-induced changes in the computer program to the total flux of information processed by the computer. The relative unsteadiness of the regulatory program of the natural biota is fantastically low, 1 bit s^{-1} / 10^{35} bit s^{-1} = 10^{-35}. (Rate of program change corresponds to the rate of information change in the course of evolution, 1 bit s^{-1}. The total information flux processed by the natural biota is equal to 10^{35} bit s^{-1}). It means that each working regulatory program is maintained by the natural biota in a steady state for the maximum possible periods of time.

Genetic information of the natural biota totally changes every 3×10^8 years. Thus, during the whole period of life existence (3.8×10^9 years) there were no more than a dozen completely different programs of biotic regulation of the environment. A working program of biotic regulation is presumably unique for each particular epoch. Evolution of the biotic regulatory program is possible due to acting geophysical and cosmic processes. That is, directional changes in parameters that cannot in principle be controlled by biota (e.g. solar activity) may lead to a situation when the old regulatory program is no longer the most effective one. As a result, there opens a possibility for a new more effective regulatory program of the biota to establish in the result of genetic modifications (i.e., appearance of new species) in the old program. New regulatory programs appearing in the course of evolution are exposed to a thorough experimental testing.

The humankind is unable to create a technological system equivalent to the natural biota, where each micron of the Earth's surface is controlled by dozens of independently functioning unicellular and multicellular organisms, each living cell processing an information flux similar to that of a modern PC. The genetic program of the natural biota cannot be substituted by any technological program of automatic control (even if this technological program is characterized by fluxes of energy and information similar to those in the natural biota), because search for appropriate technological decisions and their testing is performed by human beings and can take billions of years. Technological solutions of ecological problems can be only successful on a local scale. Globally, the only promising strategy for the modern humankind is therefore strategy of preservation of the remaining natural biota and gradual restoration of its global regulatory potential.

Further reading

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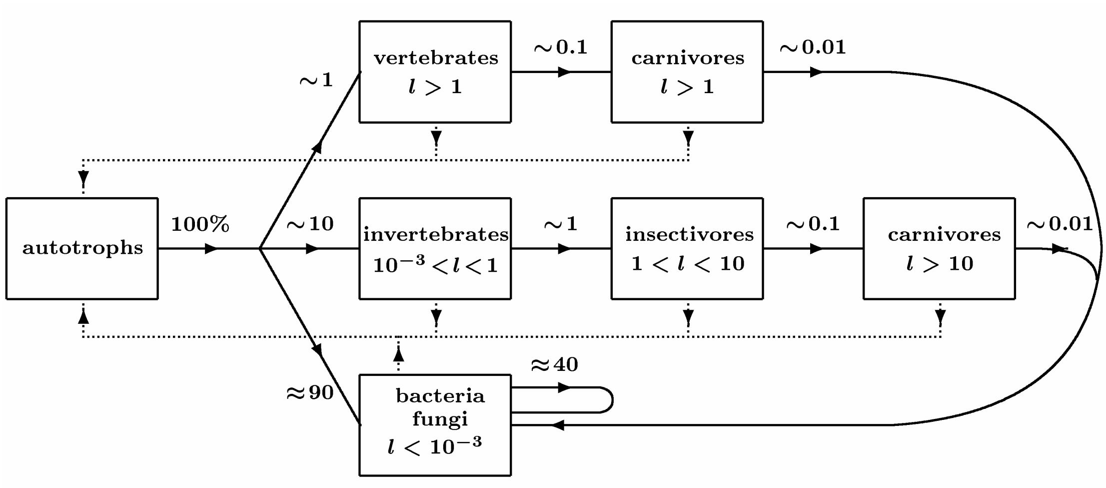

Figure 1. Natural terrestrial ecosystem represented as a cybernetic system. The division into blocks is made on the basis of the trophic level and body size l (cm) of the organisms. Feedback loops between the system's blocks are exemplified by the fluxes of organic carbon (solid arrows) coming in and out of each block and fluxes of inorganic carbon (dotted arrows) coming out of the heterotrophics blocks into the autotrophic one. For heterotrophic blocks $dM/dt = P_{\text{in}} - P_{\text{out}} - R$, where M is the store of organic carbon in live biomass within the block, P_{in} is the incoming organic carbon, P_{out} is the organic carbon produced within the block and transferred to the next trophic level, and R is respiration (decomposition of organic carbon). "Carnivores" indicate vertebrate-feeding heterotrhophs, "insectivores" indicate invertebrate-feeding heterotrophs. Numbers near solid arrows indicate the flux magnitude in terms of the percentage of ecosystem net primary productivity (100%). Numerical data of Gorshkov, V. G. (1995). *Physical and biological bases of life stability*. Berlin: Springer; Makarieva, A. M., Gorshkov, V. G., Li, B.-L. (2004). Body size, energy consumption and allometric scaling: a new dimension in the diversity–stability debate. *Ecological Complexity* **1,** 139-175.

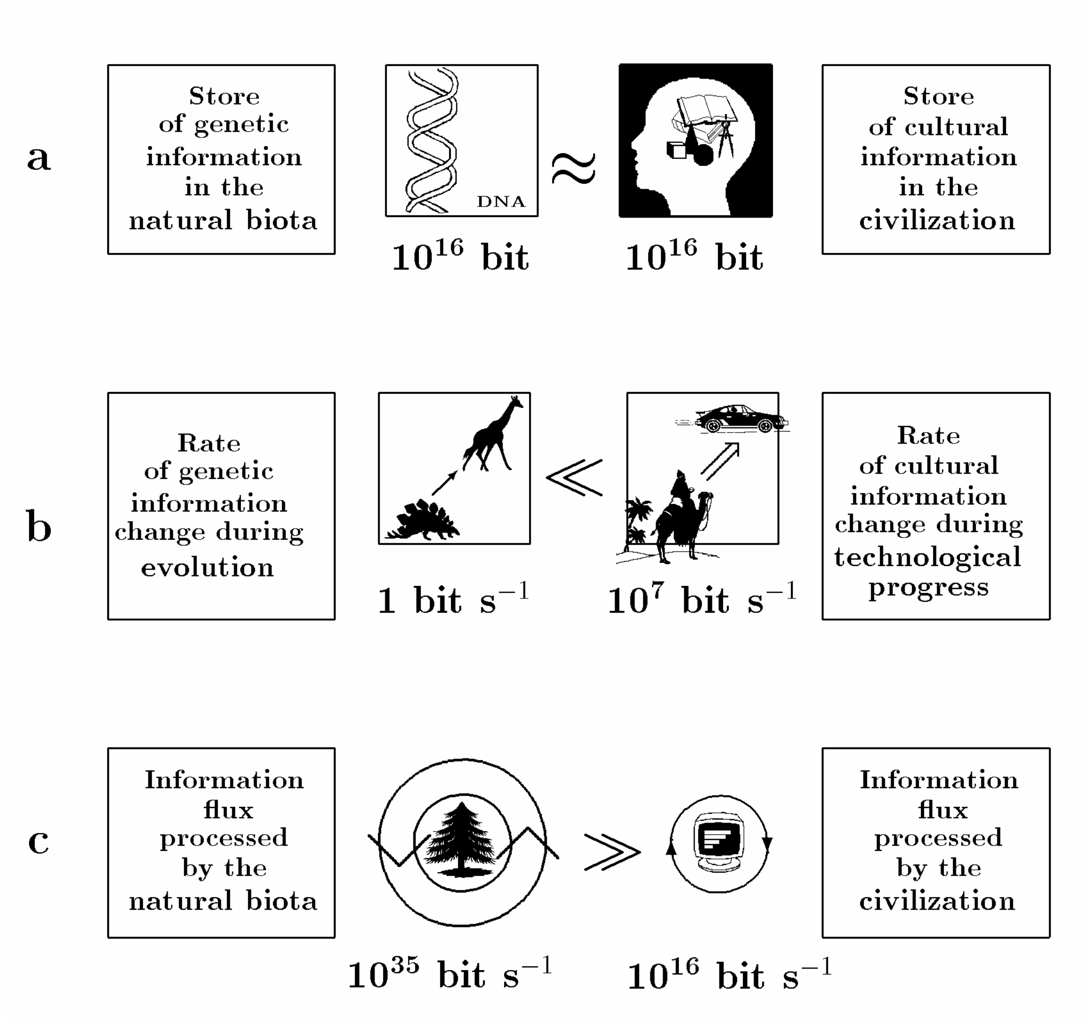

Figure 2. Stores of information (a), rates of their change (b) and information exchange fluxes (c) in the natural biota and modern civilization. After Gorshkov, V.G., Gorshkov, V.V. and Makarieva, A.M. (2000). *Biotic regulation of the environment: key issue of global change*. London: Springer-Praxis.

Table 1. Solar power and some routes of its dissipation on Earth

Power source / sink	Power	
	10^{12} W	Relative to the solar power
Total solar power coming from Sun to Earth	1.7×10^{5}	1.0
Physical processes:		
Wind power	2×10^{3}	10^{-2}
Oceanic waves	10^{3}	6×10^{-3}
Natural biota:		
Transpiration	3×10^{3}	2×10^{-2}
Photosynthesis	10^{2}	6×10^{-4}
Modern civilization:		
Energy consumption	10	6×10^{-5}
Consumption of the net primary production of the biosphere	9	6×10^{-5}

Suggested links to other articles:

Ecological informatics; Ecological informatics: Boltzmann learning; Ecological indicators: Cycling indices; Ecological indicators: Biotic integrity; Systems ecology: Ecological Network Analysis, ascendancy; Systems ecology: Systems ecology