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ПЕТЕРБУРГСКИЙ ИНСТИТУТ ЯДЕРНОЙ ФИЗИКИ  
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Order in Physical and Living Systems.  
Principal Differences in Quantitative  
Characteristics and Mechanisms  
of Maintenance Do Not Allow  
a Similar Description

УДК 910.1 Упорядоченность в физических и живых системах:  
Принципиальные различия в количественных характеристиках и  
механизмах поддержания не допускают аналогичного описания

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#### Аннотация

Замкнутые системы подчиняются второму началу термодинамики и не могут спонтанно увеличивать свою упорядоченность. В открытых физических системах, находящихся в потоках внешней энергии, возникают дополнительные макроскопические степени свободы ("ячейки памяти"), число которых возрастает с увеличением потока и упорядоченности внешней энергии. Биологические системы характеризуются молекулярными степенями свободы, плотность которых более чем на двадцать порядков превосходит плотность макроскопических степеней свободы любых открытых физических систем в равных потоках внешней энергии. Это показывает, что самоорганизация физических систем во внешних потоках энергии и самоорганизация и эволюция живых систем имеют принципиально разную природу и не могут описываться аналогичными нелинейными уравнениями.

#### Abstract

Closed systems obey the Second Law of Thermodynamics being incapable of spontaneously increasing the degree of their orderliness. In open physical systems existing in the fluxes of external energy there may arise additional macroscopic degrees of freedom (information memory cells). Their number grows with increasing power and orderliness of the external energy flux. Living systems are characterised by molecular (instead of macroscopic) degrees of freedom. In equal energy fluxes, the volume density of biological molecular degrees of freedom exceeds that of macroscopic degrees of freedom of any open physical systems by more than twenty orders of magnitude. This suggests that self-organisation of physical systems in external energy fluxes and self-organisation and evolution of living systems are fundamentally different. It follows that non-linear equations of physical kinetics that describe physical self-organisation and have been recently claimed to be capable of explaining evolution and other biological phenomena as well, are not applicable for description of information gain in living systems.

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## 1. INTRODUCTION

As is well-known, closed systems tend to a stable state of minimum order (maximum disorder, i.e. entropy). Processes of spontaneous increase of order are impossible in closed systems. This statement is known as the Second Law of Thermodynamics. Open physical systems, i.e. those consuming fluxes of external energy, may increase their orderliness. Such processes of increase of order are called for physical self-organisation.

In a physical system finding itself in a state far out of equilibrium with a high value of accumulated potential energy, there may arise powerful avalanche-like ordered processes tending the system to the equilibrium state. Examples of such processes are avalanches themselves that form due to the gravitational energy of snow masses in the mountains; cyclones and tornadoes feeding on energy which accumulates over prolonged periods of water evaporation and is quickly released during condensation of the water vapour; earthquakes with their energy coming from deformations of the Earth's core, and others. A state far out of equilibrium with accumulated potential energy is often referred to as a state of self-organised criticality (Bak *et al.* 1987; Cross & Hohenberg 1993).

One of the most common in the Earth's environment and best studied examples of physical self-organisation is the turbulent flow of gases and liquids. At some critical value of the fluid stream velocity the flow no longer remains spatially uniform (laminar). There forms a *pattern* of non-random macroscopic structures (e.g. turbulent eddies) with definite spatial characteristics (e.g. size) (Eckmann & Ruelle 1985; Cross & Hohenberg 1993). In other words, the process of space structurization occurs, which is associated with information enrichment of the system.

A characteristic property of physical self-organisation is the rigid correlation between the newly arising level of order and the value and character of the external energy supporting the considered physical process (Schuster 1984). Placing a system into a given energy flux, one observes a strictly determined probability distribution over all possible states of physical self-organisation. For example, the number and size of eddies in the turbulent flow of water in a river are dictated by the power of the water stream. In the same manner, the

character and probability of processes arising from states of self-organised criticality in a given system (e.g. the avalanche power or probability of occurrence) are determined by the character and peculiarities of the potential energy accumulated in the initial self-organised critical state.

In a state of physical self-organisation all individual newly arising ordered structures (e.g. turbulent eddies in the above considered example) continuously decay, and their ordered energy dissipates. Maintenance of an observable ordered state in a given external flux of energy is due to continuous generation of new ordered structures in place of decayed ones. When the external supply of energy is stopped or accumulated potential energy used up, all self-organised ordered states undergo decay and the system transits to the equilibrium state of maximum disorder. In this sense the word "self-organisation" is probably not the best one to characterise processes and states in physical systems. Rather than being *self-organised*, they are organised by the values and character of the external energy fluxes or accumulated potential energy.

States of physical self-organisation and processes of decay of the states of self-organised criticality are described by non-linear equations of physical kinetics (Eckmann & Ruelle 1985; Cross & Hohenberg 1993). At present many hopes are associated with attempts to describe processes of biological evolution and many characteristics of biological and ecological systems in a similar manner (Kauffman 1993; Boer *et al.* 1994; Sneppen *et al.* 1995; Pis'mak 1997). In the present article we aim at demonstration of the principal differences in organisation of physical and biological (ecological) ordered systems.

## 2. ARGUMENTS

Level of orderliness of a given system depends on the number of degrees of freedom ("memory cells") of the system. Degrees of freedom or memory cells can be interpreted as a set of structures (or variables) that are sufficient for description of the system. The more degrees of freedom, the more information can be stored in the system.

Orderliness of all physical systems that can be observed in natural fluxes of energy common to the Earth's environment, is characterised by *macroscopic* degrees of freedom. For example, certain types of turbulent flow of liquids and gases can be described by the

number and character of macroscopic eddies. Each degree of freedom is characterised by a certain value of the corresponding measurable variable, e.g. eddy size or average speed of fluid rotation. Due to limited sensitivity of any measurement, the overall number of possible values characterising each degree of freedom, is finite.

Orderliness (measure of information) of a given system is proportional to the number of degrees of freedom with uniquely determined value of the corresponding measurable characteristic. Hence, the maximum value of orderliness (information capacity) of the system can be estimated (to the accuracy of a logarithmic multiplier, see below) by the number of degrees of freedom describing the system, i.e. by the number of information memory cells. One can possibly say that appearance of new degrees of freedom in a given system leads to additional structurization (pattern formation) of the initially more homogenous (and, consequently, less information-rich) space of the system. (Note: The number of all possible states of a system with  $N$  degrees of freedom and  $k$  possible values of the measurable variable

characterising each degree of freedom is equal to  $k^N = 2^{N \log_2 k}$ . Information  $I$  (bits) stored in a system where for every one of  $N$  degrees of freedom we know concrete values of the measurable variable is defined as  $I = N \log_2 k$  if all the  $k$  values of the measurable variable are equally probable. (Using the identity

$\log_2 k = -\sum_{i=1}^k \omega_i \log_2 \omega_i$ , where  $\omega_i = 1/k$  is the probability of realisation of any of the  $k$  values, one may express information  $I$  as

$I = -N \sum_{i=1}^k \omega_i \log_2 \omega_i$ . This formula remains valid for the case when the probabilities  $\omega_i$  are different as well). Taking into account the extremely slow change of the logarithmic function with growing  $k$ , it is possible to estimate information solely by the number of degrees of freedom  $N$ .)

The number of degrees of freedom in physical systems usually grows with increasing flux of external energy. For example, in accordance with the Kolmogorov-Obukhov law, the number of eddies where the energy of fluid rotation dissipates, is proportional to the 9/4-th power of the Reynolds number (Monin 1986; Landau & Lifshitz

1995). (The dimensionless Reynolds number  $Re$  is equal to  $Re = \nu l / \nu$ , where  $\nu$  is velocity,  $l$  is characteristic length,  $\nu$  is viscosity, see also Appendix.)

It should be noted that appearance of  $N$  macroscopic degrees of freedom in external energy fluxes may either lead to *stochastisation* of the system when all possible sets of  $N$  values of the measurable characteristic are approximately equally probable over time, or to *organisation* of the system when some of them are more probable than the others. The first possibility is responsible for the seemingly controversial situation when those very phenomena (e.g. turbulence) that have been once described as self-organised, are elsewhere referred to as *chaotic* (Cross & Hohenberg 1993; Schuster 1984). The word *chaos* here pertains the temporal behaviour of the system and reflects the fact that it often proves impossible to predict the exact behaviour of the system from initial conditions (e.g. to predict the exact localisation of continuously pulsating eddies at a given timepoint). However, the unpredictable *temporal* behaviour of the system does not change the fact that the system remains organised *spatially* with discernible macroscopic degrees of freedom characterised by definite values of measurable variables. An observer standing on a river bank and watching the continuously arising and dissipating eddies and waves in the water flow around a large stone, may describe very definitely the average number, size and localisation of these ordered structures.

When the external energy flux is stopped, macroscopic memory cells disappear together with both possibilities of either stochastisation or organisation of the system and information of the system becomes zero. This can be compared to a physical system where the absolute temperature (and, consequently, thermodynamic entropy) is approaching zero. Such a system transits to the basic state which is characterised by only one molecular memory cell with a single possible physical state of it. Therefore information of this system turns to zero as well (Brillouin 1956).

In maximum energy fluxes observed in the Earth's natural environment the degrees of freedom of a physical self-organised state retain their macroscopic size. Their density per unit macroscopic volume remains limited.

This can be illustrated by a simple but environmentally very important example of a system with turbulent flow of air considered

relatively far from solid boundaries of the system (e.g. the Earth's surface). The number of degrees of freedom of such a system is determined by the number of macroscopic eddies within which the energy of matter rotation dissipates (Landau & Lifshitz 1995). Dependence of the density of degrees of freedom,  $n$ , on energy density per unit air mass,  $\varepsilon$ , can be obtained from the well-known Kolmogorov-Obukhov law (Landau & Lifshitz 1995) in the following form (see Appendix), Fig. 1:

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

where  $n_0 = 1 \text{ m}^{-3}$ ,  $\varepsilon_{cr} = 10^{-3} \text{ W kg}^{-1}$  is the critical energy density which determines transition to turbulence. (It is assumed that turbulence is absent at air velocities less than  $1 \text{ m sec}^{-1}$  which corresponds to the Reynolds number  $Re \leq 10^4$  given the atmospheric boundary layer of about  $l \sim 1 \text{ km}$ ).

The inclined solid line in Fig. 1 describes the density of the number of turbulent degrees of freedom (eddies) of the air masses dependent on the consumed power density per unit air mass,  $\varepsilon$ , as determined by Eq. (1). Flow of natural water masses, as well as other self-organised physical processes in the natural environment, are on average characterised by smaller velocity values and, as a consequence, by several orders of magnitude fewer degrees of freedom. This makes it reasonable to assert that natural ordered physical processes are unlikely to reach far out of the shaded triangle (II), Fig. 1.

In contrast to physical self-organised systems, orderliness of biological systems is characterised by molecular (instead of macroscopic) degrees of freedom or memory cells. Their number can be estimated by the number of base pairs in the DNA molecules that carry genetic program of living cells' functioning. The density of such molecular degrees of freedom exceeds  $10^{24}$  per  $1 \text{ m}^{-3}$ : the average number of base pairs (bp) in DNA molecules of a single cell equals  $10^6$  bp in prokaryotes,  $10^9$ - $10^{11}$  – in eukaryotes (Hinegardner 1976); the number of living cells per unit metabolically active volume equals  $10^{18}$  for prokaryotes and  $10^{15}$  – for eukaryotes (Gorshkov *et al.*, 2000). Hence, there exists a fantastic gap between quantitative characteristics of orderliness of physical and biological (ecological) systems. This gap

is determined by a number greater than  $10^{20}$ , Fig. 1. It follows that no changes of energy fluxes in the environment are able to increase the existing level of biological and ecological orderliness.

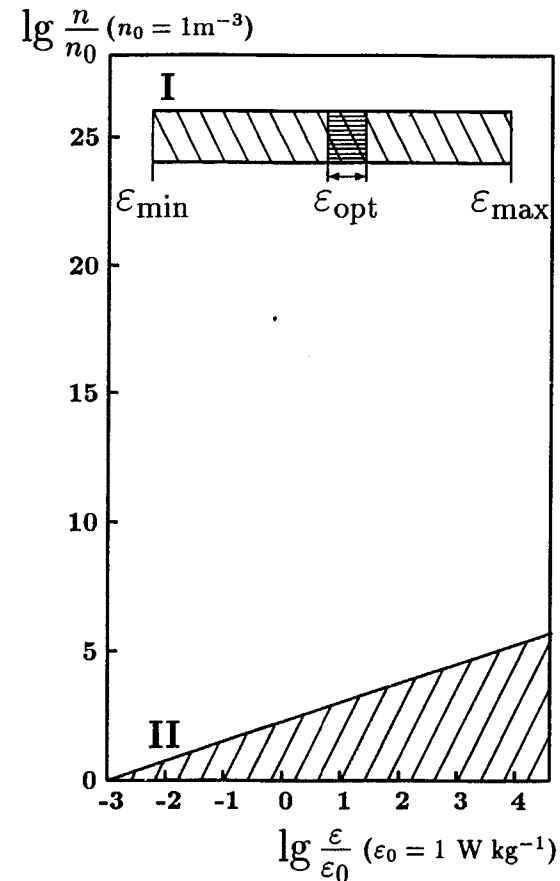
As known already from the time of Louis Pasteur, life cannot arise spontaneously in any external conditions. Experiments aimed at discovery of spontaneous generation of living organisms from organic materials were abandoned as early as in the nineteenth century, in fact nearly simultaneously with (although independently of) the recognition of impossibility of creation of perpetuum mobiles and formulation of the laws of thermodynamics. Impossibility of spontaneous generation is a fundamental and non-trivial property of living objects. It essentially means that the level of orderliness of biological objects is so high that it cannot be generated (and, consequently, cannot be maintained either) by whatever fluxes of external energy.

Instead, orderliness of organisms of every species is maintained during the whole period of species existence of the order of several million years due to internal processes of competitive interaction of individuals in populations and elimination in the course of natural selection of individuals with lowered orderliness and resulting lowered competitiveness. The appearing vacancies in the population are filled by the progeny of normal individuals with retained level of orderliness.

**Fig. 1. Organisation of physical and living systems with respect to the density of consumed energy.**

Vertical axis: decimal logarithm of the number  $n$  of degrees of freedom (memory cells) of the system per unit volume ( $m^3$ ) of physical systems and per unit of metabolically active volume ( $m^3$ ) of living systems. Horizontal axis: decimal logarithm of the external energy power consumed by unit mass (kg) of the system,  $\varepsilon$  [ $W\ kg^{-1} = m^2\ sec^{-1}$ ]. Areas occupied by biological (I) and physical (II) systems are hatched.

$\varepsilon_{min}$  corresponds to the observed minimum of metabolic power of existence (encountered in the largest protozoa, invertebrates, cold-blooded vertebrates, (Gorshkov 1981));  $\varepsilon_{max}$  corresponds the observed maximum of metabolic power corresponding to the highest possible rate of bacterial division and record jumps of animals, Table 1. Power density values in the interval  $\varepsilon_{min} \leq \varepsilon \leq \varepsilon_{max}$  are encountered in species with all registered genome sizes, from  $10^6$  bp in bacteria to  $10^9$ - $10^{11}$  bp in plants and animals.  $\varepsilon_{opt}$  (cross-



hatched) corresponds to the area of optimal metabolic power of existence encountered in more than 90% species of the biosphere irrespective of their genome size.

The inclined solid line describes the density of the number  $n$  of turbulent degrees of freedom (vortices) of the air masses as dependent on the power density  $\varepsilon$  per unit air mass, see Eq. (1) and text. Note that if we continue the inclined solid line in Fig. 1 to the right, it will reach values of orderliness common to living systems at a power density exceeding  $10^{32}\ W\ kg^{-1}$ . It is clear that at such fantastic values of power no stable molecular structures necessary for appearance of life could form.

Competitive interaction and reproduction of normal individuals requires energy expenditures. This necessitates consumption by life of external energy from the environment. However, consumption of external energy plays a principally different role in living systems as compared to ordered systems of physical nature. Orderliness of self-organised physical systems is completely determined by characteristics of the consumed energy. Physical orderliness arises in the presence of external energy fluxes, is supported by them and inevitably decays when the external energy supply is stopped. By contrast, in the absence of competitive interaction and selection, genetic orderliness of organisms of any species decays (degenerates) **even though the individuals may continue to feed and reproduce consuming energy from the environment**. This property of living systems explains why there are no species in the biosphere that would consist of individuals (or pairs of individuals) that never interact with each other and never form populations. Consideration of an imaginary ultimate case of a totally diversified biosphere where every species consists of a single individual (single pair of individuals) strikes by its sharp contrast with reality.

Formation of population is necessary for competitive interaction and selection to be switched on, which is the only guarantee against decay of genetic information of the species. The ability to reproduce alone cannot sustain genetic orderliness of any species. Reproduction essentially means copying the genetic material of the parents and the development of a new individual on this basis. Due to an unavoidable erosion of information before and during copying, the newly-born individuals are on average inevitably characterised by a lower degree of orderliness than their parents. In the absence of competitive interaction and selection this would finally lead to loss of viability and extinction of life as a whole. The very ability to reproduce is subject to decay, as well as all other highly-ordered properties of life.

Another critical difference is that — in contrast to the processes of external energy consumption that stabilise orderliness of self-organised physical systems — processes of competitive interaction, natural selection and reproduction that stabilise biological orderliness, **do not depend on characteristics of the consumed**

**external energy fluxes (nutrition)**. Instead, they are determined by the level of organisation of living objects themselves. This is clearly manifested by the fact that the metabolic power of living beings vary within universal for the whole life limits from  $5 \cdot 10^{-3}$  to  $3 \cdot 10^3$  W kg<sup>-1</sup> irrespective of the store of genetic information of the species (estimated as its genome size), Table 1. For example, bacteria with their genome sizes of the order of  $10^6$  bp may achieve the same metabolic power as do muscle cells of certain grasshoppers and mammals (with their genome sizes exceeding those of bacteria by three and more orders of magnitude, Table 1) during the highest possible jumps of these animals. These observations show that indeed the store of genetic information of living objects is independent of the power of external fluxes of energy (nutrition) consumed by living organisms.

Evolutionary processes (understood as processes of appearance of new species) are based on mutagenesis and natural selection of individuals in populations of biological and ecological systems. Evolution represents a true process of self-organisation independent of external fluxes of energy. Non-linear equations that are valid for description of physical self-organisation cannot therefore remain adequate for biological self-organisation, i.e. evolution. Neither can they describe the existing organisation of biological and ecological systems that arise once as products of biological evolution. All this pertains any level of organisation of living objects, from cells to multicellular organisms and ecological communities.

Transition of an ordered physical system, from one state to another (described as a change in probability of realisation of a finite number of possible final states) is dictated by the character of external energy acting on the system. Meanwhile changes in biological orderliness generated by spontaneous mutations are random and independent of changes in nutrition fluxes.

**TABLE 1.** Absence of correlation between the store of genetic information of a species (estimated by 1C genome size) and consumed external power per unit live mass (estimated as mass-specific metabolic rate), as exemplified by different living cell types and metabolic processes.

Species		Haploid genome size	Metabolic rate per unit mass	Comments on the type of metabolic processes	Data sources
Common name	Latin	(10 <sup>9</sup> bp)	(W kg <sup>-1</sup> )		
Bacterium	<i>E. coli</i>	0.005	7·10 <sup>9</sup>	Calculated from the maximum observed rates of bacterial division	G1, M1
Bird (budgerigar)	<i>Melopsittacus undulatus</i>	1.2	12	Minimum observed mass specific metabolic rate	G2, M2
Mammal (minke whale)	<i>Balaenoptera acutorostrata</i>	~4	0.5	Basal mass-specific metabolic rate	G3, M3
Mammal (bushbaby)	<i>Galago senegalensis</i>	4.7	(5~7)·10 <sup>9</sup>	Maximum power output per unit muscle mass during vertical jumps	G4, M4
Frog	<i>Hyla cinerea</i>	4.9	5·10 <sup>2</sup>	Maximum power output per unit muscle mass during vertical jumps	G5, M5
Insect (grasshopper)	<i>Shistocerca gregaria</i>	10.7	5·10 <sup>9</sup>	Maximum power output per unit muscle mass during vertical jumps	G6, M6
Plant (spruce)	<i>Picea abies</i>	~ 50	1	Metabolic power of dark respiration per unit mass of needles	G7, M7

**Genome size data:** [G1] – Blattner *et al.* 1997; [G2] – Bachmann *et al.* 1972; [G3] – estimated as the genome size of a congeneric species, *Balaenoptera edeni*, reported by Ginatulin 1984; [G4] – Ginatulin 1984; [G5] – Goin *et al.* 1968; [G6] – Fox *et al.* 1970; [G7] – estimated as the genome size of a congeneric species, *Picea alba*, Nagl 1976. **Metabolism data:** [M1] – Gorshkov 1981; [M2] – Hinds *et al.* 1993; [M3] – Hind & Gurney 1997; [M4] – Alexander 1975; [M5] – Marsh & John-Alder 1994; [M6] – Katz & Gosline 1993; [M7] – calculated from the data of Fig. 36 of (Larcher 1976).

Processes similar to those arising during decay of physical states of self-organised criticality may arise during decay of biological organisation as well. Various kinds of pathology (hallucinations, cardiac arrhythmia etc.) have been reasonably well described with help of non-linear equations usually applied for physical systems (Ermentrout & Cowan 1979; Glass *et al.* 1983). However, these manifestations of *decay* of the initial biological organisation (normal cardiac rhythms, normal vision) have nothing in common with *production* of orderliness in biological systems.

### 3. FINAL COMMENTS

In spite of the fact that life on Earth exists in the external flux of solar energy and consumes this energy which ensures metabolic processes of living beings, the level of orderliness of life is not determined by the value and character of the energy consumed. Life is characterised by a level of organisation (information store) which exceeds level of organisation of possible ordered physical states generated by solar and other types of external energy in the Earth's environment, by more than twenty orders of magnitude, Fig. 1.

In this sense all isolated self-reproducing, normally feeding and metabolically active living beings (single parthenogenetic organisms or heterosexual pairs of organisms in the case of sexual reproduction) behave like closed physical systems. Placed outside a population, i.e. in the absence of competitive interaction and selection that normally perform the stabilising function with respect to biological orderliness, such organisms and their progeny may only decrease their level of organisation. One has therefore good grounds to say that isolated living objects obey a biological analogy of the Second Law of Thermodynamics, in spite of consumption of energy from the environment.

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