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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

ГАТЧИНА

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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.

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 ω_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