ENTROPY AND DYNAMICS OF HIERARCHICAL SYSTEMS IN THE ANALYSIS OF THE EVOLUTION OF LIVING CREATURES

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Rezumat. Lucrarea prezintă bazele teoriei termodynamice ale evoluției biologice. Este subliniat principiul dezvoltării ierarhice a vieții și interacțiunea dintre entropie și informație în decursul procesului evolutiv.

Living creatures both functionally and morphologically are the most complex and highly organized among all natural objects. It should be noted that the behavior of living systems, including that on the cellular level, is nonequilibrium. In addition, strong inhomogeneities are observed on any level.

The course of evolution depends on changes in certain characteristic parameters, which are induced by the outer world and can be called controlling. Denoting them by \( \lambda \) for the equilibrium state, we may describe the evolution of parameters of the system under consideration in the simplest case (equilibrium state) in the form

\[
F_i(\{X_i\}, \lambda) = 0, \tag{1}
\]

where \( F_i \) is an arbitrary complex function depending on macroscopic variables of the system and parameters \( \lambda \).

This relation imposes certain limitations. For example, the laws of evolution have to be such that the requirement of positiveness of temperature and chemical concentration characteristic of this system should be satisfied.

As is well known, nonequilibrium systems are characterized by a tendency toward irreversibility, which is described by entropy \( S \), defined as a logarithm of the number \( W \) of possible states of the system under the given conditions:

\[
S = k \ln W. \tag{2}
\]

A possible state of the system is determined by a physical parameter, which is characterized by the multiplier \( k \). The quantity \( W \) can be a complex function of signs and conditions.

If the possible state of the system is characterized by a distribution function \( f(x, t) \), then relation (2) takes the form

\[
S(t) = -k \int f(x, t) \ln f(x, t) dx. \tag{3}
\]

Here, depending on the specific form of \( k \) and the character of averaging in writing \( f(x, t) \), expression (3) can describe entropy in the Boltzmann, Shannon, or Gibbs form. In particular, on this basis, a distribution function for entropy is introduced in [2].

The determination of the Boltzmann information (entropy) is always connected with the variational problem of finding the maximum of probabilities, the solution of which leads to Lagrange multipliers. This means that, for the Boltzmann information, there exists an identical mechanical description based on energy with the properties of a potential of forces, characterized by Lagrange multipliers, and quantities in the form of entropy itself.

We would remind that Lagrange multipliers represent variables with the help of which one constructs the Lagrange function in investigating problems of a conditional extremum.

In variational calculus, with the use of Lagrange multipliers, it is convenient to obtain the necessary conditions of optimality in the problem of a conditional extremum as the necessary condition of an unconditional extremum of a certain composite functional.

The classical open thermodynamic systems are characterized mainly by the interaction of energy with information. In living systems, there is no exchange between energy and information or flux of information directly, which would in themselves play a substantial role in the life processes.

For nonisolated systems, which exchange energy and substance with the outer environment, the change in entropy represents a sum of two terms. One of them \( d_eS \) is attributable to the exchanges taking place here. The second \( d_iS \) is induced by the processes inside the system [3]:

\[
\frac{dS}{dt} = \frac{d_eS}{dt} + \frac{d_iS}{dt}. \tag{4}
\]

For an isolated system, \( d_eS = 0 \), and relation (4) is reduced to \( dS = d_iS \geq 0 \).

For irreversible processes (chemical reactions, heat transfer, diffusion, viscous dissipation, etc.), it is possible to determine the corresponding internal flux \( I_i \), reflecting the rate of course of the process, and also
the driving force \( X_i \), reflecting the corresponding irreversible limitation. The following linear relation between \( I_k \) and \( X_i \) can be established:

\[
I_k = \sum_i L_{ki} X_i ,
\]

(5)

where \( L_{ki} \) are phenomenological coefficients.

According to the Onsager principle, the additional relation \( L_{ki} = L_{ik} \) [4] is satisfied for equation (5).

Depending on characteristics of the system under consideration, the quantity \( d_S S \) can be both positive and negative. If \( d_S S \) is negative and exceeds, by its absolute value, \( d_S S \), then certain stages of evolution can proceed with a total decrease in entropy:

\[
\frac{dS}{dt} < 0 .
\]

(6)

This means that, in the course of evolution, the degree of order decreases due to the outflow of entropy.

An important distinctive feature of life energy as compared with engineering thermal processes consists of the fact that it uses electrochemical thermodynamic cycles. Here, living systems use not internal energy (as a heat engine) but free energy, i.e., thermodynamic potential, whose differential (with regard for chemical and electric energy) is

\[
dF = -S \, dT + \nu \, dp + E \, dD - \sum_i n_i \, d\mu_i ,
\]

(7)

where \( n_i \) is the concentration and \( \mu_i \) is the chemical potential.

A principal feature of free energy consists of the fact that entropy \( S \) is not among the independent variables of problems. This means that the interaction of energy with the amount of information coming from without is not determining for the life processes and its evolution. The most important factor for genetic mechanisms is the property of substance, and, hence, chemical potential has to be here an independent variable. In living systems, energy production exceeds its dissipation, and the energy excess is accumulated.

Using some ideas of information theory, A. N. Kolmogorov introduced the concept of dynamic entropy, which is also called \( K \)-entropy and is denoted by \( h \) [5]. He defined \( K \)-systems as quasi-sureal ones, which emphasizes their analogy with regular random processes [6].

A substantial development of the concept of a \( K \)-system was connected with somewhat more special Ornstein’s theory [7], where auxiliary random processes are used in a direct way. A random stationary process can be considered as a process \( \{X(t)\} \) for which the space \( \Omega \) of sample functions of \( \omega \) serves as a space of elementary events. Note that a sample function is a function \( X = X(t) (\omega) \) of argument \( t \), which corresponds unambiguously to every observation of the random process \( X(t) \in E, t \in T \), where \( \{\omega\} = \Omega \) is the set of elementary events. The random process \( X \) is characterized by a probabilistic measure in the space of sample functions.

In the course of evolution, dynamic phenomena are possible, and the analysis of such systems is based on \( K \)-entropy.

Life cannot exist without the mechanism of energy production for metabolism. The principal feature of life as an open thermodynamic system consists of the fact that the outer environment interacts with its forms and processes on the basis of synthesis of information by means of changes in the entropy normalization. Since the synthesis of information is a change in the signs and conditions in the determination of entropy, hierarchy is a distinctive feature of the synthesis of genetic information [8 – 10]. This means that every time a change in the signs and conditions creates a local way of counting entropy. Morphological hierarchy represents a symbiosis becoming more and more enlarged.

The hierarchical series for entropy as a measure of information was written in the form

\[
S_k = S_0 + S_1 + S_2 + \ldots \left[ 0, 1, 2, \ldots (k - 1) \right] ,
\]

(8)

where the entropy of the \( k \)-th kind of living substance is

\[
S_k = S_{k,gen} + S_{k,self} .
\]

(9)

Here, \( S_{k,gen} \) is the sum of the measure of genetic information and \( S_{k,self} \) is the measure of information in the processes of self-organization, for which the properties of elements of the system are created by the quantities \( S_{k,gen} \).

The number showing in what ratio the amount of information is reduced in going to the next hierarchy of synthesis of information is called the value of genetic information

\[
Z_k = S_{k,gen} / S_{(k+1)gen} .
\]

(10)

The value of genetic information falls with the evolution of life [5].

Genetic information as the memorization of a random choice always arises as a result of interaction with the environment, where the realization of memorization in the form of multiple reproduction occurs on the basis of processes that differ in principle from those which have created the initial genetic chance. This stepwise synthesis of information has a hierarchical character and is described by entropy. The latter is determined by the probability of these or those processes, and, hence, the forms of life get complicated, entropy within the given step of hierarchy decreases.

We can agree with the assertion [8 – 10] that life is conditioned by the hierarchical synthesis of chances, and, for every subsequent hierarchy, its own conditions, differing from the conditions at the previous steps, are synthesized. As a result, the entropy created by new states of the system, which are controlled by new conditions, is added to the entropy describing its previous state. Therefore, the evolution of life to the side of more organized forms is a process of hierarchical increase in total entropy. Life represents a natural (and, hence, spontaneous) process of increase in entropy. Exactly the hierarchy of synthesis of information is the evolution of life.
REFERENCES
