Chapter 2
General Thermodynamic Characteristics of Living Systems

This chapter can be considered as the author's contribution into the understanding of *what life is*. This theoretical investigation corresponds with the second goal of astrobiology that is formulated as "to determine the general principles governing the organization of matter into living systems" in the first issue of the journal *Astrobiology* (Morrison 2001). The investigation is carried out through the comparison of main types of natural systems (the both biological and non-biological ones) involved into consideration in the framework of astrobiology. The key criterion for the conducted comparison is a system's thermodynamic macrostate, i.e., the balances between the contributions of entropy, free energy, and information during its existence in the outside world (including exchange processes). According to the author's opinion, such comparison is a required step in our efforts to get the 1st goal of astrobiology formulated as "to understand how life arose on the Earth" (Morrison 2001). Astrobiology is a very appropriate field to study both origin of terrestrial and extraterrestrial life, as general principles governing the organization of matter into living systems should be common for the entire Universe.

2.1 Thermodynamic Background for Comparison of Natural Systems

2.1.1 Key Notions: Entropy, Free Energy, and Information

Entropy (S), free energy (F), and information (I) are the key notions determining the macrostate of a system and its trend of evolution. Entropy (S) is an integrated characteristic: It cannot be reduced to the sum of a system's components and described by strict equations only. When describing self-organization in open systems, the entropy notion serves as both the measure of energy value (the more the entropy, the less the useable energy value) and the measure of disorganization

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(the more the entropy, the higher the disorganization) (Ebeling et al. 1990; Lin 1996). High-value energy can be defined in terms of free energy. Free energy of a simple physical system is estimated from the following equation:

$$A = U - TS, \tag{2.1}$$

where A is free energy, U—inner energy, T—absolute temperature, and S—entropy.

This equation establishes the dependence between inner and free energy, as well as between entropy and free energy, of a system. The whole inner energy of a system can be subdivided into two parts: The first one is bound energy, which cannot be converted into work, and the second one is free energy, which can be converted into any kind of work (mechanical, chemical, etc.). Macroscopic work under isothermal conditions is defined by the difference of free energy (initial and final states of a system) but not by the difference of inner energy. This is a physical sense of the notion «free energy». In a course of the isothermal transition of a system from the state with value of free energy A_1 into the state with value A_2, the system carries out work $A = A_1 - A_2$ (in case of a reversible process).

Value of free energy of a simple physical or chemical system can be precisely estimated by means of definite equations. For instance, we can precisely estimate a change in free energy during a chemical reaction. Unlike simple physicochemical systems, all biological systems are characterized by irreversible processes and extraordinary high complexity. Due to this reason, free energy of biological systems cannot be precisely estimated. However, even in biological systems, the notion "free energy" saves its general sense providing their ability to carry out work. So, free energy is a very appropriate criterion to compare various types of natural systems—simple and complex, and non-living and living. It is implied that the term "free energy" used in this book corresponds to Gibbs energy. But Gibbs energy is applicable for strict estimations. As the author uses the term "free energy" in a general sense, he denoted it as F (not G or A).

A smaller part of entropy transmission is connected with informational processes. Putting of information (I) into a system reduces its disorganization. From the physical point of view, information can be understood as a value that reduces uncertainty in a system state. Transfer of information in a system is always related to the corresponding transfer of entropy. An information flow represents a special case of entropy transfer between two systems. Informational entropy is the form of entropy directly connected with informational processes (Ebeling et al. 1990; Feistel and Ebeling 2011). So, entropy, free energy, and information are interrelated values. Generally, contributions of free energy and information decrease entropy in a system, and vice versa. This thought can be expressed in various but similar formulations. For instance, we can read in Wikipedia the following definition: "In physics, entropy, meaning "transformation", is a measure of the unavailability of a system's energy to do work."

In open systems, the entropy change (dS) adds up of the internal production of entropy (d_iS) and the entropy exchange with the outside world (d_eS). Therefore, the value of entropy change can be positive or negative, dependent on the exchange in the substance, energy, and information with the surroundings. In an open system, entropy can be decreased if the system exports entropy ($d_eS < 0$), and the export exceeds the internal entropy producing, i.e.,

$$dS < 0 \text{ if } |d_eS| > d_iS \geq 0 \qquad (2.2)$$

The inequality 2.2 may occur only under nonequilibrium conditions, because near the equilibrium, the inequality $d_iS > 0$ is always dominant. The entropy export is a non-spontaneous process that needs the "entropy pump." The pump works at the expense of free energy inflow from the external or internal source. The energy and structural conditions necessary for entropy export are as follows (Ebeling et al. 1990):

1. Supply of free energy into a system must prevail over the internal energy change and energy expenditure because of the entropy production.
2. Formation of specific low-entropy structures in a system in the course of self-organization. To start the formation of such structures, the entropy export must exceed a certain critical value (i.e., self-organization is a supercritical process).

2.1.2 *Universal Spontaneous and Non-spontaneous Processes Related to Entropy Change*

Multitude of processes that take place in the Universe results in entropy change. It is known that they can be united into the two types of universal processes: *spontaneous* processes resulting in increase in entropy and *non-spontaneous* ones resulting in its decrease. Due to spontaneous processes, a system transits into the most probable state, while non-spontaneous processes facilitate its transition into the less probable state. The principal distinctions between these opposite processes are tabulated in Table 2.1. Spontaneous processes go on perennially and

Table 2.1 Principal distinctions between spontaneous and non-spontaneous processes

A spontaneous process	A non-spontaneous process
Does not demand expenditure of energy (proceeds by itself)	Demands expenditure of energy
Leads to decrease in the corresponding gradient (proceeds down the energetic gradient)	Leads to the increase in the corresponding gradient (proceeds against the energetic gradient)
Results in entropy rise and free energy lessening	Results in entropy lessening and free energy rise
Increases chaos and disorganization in a system	Increases level of organization/order in a system

everywhere in the Universe by themselves; they do not require expenditure of energy to proceed.

Non-spontaneous processes demand energy expenditure. Due to this reason, non-spontaneous processes take place only in combination with spontaneous processes. Any non-spontaneous process proceeds at the expense of the corresponding spontaneous process taking a part of its energy. This is a reason why energy of a non-spontaneous process is always lower than energy of the corresponding spontaneous process. In natural systems, spontaneous processes are often designated as *basic* processes, while developing on their basis, non-spontaneous processes are known as *coupled* ones.

One more notion that is important to understand nature of these universal processes is an energy gradient. Gradient is a vector indicating the direction of maximal change in a certain value in space. The stronger the change, the bigger the gradient. Energy gradient expresses any change in energy over time or space. It can be related to various types of gradients: temperature, pressure, concentration of components, electric field, gravity, etc. Spontaneous, or basic, processes result in decrease in an energy gradient (i.e., proceed "down" of it), while non-spontaneous, or coupled, ones lead to the increase in the gradient (proceed "against" of it). For instance, work of an electric battery leads to its discharging. This is a basic process that results in lessening of the electric field gradient (voltage). Charging of the battery increases the electric field gradient. This is a coupled process that demands expenditure of energy. Cooling of a glass of hot water is a spontaneous process; it reduces the gradient of temperature between the glass and the outside world. On the contrary, heating of water in a kettle is a non-spontaneous process; it cannot proceed by itself and needs energy supply. This thesis is a consequence of the second law of thermodynamics; its initial formulation given by Rudolf Clausius is the following: *Heat cannot pass spontaneously from a cooler to a hotter body*. The opposite direction of a gradient changing is the best criterion to distinguish spontaneous and non-spontaneous processes. Some more examples of these processes are given in Table 2.2.

Table 2.2 Examples of spontaneous and non-spontaneous processes

Gradient	Example of a spontaneous process ("down" the gradient)	Example of a non-spontaneous process ("against" the gradient)
1. Temperature (heat energy)	Cooling of a container with liquid	Heating of a container with liquid
2. Pressure	Deflation of air from a tire	Pumping of air into a tire
3. Concentration of components	Gradual equalization of a salt concentrations in a water volume during the dissolving (diffusion process)	Growth of the concentration gradient in a living organism during molecule transference from their low content locations to higher ones, in defiance of the second law of thermodynamics (active transport)
4. Gravity (hypsometric)	Fall of rain drops	Ejection of hot water from a geyser

So, all the time the counter spontaneous and non-spontaneous processes proceed in the Universe at different levels and in various modifications. A result of their contradictory interaction consists in entropy change connected with free energy and information changes. This result occurring in a certain part of the Universe's spatiotemporal continuum can be approximately expressed through the balances "entropy/free energy" (major part of entropy) and "informational entropy/information" (smaller part of entropy). As stated above, such balances cannot be precisely estimated in large complex natural systems. Besides, free energy, information, and entropy cannot be strictly correlated because they are not measured in the same units (energy is measured in joules, information—in bits). Due to this reason, instead them, the author uses less strict terms "contribution of free energy (F)," "contribution of information (I)," and "contribution of entropy (S)." Such qualitative analysis of the balances allows us at least evaluate prevalence of the contributions into a natural system through examining into the occurred transformations in it. For instance, the general tendency of free energy accumulation in the Earth's biosphere is obvious during four billion years (it will be considered further). Therefore, the balance for the biosphere can be expressed through the following inequality: F > S (contribution of free energy > contribution of entropy).

2.2 All-Round Comparison of Biological and Non-biological Systems

2.2.1 Classification of Natural Systems Based on the Thermodynamic Criteria

The original classification of natural systems was elaborated to compare biological and non-biological systems. Its previous version was published in Kompanichenko (2003). The classification embraces main types of natural systems that are involved into consideration in the framework of astrobiology. This classification is thermodynamic as it is based on the balances "entropy contribution/free energy contribution" inside natural systems as well as between them and their surroundings. The important taxonomic criterion is a free energy surplus or its deficit in a system in regard to its surroundings. In other words, the criterion determines direction (sign) of the free energy gradient between a system and the outside world (positive or negative). Surplus of free energy (the positive gradient) provides the ability of a system to carry out work, while its deficit (the negative gradient) indicates the disability to work. The notion «work» is the most general equivalent of various transformations occurring in a medium (environment) due to radiation of a star, eruption of a volcano, existence of biological organisms, and activity of human society. All the listed types of systems are characterized with surplus of free energy in respect of the surroundings. Unlike them, many other natural systems cannot execute work by own activity. For instance, a stone or harden flow of lava has not the free energy surplus; correspondingly, their free energy gradient with the outside world is negative. So, the chosen criterion seems very appropriate for comparison of natural systems.

2.2.1.1 Active and Passive Natural Systems

Based on the chosen criterion, natural systems of the Universe can be united into two broad groups.

1. Active, or self-complicating, systems having surplus of free energy in respect of the surroundings (Table 2.3). These systems concentrate free energy by own nature that provides their ability to execute work in the outside world. They are stars and their associations, active planets and satellites (possessing volcanic activity), magmatic systems (a column of magmatic chambers or a separate chamber), hydrothermal systems (rising flows of hot fluid in host rocks), all biological systems (from a cell to biosphere), and all social systems of different ranks whose activity in the environment is maintained by free energy generating in people.
2. Passive, or non-self-complicating, systems having not surplus of free energy in respect of the surroundings. These systems are unable to execute a work in the outside world independently, without application of the external forces. They are black holes; cosmic gas/dust clouds; massifs of igneous rocks, stones, and crystals; organic remains of soils; archaeological monuments of past civilizations; etc. The atmosphere and hydrosphere take intermediate position as they are able to carry out work at the expense of inner fluctuations (surf, hurricane).

Table 2.3 Classification of natural systems based on their free energy gradient in respect of the surroundings

	Natural systems		
Types of systems	Active, which possess free energy surplus in respect of the surroundings		Passive, which do not possess free energy surplus in respect of the surroundings
	Systems	*Their surroundings*	
Cosmic	Stars (and their associations), active planets, and satellites	Outer space	Black holes, cosmic gas/dust clouds, asteroids, meteorites
Geological	Magmatic and hydrothermal systems (on active planets)	Solid lithosphere of planets	Atmosphere, hydrosphere, lithosphere, massifs of rocks, stones, crystals
Biological	Living organisms and communities	Geospheres	Products of destruction: coal, oil, gas deposits, humus
Social	Different-rank communities of people	Biosphere	Archaeological monuments of past civilizations

Ability of active systems to carry out work in the surroundings is the first feature that distinguishes them from passive systems. The second distinctive feature consists in their ability for continuous complication of the internal structure. All active systems go through the moment of origination, development, reaching of the peak, aging, and dying. In general, this cycle implies rise of the complexity (organization) level at the ascending branch and degression of the level at the descending branch. The complexity increases through synthesis and cooperation (Table 2.4).

The ability of active systems for structural complication through self-development allows us to use one more term for their designation: «self-complicating systems». There exist self-complicating systems of different ranks. For instance, active planets or planetary biospheres are self-complicating macrosystems, while living cells or "cybotactic" groupings of magma represent self-complicating microsystems. The term «self-complicating system» particularly correlates with the term «self-organizing system». The notion of self-organizing system was suggested by Ashby (1964). He considered a self-organizing system as a self-adapting system, whose adaptation to changing conditions, or optimization of the control processes, is realized by means of changes in the control structure. Actually, the term «self-organizing system» is applicable only to biological and social systems having highly developed control structures. As for stars and active geological systems, the question about their control structures and the ability for self-adaptation is disputable.

Summing up, active systems possess three principal features that distinguish them from the passive systems: (a) the availability of surplus free energy providing their ability to carry out work in the surroundings; (b) self-complication of internal structure at the ascending branch of their existence; and (c) active exchange of energy and matter (as well as information in complex systems) with the outside world.

Table 2.4 Structural complication of active systems at the ascending branch of their cycle of existence

Stars	Magmatic systems	Hydrothermal systems	Biological systems	Social systems
Accumulation of more and more complex atoms in the course of thermonuclear reactions	Progressive polymerization of magma (related to increase in silica concentration) during evolution of magmatic systems	Complication of fluid structure through mass formation of complex compounds at the peak of hydrothermal systems evolution	Complication of structure and ties in a growing organism and the evolving biosphere	Complication of structure and ties during the transition from tribal societies to the planetary human civilization

2.2.1.2 Brief Description of the Active Systems in the Classification's Context

The description of main types of active natural systems is given below. It is composed of well-known knowledge, but the distinguished principal features are in a focus of the consideration.

Stars and Active Planets

A star is a gas (plasma) sphere where the thermonuclear reactions proceed. Stars and their associations originate in interstellar gas clouds. Since the moment of birth, a star goes through the cycle of existence. In the course of its evolution, hydrogen (initial element of a star) gradually burns down and transforms into more complex elements. Heavy elements (iron, etc.) accumulate in a core of a star. A star dies off, when abundance of hydrogen is exhausted.

Two contradictory forces balance each other during lifetime of a star: (1) gravitational compression directed inside a star and (2) light (gas) pressure directed outside. Energy of a star is generated at the expense of thermonuclear reactions. The simplest one is proton–proton reaction (four hydrogen atoms form one helium atom). Other reactions (in particular, the carbon–nitrogen one) are responsible for the synthesis of more complex atoms. So, the inner structure of a star complicates in the process of evolution.

A star permanently radiates energy and from time to time throws out a part of own mass. The outflow of matter is maintained by light pressure. Some amount of substance (dust, meteorites, and comets), on the contrary, falls on a star. On the whole, this is the process of matter exchange between a star and the outer space directed mainly from a star into outer space. In the long run, the outflow of mass occurs at the expense of free energy generating in a star. This is a kind of work provided by huge surplus of free energy.

Active planets and satellites possess big surplus of endogenous energy responsible for their geological evolution. The geological evolution of Earth began about 4.5 billion years ago. Since the moment, the transformation of various geospheres (core, mantle, crust, hydrosphere, and atmosphere) and geological structures proceeds continuously. In general, the geological evolution is an irreversible process directed to the complication of geological structures, magmatic and ore formations, and composition of rocks. Geochemical evolution of Earth is defined by two opposite tendencies: differentiation (cleaning) and homogenization (mixing) (Verhoogen et al. 1970).

Spreading of the oceans and formation of new mountains are examples of grandiose work realizing at the expense of endogenous (free) energy of Earth. On the one hand, Earth dissipates a part of own endogenous energy into outer space; on the other hand, it is obtained exogenous energy from Sun. The exchange of matter takes place too. The Earth's atmosphere gradually loses gases into outer space that is compensated by means of gas inflow from the mantle and core. Another flow of matter (meteorites, dust) directs to Earth.

Besides Earth, there exist some other active cosmic bodies in the solar system, in which endogenous energy provides various kinds of giant work: Io, the Jupiter's satellite, where volcanic eruptions are observed; Europa, another moon of Jupiter, whose ice cover is flickered by plentiful recent tectonic faults; and Venus, possessing very thick atmosphere, in spite of gas dissipation into outer space. Complication of inner structure of planets (satellites) during their geological evolution, as well as intensive exchange of matter and energy with outer space, ceases, when they become cold and transform into passive systems. Our Moon is an example of such body.

Magmatic and Hydrothermal Systems

A magmatic system represents a magma chamber, or a column of magma chambers, stretching out from the asthenosphere to upper part of the Earth's crust. Magmatic systems in the upper mantle and crust begin to grow inside the asthenosphere layer (the depth between 50 and 300 km), at the expense of endogenous heat inflow from the Earth's bowels. This leads to the expansion of the melted rock volume. For thousands and millions years, magma moves forward to the surface forming a vertical column of chambers. Juvenile water (fluid), moving away from magma, gives an initial impulse to the evolution of hydrothermal systems. Fluid rises up to the subsurface zone through cracks and pores mixing with the groundwater of atmospheric origination. On reaching the surface, thermal water discharges in forms of hot springs, pools, and geysers. Hydrothermal systems in the Earth's crust represent recycling water flows heating at depth and cooling near surface.

Complication of a magmatic system structure proceeds in the course of its evolution. Formation of new magmatic chambers and their apophyses leads to morphological complication of the column and simultaneously complicates the inner structure of a melt by means of its progressive polymerization. According to the ionic-cybotactic theory, magma consists of microscopic «cybotactic groupings» of two contradictory types: long-range groupings (oxides Fe, Mg, Ca) and short-range ones ($Si_xO_y^{z-}$) (Esin and Geld 1966). These groupings continuously appear, grow, and destroy in magma, similar to living organisms in the biosphere. General trend of a magmatic system (column) evolution is related to the rise of silica concentration and correspondingly the short-range grouping in its frontal (upper) zone. In the most cases, a final result of the magmatic differentiation consists in the formation of acidic magma (sometimes rich in alkali); then, it crystallizes in the form of a granitoid massif. Acidic melt represents the highest level of polymerization. It consists of unbroken network of polymeric radicals of the type $Si_xO_y^{z-}$ (Esin and Geld 1966; Anfilogov et al. 1978; Kompanichenko 1984).

Similar structural complication takes place in the course of a hydrothermal system evolution. The post-magmatic hydrothermal process usually begins since the temperature 600–500 °C. The highest complexity of the solution structure is attained within the temperature interval from 350–300 to 150–100 °C. In this period, diversity and concentrations of complex and polymeric compounds (including hetero-organic ones) are maximal. The following decrease in temperature leads to the disintegration of soluble complex and polymeric compounds. This process is especially clear in zones with strong geothermic gradients (Fyfe et al. 1978). Korzhinsky (1994) distinguished four most universal stages of a hydrothermal process during temperature fall: early alkaline, acidic, late alkaline, and neutral.

Surplus of free energy in magmatic and hydrothermal systems directs the energy flow in the surroundings. The flow provides replacement, transformation, and assimilation of the host rocks. This work can be executed in various forms. For instance, the volcanic process can create new mountains, while the hydrothermal process can transform a low-temperature mineral association into a higher-temperature one.

Biological and Social Systems

The biological type includes systems of various ranks—from unicellular organisms and small populations (biotic microsystems), to ecological macrosystems and the entire biosphere (megasystem). A biotic (i.e., proper living) system exists inseparably with the environment. The term «biotic system» is usually used, when an organism, or community, is considered independently of the adjoining environment. Such consideration is conditional, because any organism may exist only through exchange of matter, energy, and information with the environment. The term «biological system» is more general and implies interaction the both constituents—organisms and their environment. The complication of inner structure of a growing biological system is obvious. Movement, hunting, and absorption of food are various kinds of the work executing by animals. The work of plants results in the change of the atmospheric composition, transformation of clay and sand into soil, and synthesis of biomass.

Biological regularities are in the background of all social systems. Therefore, social systems also possess the distinguished features of active systems: the ability to carry out work at the expense of free energy surplus, complication of inner structure, and exchange of matter, energy, and information with the environment. The general distinction of social systems from biological ones consists in their ability for exchange of highly organized information.

The general tendency to complication (or rise of order) in a course of the Universe evolution is well investigated. It is especially obvious if this process is considered starting since the Big Bang, when the elementary particles existed only. In Table 2.5, the author represents this tendency as two parallel and interrelated processes: the complication of matter and the complication of active natural systems (Table 2.5).

Table 2.5 Scheme of matter and active systems complication in a course of the Universe evolution

Evolution of the Universe	Stages of the Universe evolution							
Evolution of matter	Big Bang followed by the Origin of Stars	Elementary particles → Simple atoms (H, He) → Complex atoms	Origin of Planetary Systems	Simple molecules → Complex molecules → Polymeric organic macromolecules	Origin of Life	Proteins, genes, tissues, and other structures of organism	Origin of Intelligent Life	Buildings, spacecrafts, paintings, and other things created by humans
Stages of matter evolution		*Physical evolution of matter*		*Chemical evolution of matter*		*Biological evolution of matter*		*Social evolution of matter*
Evolution of active systems		Stars Galaxies Active planets		Magmatic systems Hydrothermal systems (on active planets)		Organisms Species Ecosystems Biosphere		People Settlements Countries Humankind
Stages of active systems evolution		*Evolution of astrophysical active systems*		*Evolution of geochemical active systems*		*Evolution of biological active systems*		*Evolution of social active systems*

2.2.2 Spontaneous and Non-spontaneous Processes in Passive and Active Natural Systems

It was stated above that spontaneous (basic) processes take place in all passive and active systems. Non-spontaneous (coupled) processes are the characteristic of active systems, while in passive systems, they are usually absent. For this reason, energy gradients in passive systems gradually decrease, and the processes in them come to various destructive events. Massifs of igneous rocks, mountains, stones or crystals, and harden flows of lava that belong to the passive type of natural systems gradually destroy. The same happens with the planets and satellites, which lost geological activity (Moon is the example). Archaeological monuments of past civilizations gradually ruin too. This feature corresponds with the disability of passive systems for self-complication and/or self-organization.

Non-spontaneous (coupled) processes occur in some kinds of natural systems, like the atmosphere and the ocean, which are intermediate between passive and active ones (they are not specially considered in this book). From time to time, the pressure gradient rises in local parts of the atmosphere (this is a result of the coupled process). Then, the wind or hurricane—a basic process—appears and decreases the gradient. Such events can be considered as usual fluctuations in the systems possessing fluid medium.

Macro- and microfluctuations of different ranks regularly appear in various parts of active non-biological systems. Any substantial fluctuation is initiated by the rise of a certain energetic gradient; then, developing spontaneous processes decreases it. For instance, pressure and temperature rise in a magma chamber leads to the increase in the energetic gradients between the chamber and the host rocks. In a course of the following volcanic eruption, the energetic gradients fall. Fluctuations in plasma of stars are initiated by the change in the inner energetic gradients too.

The contradictory interaction between basic and coupled processes in hydrothermal systems was studied in detail by Golubev (1990). This interaction occurs in the front of a mobile temperature (or geochemical) barrier during mineral formation. A concentrating of substance in solution within the mineral formation zone proceeds through changeable dissolution–deposition process. Concentrating is a non-spontaneous (coupled) process. It represents the gradual substance transfer against the concentration gradient and results in the gradient increase. This work demands energy expenditure. Energy for the work is provided by means of spontaneous (basic) process—just *cooling* of the filtrating solution. In fact, this is a kind of "natural heat machine," in which the work on concentrating of dissolved substance is executed at the expense of heat energy of the solution. In this way, rich ore deposits of hydrothermal genesis were formed.

Summarizing, the both types of universal processes take place in active non-biological systems. These systems use available surplus of free energy for own development, including rise of internal gradients and complication of the inner structure. Increase in the gradients is achieved by means of coupled process, which use a part of the corresponding basic process energy.

In biological systems, numerous biophysical, biochemical, and nervous–mental processes take place. A part of them can be united into basic universal processes as they lead to the destruction of a biological system and entropy rise. Another part belongs to coupled universal processes. They facilitate increase in the free energy surplus and efficiency of the system self-renovation (or self-organization). Incessant interaction between the basic and coupled processes is a required condition of a living organism existence. A couple of examples of these contradictory processes are given below. Damages that appear in DNA chains are a kind of destructive (basic) processes. Restoration of DNA chains is carried out by means of the reparation enzymes; this is a self-renovating (coupled) process (Burmistrova et al. 1982). From time to time, the synthesis of proteins with disturbed primary structure happens in organisms; this is a kind of destructive basic process. The immune system brings such proteins out of the organism that contributes into self-renovating (coupled) process.

2.2.3 Two Separating Lines Between Non-biological and Biological Systems

The proposed thermodynamic classification of natural systems allows us to draw two separating lines between living and non-living natural systems. As it is shown in Fig. 2.1, the first line differentiates passive and active systems. The second line lies between active non-living and living (biological and social) systems. Active non-living and passive systems represent the whole inanimate nature. The

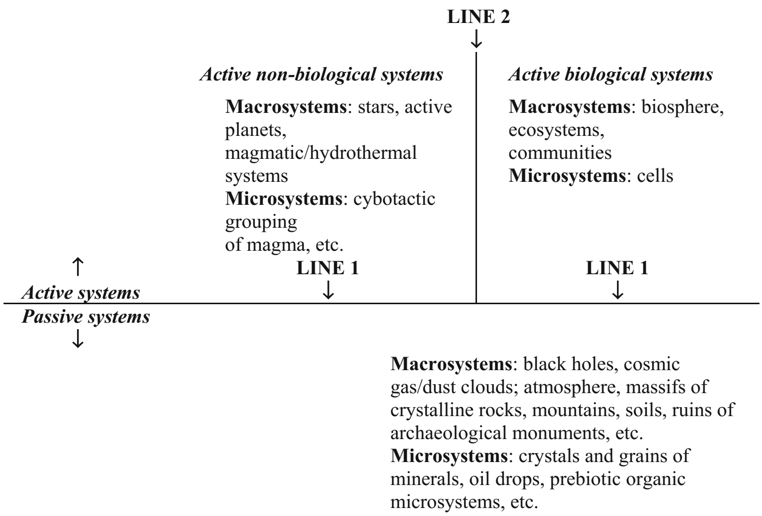

Fig. 2.1 Two separating lines between biological and non-biological systems

separating line within living systems (between biological and social ones) is not under consideration in this book.

2.2.3.1 First Separating Line: Thermodynamic Difference Between the Passive and Active Biological Systems

All biological systems are active. The three characteristic features of active natural systems distinguishing them from passive systems were stated above: surplus of free energy, self-complication of internal structure, and active exchange with the outside world. So, these features can serve as the first separating line. This line rather clearly separates these groups of natural systems. Nevertheless, some cases demand a special discussion.

A part of scientists doubt that there exists a strict boundary between living cells and some kinds of prebiotic microsystems obtained in vitro (such as RNA World macromolecules or proteinoid microspheres). Sometimes, prebiotic organic microsystems are considered to be very close to the living state (for instance, Fox et al. 1994). Actually, the ability of carbon atoms to form steady chains and cycles with each other, as well as with other atoms (hydrogen, nitrogen, oxygen), causes a great number of organic compounds. Possessing the highest level of chemical complexity, macromolecules of RNA World and polyamino acids complete the chemical evolution of matter (Table 2.5). However, the prebiotic microsystems do not possess the common features of self-complicating systems listed above: the surplus of free energy (providing the ability to carry out work) and *active* exchange of energy, matter, and information with the surroundings. Due to this reason, the author refers prebiotic microsystems to the passive type. However, under specific nonequilibrium conditions (that will be considered in the next chapters), a certain kind of prebiotic microsystems can be converted into primary living units.

Another kind of passive microsystems, which is sometimes compared with a functioning cell, is a growing crystal. The distinguished features of the active systems make possible to differ them. A growing crystal increases in size, but not complicates the crystal lattice's structure. The Earth's atmosphere and hydrosphere are two more examples of natural macrosystems that are conditionally referred to the passive type. They possess the ability to carry out work (by means of hurricanes, surf, etc.). But they do not evidently complicate the inner structure by themselves in a course of time. Change of the atmosphere's composition during the last four billion years is mainly connected with the influence of living beings.

2.2.3.2 Second Separating Line: Thermodynamic Difference Between Active Non-biological and Biological Systems

It was stated above that all active systems have energy surplus in respect of the outside world. In other words, they are characterized with the positive energy gradient in comparison with the surroundings. As a result, there exists the flow of energy (by way of dissipation and work on transformation) into the outside medium. The work is executed at the expense of free energy flow that is a part of the whole energy flow (Fig. 2.2).

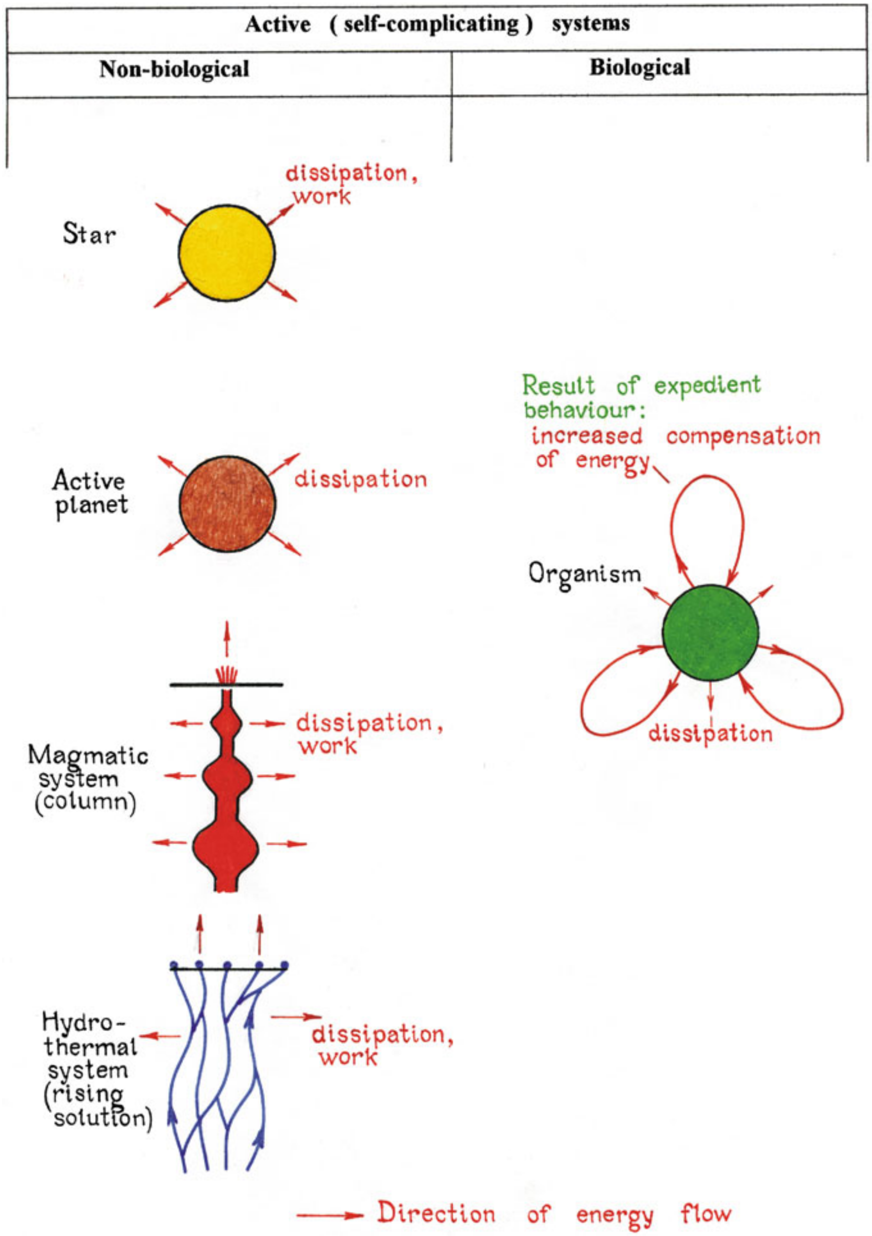

Fig. 2.2 Directions of energy transfer between active systems and the outside world

The distinction between active non-biological and biological systems in this principal aspect consists in opposite directions of the free energy flows. This distinction is connected with different energy sources of these types of systems. Accumulation of free energy in a star proceeds at the expense of energy-productive thermonuclear reactions. Volcanic process on active planets is maintained by means of energy saved in the melted core and produced through radioactive decay. Magmatic and hydrothermal systems get energy with heat flows rising from the bowels of a planet. So, all non-biological active systems whether use own potential energetic reserve, or obtain input of energy from the surroundings. In both cases, they do not extract actively free energy from the environment. The vector of energy exchange (by way of light, heat, and work) directs from these systems outside; they enrich surroundings with energy (Fig. 2.2, left). On the contrary, biological systems accumulate free energy only at the expense of its active extraction from the environment through exchange processes, in spite of the inevitable dissipation (Fig. 2.2, right). Their vector of free energy exchange is directed inside. This process maintains their positive energetic balance in respect of the environment. Therefore, the key thermodynamic property of biological systems that distinguishes them from all passive and active non-biological systems is *the ability for active extraction of free energy from the environment.* Just this property can serve as the border separating active non-biological and biological systems.

2.2.4 Thermodynamic Nature of the Biological Organization

The described above distinction is reflected in Fig. 2.3. The both active non-biological and biological systems possess energy surplus in respect of the surroundings that sustains their positive energy gradients. The difference consists in the direction of energy transference between a system and the surroundings. In the non-biological systems, the energy flow is directed along the gradient outside, from high to low concentrations. Entropy gradually rises in them, in congruence with the second law of thermodynamics. Correspondingly, the contribution of basic processes in these systems prevails over the contribution of coupled ones:

$$\text{Contribution of entropy } (S) > \text{Contribution of free energy } (F) \quad \text{(inequality 2.3)}$$

Unlike them, in biological systems, the energy flow is directed against the gradient. Such tendency results in free energy accumulation in biological systems, that is especially clear on the example of the Earth's biosphere evolution. Free energy transfer against the gradient is related to the coupled processes, whose contribution in this case prevails over the contribution of basic processes. This ratio between the free energy and entropy contributions in biological systems can be expressed through the following inequality mentioned above:

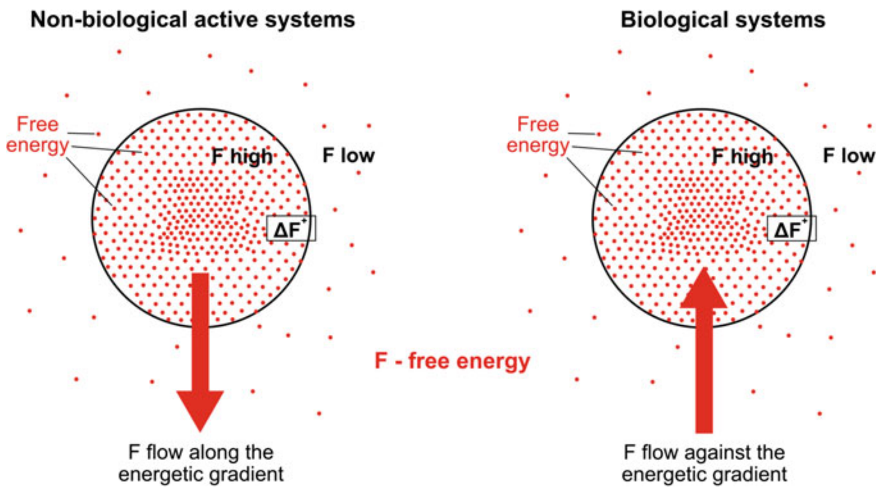

Fig. 2.3 Total free energy flows between natural systems and their surroundings

$$\text{Contribution of free energy } (F) > \text{Contribution of entropy } (S) \tag{2.4}$$

Information also accumulates in a course of the biosphere evolution related to the prevalence of the coupled processes over the basic ones:

$$\text{Contribution of information } (I) > \text{Contribution of informational entropy } (S_i) \tag{2.5}$$

The integrated inequality for a biological system can be written as follows:

$$F + I > S_t \tag{2.6}$$

where F—contribution of free energy, I—contribution of information, and S_t—total contribution of entropy (related to energetic and informational processes).

The analysis of the inequality 2.6 allows us to make the following conclusions.

1. Entropy in biological systems acquires negative values because of free energy and information prevalence. The term "negative entropy," or shortly "negentropy," is widely used for the consideration of thermodynamic processes connected with the existence of biological systems. Correspondingly, it can be stated that a biological system in the thermodynamic context is characterized with the negentropy method of organization. Continuous prevalence of free energy and information over entropy results in: (a) their accumulation in the course of biological evolution and (b) maintenance of the positive energy and information gradients in biological systems in respect of the environment. Accumulation of free energy and information during the biosphere evolution is proved by many

facts (f.i.: Vernadsky 1980; De Duve 2002). In particular, this tendency displays through accumulation of high-energy substance (Gladyshev 1995).

2. The essence of the notion *entropy* implies that it never decreases; entropy may only rise or to be steady. Decrease in entropy in biological systems is a result of the working entropy pump that exports entropy outside. The entropy export from living systems prevails over its internal production (in accordance with inequality 2.2). In this way, negative entropy increases and positive entropy (i.e., proper entropy) decreases (Ebeling et al. 1990; Elitzur 2002; Polishchuk 2002; etc.). It is possible that entropy in some active non-biological systems can temporarily decrease at the period of huge free energy inflow (for instance, when a magmatic system gets powerful energy impulse from the bowels of Earth). According to Ebeling and Feistel (Ebeling et al. 1990; Feistel and Ebeling 2011), the distinction between these types of systems in this context consists in different position of the entropy pump: It is located outside of active non-biological systems but inside the biological systems. A living organism is able to be active with respect to the environment because of the entropy pump inside; it is able to continuously export entropy at the expense of the own method of organization. The entropy pump sustaining the existence of a geological system, such as a volcano (magmatic chamber), is external. Geological or cosmic systems do not possess the internal low-entropy structures providing the efficient entropy export.
3. The negentropy biological organization implies the availability of the "over-entropy" free energy and information. Correspondingly, free energy, as well as information, in biological systems can be divided into two parts (Fig. 2.4). The first one compensates the entire entropy contribution, while the second one is excessive in respect of the entropy level (i.e., it is "over-entropy"). Persistent availability of the "over-entropy" free energy is maintained by means of the entropy pump that acts through exchange processes (Fig. 2.4, right up). The same principle refers to information and defines the difference between bioinformation and information in physical world (Fig. 2.4, right down). The over-entropy free energy and information being not suppressed by entropy provide the existence of negentropy organization in living beings. Considering a living cell from this point of view, we can come to the conclusion that the over-entropy free energy and information exist in a living cell in the both bound (ATP, DNA) and free (circulating flows) forms. In particular, these circulating flows can be involved into the process of nucleoprotein interaction in a living cell being a factor of its organization.

The positive balance of the contributions of free energy and information in respect of the entropy supports viability of biological systems (organisms, communities, species, etc.) and provides the tendency to their sustainable development. The negative balance $F + I < S_t$ launches the tendency to degradation that can be resulted in the following extinction due to natural selection. However, a biological system is able to change the balance through self-organization.

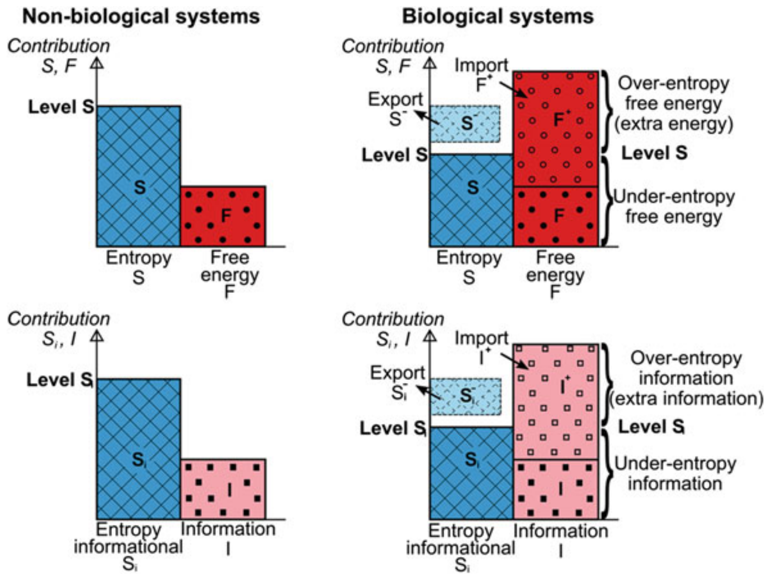

Fig. 2.4 Contributions of entropy, free energy, and information in natural systems

2.2.5 Negentropy Barrier: Necessity of Thermodynamic Inversion to Launch Life Processes

It follows of the previous sections that living systems are energetically non-compensated. Their unique thermodynamic feature consists in prevalence of the total contribution of coupled processes over the total contribution of basic processes. However, the coupled (non-spontaneous) process develops using only a part of the related basic (spontaneous) process energy. For this reason, the energy of coupled process cannot exceed the energy of corresponding basic process. This ratio can be explained on the simple example. A sliding down skier (spontaneous process along the gravity gradient) cannot rise up to the same altitude level of the opposite hill (non-spontaneous process against the gravity gradient) without his/her additional efforts. This situation is usual for inanimate world if we image, for example, a rolling stone instead a skier. However, actually a skier can get the much higher hypsometric mark on the opposite hill but only at the expense of own additional efforts provided energy expenditure. Life develops on Earth against the energy and informational gradients due to the predominance of non-spontaneous processes—from a certain starting point that can be defined as the initial negentropy impulse in a prebiotic system. Since such radical transformation that laid foundation the primary living units, they arose as the energy-wise uncompensated systems. To exist, living systems must extract a missing quantity of free energy from the environment and remove entropy. This obvious and accepted thesis emphasizes that a biological system, consisting of a biotic system (organism or community) and the environment, represents itself the united whole. There is no such close relation between non-living systems and their surroundings. Passive systems simply exist in a medium. Active non-biological systems (stars or magmatic systems) develop in the surroundings, but their exchange processes are limited because they do not need external energy to exist.

Therefore, energy prevalence of basic processes over coupled ones in the non-living world (including all types of prebiotic microsystems) forms a thermodynamic barrier on the way to the negentropy living world. It is the energy prevalence of coupled processes and the negentropy organization that can provide its emergence. Besides, special conditions are necessary to overcome the negentropy barrier. One of the conditions is the loss of the negentropy barrier; in principle, this is possible in heterogeneous systems being under far-from-equilibrium conditions (see below). Because of the entropy notion duality (measure of both energy value and disorganization), the balance $F + I/S_t$ is relative: Absolute equality in this ratio is unattainable, as free energy and information are measured in different units. It follows that there exists a field of indeterminacy close to the negentropy barrier $F + I \approx S_t$. This field admits producing prevalent entropy in one part (high-entropy structures) of the nonequilibrium heterogeneous system, and the prevalence of free energy and information in its other part (low-entropy structures). In fact, the negentropy barrier mitigates in such a heterogeneous system.

It follows that biological evolution proceeds in the thermodynamic direction opposite to the evolution of non-biological natural systems, i.e., opposite to the spontaneous entropy increase. As the thermodynamic trend of the biosphere evolution is the phenomenon being not the characteristic of any non-biological natural system, the biological evolution beginning implies the inversion in the tendency of free energy change in a prebiotic system from dissipation to continuous increase. The resulting flow of free energy directs outside a non-biological system but inside a biological system (Fig. 2.5, up). So, the thermodynamic inversion consists in the turn of the directions of free energy flows in the course of a prebiotic system transformation into the primary living unit. Besides, the inversion in the tendencies of information change (from spontaneous loss to enduring accumulation) and entropy change (from positive to negative values) must simultaneously occur. The turn in these balances determines the new quality of informational and energetic processes in a biological system. On the whole, thermodynamic inversion can be understood as the inversion of entropy, when a natural system transits into the state characterized by continuous entropy deficit due to the surplus of free energy and information and their reorganization (Kompanichenko 2012). Correspondingly, the coupled processes become dominant over the basic ones in the inversed (i.e., biological already) system.

The negentropy barrier may display in plural forms. Thus, Strazewski (2007) wrote about a high-entropy penalty for the formation of polynucleic acid-ordered association. The penalty can be considered as one of the barrier's constituents. At the inversion moment, the formation of biopolymer functional sequences (based on programming) instead of spontaneous self-ordered associations of nucleic and amino acids needs additional negentropy input. One more constituent is the entropy pump within the organic microsystem appearing at the inversion moment. To launch the

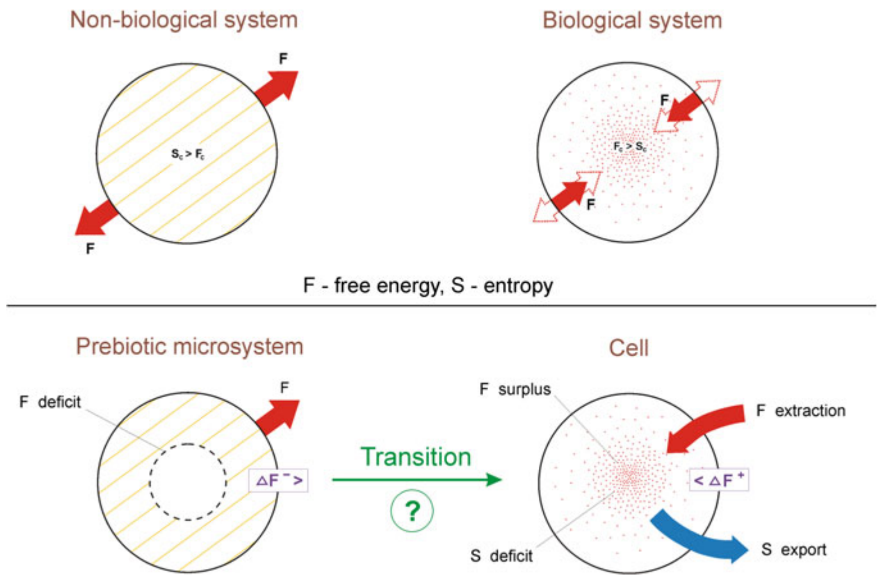

Fig. 2.5 Scheme of the principal thermodynamic difference between non-biological and biological systems. *Up* directions of the resulting free energy flow in non-biological and biological systems. *Down* the transition from a non-living prebiotic system into the living unit (arising of free energy import and entropy export)

pump, the entropy export must exceed a certain critical value. Therefore, the transition over the negentropy barrier implies necessity of extra-high negentropy impulse (in other words, a huge contribution of free energy and information) in a prebiotic chemical system along with the radical transformation of internal processes.

Thermodynamic negentropy barrier is an obstacle for prebiotic systems transformation into primary living units. So, the origin-of-life principal question is, how the thermodynamic inversion in prebiotic microsystems may occur (Fig. 2.5, down)? How the entropy pump starts to work? Such a transformation demands very specific conditions that will be considered in the next chapters.

2.3 Fundamental Properties of Biological Systems: Detailed Elaboration

It was stated in the previous section that the ability for the accumulation of free energy and information through active extraction from the environment is a key distinction of biological systems from non-biological ones. The distinction can be considered as the most fundamental biological property. This section is devoted to the detailed elaboration of other fundamental properties of biological systems, the both unique (which are not peculiar to any non-biological system) and non-unique ones, taking into consideration the above classification of natural systems. As a basis for the elaboration, the contributions of 73 competent world scientists into the book *Fundamentals of Life* (edited by Palyi et al. 2002) were used. The book is the Proceedings of the Workshop on Life that hold in Modena (Italy) in 2000, in which the author also took part. It contains 78 short definitions of life (or opinions concerning this problem) and 25 selected fundamental papers. More or less definite properties of life are substantiated in 64 short definitions and papers. Usually, each author distinguished from three to five properties of biological systems that are, in his/her opinion, the most fundamental. In sum, the authors suggested about 230 biological properties. But the properties suggested by different authors are very often identical or similar. Among the most popular properties are self-reproduction (indicated by 27 authors), capable of (negentropy) evolution (26), extraction of free energy and matter from environment (16), performance and control metabolism (15), ability for storage and replication of genetic information (12), growth (10), thermodynamic and chemical disequilibrium (9), autocatalysis (9), existence of genome and genetic code (7), availability of membranes as geochemical barriers (7), highest level of complexity (7), foresight and ability for modify own behavior (7), composition of carbon-based polymers (6), etc. However, these properties were distinguished without any comparison with non-biological natural systems. Due to this reason, it is impossible to recognize, which of the properties are actually peculiar to living systems only, and which of them might display in non-living ones. To clarify this question, the given set of properties underwent the analysis with the following integration; the preliminary results were published in Kompanichenko (2004, 2008).

In accordance with the author's comparison and integration of this set, 31 fundamental properties of biological systems have been formulated. They are subdivided into two groups. The 19 of them are considered as unique biological properties, which are not peculiar to any other natural system (Table 2.6, left column). The rest 12 of them are attributed to the non-unique properties (Table 2.7, left column). These or similar properties can display in some non-biological systems, although they are devoid of any biological specificity (Tables 2.6 and 2.7).

The set of nineteen unique properties have been integrated by the author into the four key unique biological properties that more or less definitely embrace all of them (Table 2.6, middle column). These four properties were initially outlined in the book Fundamentals of Life (2002) but have been substantially revised in the course comparison with the properties distinguished by the other authors. The description of the fundamental biological properties is given below.

2.3.1 Unique Fundamental Properties of Biological Systems

Two sets of the unique properties of biological systems are given in Table 2.6. The first set is composed of the nineteen fundamental properties (called "particular") that were distinguished by the researchers listed below in Table 2.6. These authors

Table 2.6 Unique fundamental properties of biological systems and their generalization (the list of researchers who distinguished the fundamental properties is given below)

Particular unique properties substantiated by the listed researchers	Researchers who distinguished this or similar property (number in the list)	General unique properties (integrated by Kompanichenko)	Comments that support objectivity of correlation between the particular fundamental property and the corresponding general property
1. Ability for extraction of (free) energy and matter from the environment	2, 3, 5, 10, 14, 16, 37, 38, 41, 45, 46, 47, 50, 52, 54, 62	**Property 1**. Ability to concentrate free energy and information (by means of their extraction from the environment)	Extraction of free energy directly corresponds with the essential part of the 1st general property. Extraction of matter is the rewording process of constructive assimilation (the 10th particular property correlating with second general one)
2. Capable of evolution, including the increase in complexity/hierarchy (3, 6, 17, 18, 22, 32, 38, 50) and the display of self-perfecting logic (2, 16, 52, 59, 63)	1, 2, 4, 5, 6, 7, 11, 12, 13, 16, 17, 19, 28, 34, 35, 39, 42, 43, 44, 46, 49, 50, 54, 60, 62, 63	- I I -	Continuous concentration of free energy and information is closely related to the ability of a biological system to self-complicate and self-perfect
3. Performance and control of metabolism, including autocatalysis (6, 11, 17, 20, 37, 38, 39, 41, 60), cyclic chemical processes (6, 19, 20, 22), feedback loops (37, 47) and active transport (13, 62)	1, 2, 4, 6, 9, 10, 11, 13, 16, 17, 19, 20, 21, 22, 23, 25, 29, 37, 38, 39, 41, 47, 50, 60, 61	- I I -	Metabolism could be considered as one more general property. However, active transport and the metabolic network cannot proceed without the prevalence of free energy contribution over the entropy contribution in a living organism. Efficient control of metabolism takes place in case the information input prevails over the disinformation input

(continued)

Table 2.6 (continued)

Particular unique properties substantiated by the listed researchers	Researchers who distinguished this or similar property (number in the list)	General unique properties (integrated by Kompanichenko)	Comments that support objectivity of correlation between the particular fundamental property and the corresponding general property
4. Capacity to accumulate, reorganize (with increase in the hierarchical level of organization), and transmit genetic information, including capacity of self-instruction	1, 8, 10, 11, 13, 15, 16, 22, 28, 30, 34, 35, 41	- I I -	Accumulation (concentration), reorganization, and transmission of the genetic information are different sides of the common process that is reflected in first general property
5. Availability of the genome and genetic code	1, 14, 19, 27, 28, 48, 50	- I I -	Genome and genetic code are molecular structures that, which are involved into the process leading to the accumulation (concentration) of the biological information
6. Growth through redundancy	40	- I I -	“Redundancy” is a result of the process of free energy concentration. Free energy surplus provides a living organism with necessary resources to grow
7. Vital force distinguishing living systems from inorganic nature	25	- I I -	Rewording, “vital force” is surplus “over-entropy” free energy that is generated in a living organism maintaining its existence
8. Concentrative encapsulation (high concentration in a small volume) and topical location	4, 15	- I I -	The concentrative encapsulation process is based on the ability of a living system to concentrate free energy and information

(continued)

Table 2.6 (continued)

Particular unique properties substantiated by the listed researchers	Researchers who distinguished this or similar property (number in the list)	General unique properties (integrated by Kompanichenko)	Comments that support objectivity of correlation between the particular fundamental property and the corresponding general property
9. Irritability	10, 58	**Property 2**. Ability to exhibit the intensified counteraction to an external influences	Irritability demonstrates the ability of a living organism for intensified respond to actions from the outside world
10. Resistance to decay by constructive assimilation	53	- | | -	Resistance to decay by constructive assimilation is one of the ways to execute intensified counteraction to destructive influences from the outside world
11. Perpetuate own structure, dynamics, and state by countering external changes	16	- | | -	The analogy between the 11th particular property and the second general property is obvious
12. Purposefulness and foresight	8, 35, 50	**Property 3**. Expedient behavior	Purposefulness and foresight are attributes of the expedient behavior
13. Ability to manipulate (or advantageously modify) the environment	8, 22, 38	- | | -	Ability to manipulate the environment is an attribute of the expedient behavior
14. Ability for motion	10, 13, 18, 62	- | | -	Motion is one more display of the expedient behavior
15. Ability to modify own form and behavior	3, 19, 25, 38	- | | -	Expediency as inalienable quality of a living being includes the ability to modify own form and behavior

(continued)

Table 2.6 (continued)

Particular unique properties substantiated by the listed researchers	Researchers who distinguished this or similar property (number in the list)	General unique properties (integrated by Kompanichenko)	Comments that support objectivity of correlation between the particular fundamental property and the corresponding general property
16. Self-regenerating (self-rejuvenating)	10, 16	**Property 4**. Regular self-renovation (on the different hierarchical levels: molecular, tissue's, genome's, organism's, species', biosphere's)	Self-regenerating can be considered as a self-renovation that proceeds mainly on the molecular and tissue's levels
17. Capability for self-replication	4, 5, 19, 26, 30, 43, 46, 56, 58, 59, 60	- I I -	Self-replication is a self-renovation on the genome's level
18. Capability for self-reproduction	1, 2, 7, 9, 10, 12, 15, 16, 17, 18, 19, 20, 21, 22, 23, 25, 28, 29, 36, 38, 47, 48, 49, 50, 60, 62, 63	- I I -	Self-reproduction is a self-renovation on the organism's level
19. Stability through generations	20	- I I -	Stability through generations is a self-renovation on the population's and species' levels

Note to Tables 2.6–2.7. The list of authors whose contributions into the book "Fundamental of Life" (Palyi et al. 2002) were used to distinguish 31 particular fundamental properties of biological systems.

1 D.L. Abel; *2* A.D. Alstein; *3* M. Anbar; *4* G.O. Arrhenius; *5* H. Baltscheffsky, A. Schultz & M. Baltscheffsky; *6* L. Boiteau; *7* A. Brack; *8* D. Brin; *9* R. Buick; *10* M. Colin-Garcia and A. Guzman-Marmolejo; *11* D.W. Deamer; *12* A.H. Delsemme; *13* K. Dose; *14* C. de Duve; *15* F.R. Eirich; *16* A. Elitzur; *17* A.S. Erokhin; *18* J. Farmer; *19* R. Guerrero and L. Margulis; *20* R. C. Guimaraes; *21* V.K. Gupta; *22* V.A. Gusev; *23* R.M. Hazen; *24* R.J-C. Hennet; *25* R.D. Hill; *26* N. Horowitz; *27* H.P. Yockey; *28* G.F. Joice; *29* L. Keszthelyi; *30* G. von Kiedrowski; *31* E.I. Klabunovsky; *32* V.M. kolb; *33* B. Kopperhoefer; *34* W.E. Krumbein; *35* H. Kuhn; *36* I.S. Kulaev; *37* N. Lahav and S. Nir; *38* D.Z. Lippmann; *39* P. Lopez-Garcia; *40* L. Marco; *41* S. Mendez-Alvarez; *42* S.I. Miller; *43* S.J. Mojzsis; *44* Y. Momotani; *45* C.K.K. Nair; *46* K.H. Nealson; *47* S. Nir; *48* H. Noda; *49* T. Owen; *50* G. Palyi, C. Zucci and L. Cagliati; *51* B.F. Poglazov; *52* R.F. Polyshchuk; *53* M. Rizotti; *54* M. Russell; *55* X. Sallantin; *56* D. Schulze-Makuch and L.N. Irvine; *57* R.I. Scorei; *58* J. Siefert; *59* A.A. Spirin; *60* E. Szathmary (and T. Ganti); **61** C.Y. Valenzuela; *62* T.G. Waddell; *63* J.T-F. Wong; *64* V. Kompanichenko

formulated some of the nineteen properties or similar to them. The second set consists of the four fundamental properties (called "general" or "key") suggested by the author on a basis of the particular properties integration.

Table 2.7 Non-unique fundamental properties of biological systems and their correlation with similar properties peculiar to some non-biological systems (on the basis of the contributions of the researches whose list is given in Table 2.6)

Non-unique fundamental properties of biological systems	Researchers who distinguished this or similar property (number in the list)	Examples of non-biological systems which also possess this or similar property	Comments that support correlation between the non-unique property in biological and non-biological systems
1. Composition of carbon-based polymers (aggregates)	2, 9, 19, 21, 37, 53	Coacervates, organic microsystems in ocean, oil drops	Correlation is obvious
2. Availability of membranes as (bio)chemical barriers	2, 9, 11, 13, 19, 53, 54	Micelles, vesicles	Correlation is obvious
3. Optical activity (homochirality, dissymmetry) of molecules	31, 34, 55	Proteinoide microspheres (obtained experimentally by S. Fox with co-authors)	Ratio of L- and D-amino acids in proteinoid microspheres may significantly differs from the racemic ratio
4. Chemical polarity of compounds and structures	(64)	Proteinoid microspheres	Chemical polarity of amines and acids in amino acids that are substrate for proteinoide microspheres
5. Ability for growth	1, 10, 13, 18, 20, 21, 25, 38, 41, 47	A magmatic system (column of chambers or volcano)	Growth of a magmatic system begins with the small deep chamber and completes with formation of the extensive column of chambers
6. Heredity	44	A magmatic system	Chemical composition of the successive magmatic intrusions usually changes but some specific geochemical characteristics trace through all intrusions
7. Ability to carry and accumulate information	1, 8, 16, 22, 34, 41	A crystal	A crystal accumulates structural and geochemical information during own growth and the following transformations, although it cannot reorganize and transmit the information

(continued)

Table 2.7 (continued)

Non-unique fundamental properties of biological systems	Researchers who distinguished this or similar property (number in the list)	Examples of non-biological systems which also possess this or similar property	Comments that support correlation between the non-unique property in biological and non-biological systems
8. Continuous transformation and rearrangement of molecules	45	A magmatic chamber	A magmatic melt is composed of the different cybotactic groupings that are in a process of incessant interaction and re-distribution
9. Life cycle, autonomy (perform work), individuality	15, 16	A star or magmatic system	Any star or volcano goes through its cycle of existence and performs work in the outside world
10. Thermodynamic and chemical nonequilibrium	2, 6, 9, 24, 33, 46, 54, 56	Chemical and physical dissipative structures (oscillating chemical reactions, Benard cells)	All dissipative structures (the both chemical and biological) can exist only under nonequilibrium thermodynamic and chemical conditions
11. Integrity of structures in a living organism (autoorganization of molecules and emergent properties)	1, 2, 8, 18, 21, 51	Chemical and physical dissipative structures	Cooperative events are characteristic features of all dissipative structures due to the synergy effect and emergent properties
12. Capability for self-organization and self-maintenance	4, 5, 19, 32	Chemical and physical dissipative structures	Existence of dissipative structures is maintained through the process of self-organization

The second set includes the following four general biological properties.

1. The ability to concentrate free energy and information (by means of their active extraction from the environment and internal reorganization);
2. The ability for the intensified counteraction to an external influence;
3. Expedient behavior or the expedient character of interaction with the environment;
4. Regular self-renovation at different hierarchical levels (from molecular to biosphere’s), including self-reproduction.

According to the author's generalization, each of the nineteen particular properties either directly corresponds with a certain general property (or its part), or inevitably follows of it. The short comments that support the correlation between the sets are adduced in the forth column of Table 2.6. For instance, the 1st and the 4th particular properties are direct constituent of the 1st general property, while the 2nd–3rd and the 5th–8th particular properties inevitably follow of it. As an open biological system continuously accumulates free energy and information, it inevitably displays the ability for growth and evolution; this ability implies at least the ability for self-maintenance of existence by means of metabolic processes, operational genetic structures, and so on. The particular 9th–11th properties correspond with the 2nd general property, the particular 12th–15th—with the 3rd general one, and the particular 16th–19th—with the 4th general one.

The 1st general property: the ability to concentrate free energy and information. This property is a key point of the thermodynamic method of biological organization. It was substantiated in the previous sections already.

The 2nd general property: the ability for the intensified counteraction to an external influence. All natural systems interact with the outside world in the course of existence. They exert actions to the medium and get influences from it. A produced effect of a system in the surroundings, as well as the effect of an external influence to a system, can be evaluated in units of energy and presented as the ratio «Energy effect of an external influence to a system/Energy effect of a system's response to this influence». This ratio is very appropriate for further comparison of biological and non-biological systems.

In non-living world, the response of a system to an external influence can be considered on the basis of the Le Chatelier's principle (in chemistry) and the Newton's third law (in physics). One can read in Wikipedia the popular definition of the Le Chatelier's principle: "When a system at equilibrium is subjected to change in concentration, temperature, volume, or pressure, then the system readjusts itself to (partially) counteract the effect of the applied change…" The word "partially" is a key in the context of our consideration. That means the response of a chemical is *weakened* in comparison with the executed influence. The Newton's third law postulates: "When one body exerts a force on a second body, the second body simultaneously exerts a force equal in magnitude and opposite in direction on the first body." In general, this law implies that an action is equal to the counteraction. Nevertheless, in the real world of mechanics, the counteraction is actually weakened in comparison with the initial action because of friction and air resistance.

So, passive natural systems always exert the weakened counteraction to an external influence, i.e., the ratio "Energy effect of an external influence/Energy effect of the system's response" is positive. A billiard ball impacted by the second one exerts the counteraction and stops the second ball. The initial energy of the executed impact is always higher (at least a little) than the energy of the second ball's counteraction because of friction and air resistance. The same concerns active non-biological system. They may respond to external influences, in particular, through a process of (non-biological) self-regulation that is a kind of the weakened response. For example, during the rise of magma to the surface, a temperature of the host rocks decreases that initiates rapid cooling of the upper zone of a magmatic chamber. Decrease in temperature approaches crystallization of melt in this zone. There exist many evidences that concentrations of the most easily melted components of magma (fluid, silica) significantly increase at the top of magmatic chambers. Due to such segregation, gas–steam explosions and silica-rich lava are often prevalent at the beginning of the contrast volcanic eruptions, while silica-pure basic (basaltic) lava completes this process; in particular, such succession was detected in Kamchatka volcanic region. So, the abundance of easily melted components decreases the temperature of magma crystallization in the fast cooling zone, and the process of magma crystallization stops. Such self-regulation maintains integrity of magmatic systems. So, self-regulation itself cannot turn the process of energy exchange to heat transfer from a cool (host rocks) to hot (magmatic chamber) area, i.e., against the energetic gradient and the second law of thermodynamics. Therefore, self-regulation of the kind can also be considered as the weakened response to an external influence. Correspondingly, the ratio "Energy of external action/Energy of counteraction" is also positive. The non-biological active systems do not possess any internal mechanism that might strengthen the counteraction.

Unlike the considered types of natural systems, biological systems are able for active counteraction, i.e., to the intensified response to an external influence. In this way, a tree can compensate a lost branch by means of several new branches. An ant is able to carry a load that is much heavier than its own weight. A frog can respond to a light touch by very energetic contraction of muscles. On the whole, the ratio «Energy of external action/Energy of counteraction» can be as negative (that primarily characterizes viable forms of life) or positive (primarily characterizes degrading forms of life). Striving of a living being to compensate the spent energy in plenty is an inherent feature of its organization. It is well known that working structures of an organism develop, while non-working ones atrophy.

The general mechanism of intensified counteraction is connected with peculiarities of interaction between the universal spontaneous (basic) and non-spontaneous (coupled) processes. Spontaneous processes proceed inevitably in the both closed and open systems, while non-spontaneous ones take place only in open ones through free energy expenditure. Open systems, in particular all biological, get various external influences and exert back influences in the surroundings. Absence of external influences leads to the transformation of an open system into closed one, with the following fast rise of entropy and simplification of inner structure. So, influence on exchange is a necessary factor that maintains coupled processes in a system.

Besides the intensified (active) reaction, a biological system possesses the weakened (passive) reaction to external influences. The intensified reaction is its unique property, while the weakened one is peculiar to non-biological active systems as well. As it was considered, the weakened reaction may display through a self-regulation. For instance, a damaged tree can restore its functions by means of the both direct healing of the broken branches (passive counteraction) and arising of new branches (active counteraction). Reaction of a human being to frost can consist in the both putting on gloves (active counteraction) and internal transfer of heat energy into the cooling hands (passive counteraction). So, actions of living beings in the environment are various kinds of passive and active reactions to external influences; i.e., in the long run, the actions are maintained by changes in the outside world. Absence of external actions to an organism means absence of its intensified counteraction. In this case, the extraction of free energy is also equal to zero. However, too strong external actions may exceed an organism's ability for adaptation. This conclusion corresponds with major thesis of the stress theory by Selye (1974): An optimal stress is necessary for life; absence of stress, as well as too strong "distress", leads to death.

The 3rd general property: expedient character of interaction with the environment (expedient behavior). The ability of a living organism for the intensified response (counteraction) to an external influence is provided by the free energy supply. The positive free energy gradient of a biotic system in respect of the environment maintains this ability. The spent free energy restores in plenty in some time.

However, choice of the most optimal direction of a living organism counteraction is being prepared through coordination of all its structures and functions. So, the most efficient counteraction is based on both the ability to execute an energetic action in the environment (by using the supply of accumulated free energy) and the ability to choose the most profitable way of it (on a basis of the accumulated information that reflects the outside world). Just a combination of these factors permits a living being's counteraction to prevail over the stress of external influence and get the profit during exchange of energy and information with the environment. Possessing over-entropy free energy and information, a living being, or community has sufficient freedom to recombine them to achieve favorable conditions for the existence. According to the author's opinion, the most precise term to designate this property is "expediency." So, the third general unique property of a biological system is its *expedient behavior*, or more strictly *expedient character of its interaction with the environment*. Expedient behavior is based on the over-entropy information that accumulates in a biotic system and reflects changes occurring in the environment. In this way, unicellular organisms possess the ability for various taxis, plants strive to grow closer to optimal sunlight, and animals move to areas with abundant food.

The 4th general property: regular self-renovation at different levels. The processes of self-renovation prevail over the processes of destruction in any viable living system. This is an inevitable consequence of the positive balance "the contribution of coupled processes/the contribution of basic processes" that is peculiar to biological systems. So, *the regular self-renovation* can be considered as the fourth general unique property. The self-renovation proceeds on the different levels: cellular structures' (restoration of nucleotide chains and renovation of proteins), organism's (self-replication of DNA and self-renovation of cells), species' (self-reproduction of organisms), and biosphere's (self-renovation of species and ecosystems). Continuous opposition between basic and coupled processes in living systems implies that biological structures of various ranks all the time gradually disintegrate due to the contribution of entropy but simultaneously renovate through the contributions of free energy and information.

2.3.2 Non-unique Fundamental Properties of Biological Systems

The twelve fundamental properties of biological systems, which are defined as non-unique by the author, are given in Table 2.7. They are not strictly peculiar to living systems only. The same or similar features characterize some non-living systems as well, although they are devoid of any biological specificity. Ability to growth possesses, for instance, a magmatic system too. Many kinds of abiogenous organic microsystems or particles in ocean are composed of carbon-based polymers. Continuous exchange of matter and energy takes place in both biological and non-biological active systems. These properties demonstrate that there is no absolutely strict barrier between living and non-living systems: Nature is a single whole. Some examples of non-biological systems, which also possess the properties similar with the non-unique biological ones, as well as the necessary comments, are also given in Table 2.7. The non-unique properties can be united into three groups.

The first group concerns the compositional peculiarities of biotic systems (Table 2.7, properties 1st–4th): composition of carbon-based polymers; availability of membranes; and optical activity of molecules. One more important property, which was not clearly indicated by the listed researchers, should be added to this group: chemical polarity of the compounds and structures (alkaline and acid parts of amino acids, polypeptide and polynucleotide chains, etc.). Some non-living prebiotic models also possess this property. For instance, the ratio of L- and D-amino acids in proteinoid microspheres may significantly differ from the racemic (about 50/50%) ratio that characterizes the entire non-biological world. But anyway, it is far from the ratio that is peculiar to living organisms (almost absolute prevalence of the L-forms).

The second group consists of the properties, which display in existence of various non-biological active and sometimes passive systems, such as stars, magmatic chambers, and crystals (Table 2.7, properties 5th–9th). They are the ability for growth, heredity, ability to carry and accumulate information, continuous rearrangement of molecules, and life (existence) cycle. Plenty of variable organic microsystems existing among the geological media or obtained for laboratory experiments also possess these properties, but they not belong to living world. Although these non-unique properties are attributed to some non-biological systems, they reveal in biological systems at a higher level of organization (complexity) and always possess the biological specificity. For example, a crystal continuously accumulates information about own growth and transformations. Based on this information, one can trace all stages of its existence. But a crystal being a kind of passive system cannot reorganize and transmit information.

The last three properties are united into third group (Table 2.7, properties 10th–12th). They concern the peculiarities of cooperation between molecules/structures and processes in living beings: thermodynamic and chemical nonequilibrium; integrity of structures; and capability for self-organization. In non-biological systems, similar properties display in the rare class of dissipative structures that may exist under far-from-equilibrium conditions only. Such events may occur in a course of phase transitions too. These phenomena are well investigated in the framework of nonequilibrium (irreversible) thermodynamics; they are often considered as processes of self-organization (Nicolis and Prigogine 1977; Haken 1978; Prigogine and Stengers 1984; Prigogine 1989; Ebeling et al. 1990; Feistel and Ebeling 2011). Some unusual chemical and physical systems (oscillating chemical reactions, a laser, etc.) are referred to the class of dissipative structures together with all biological and social systems. So, the distinguished properties 10th–12th are common for all systems of this class (including the both non-biological and biological ones).

In fact, the non-unique properties can be considered as the connecting thread between animate and inanimate nature, while the unique ones emphasize the strict barrier separating them. During the origin-of-life process on the ancient Earth, the unique properties appeared for the first time, unlike the non-unique ones that transited from the maternal geological medium and acquired biological specificity. Therefore, the non-unique properties may serve as a “load-star” to characterize conditions in the geological cradle of life, especially in immediate temporal proximity to the emergence of the simplest living units. From this point of view, the 10th, 11th, and 12th non-unique biological properties are very substantial. They indicate specific nonequilibrium processes providing cooperative behavior of molecules and self-organization.

Based on the distinguished non-unique properties, the following general conditions in the maternal medium of the origin of life can be outlined: availability of diverse organic matter (the consequence of non-unique properties of the first group); incessant processes of reorganization that facilitate synthesis of complex compounds and growth of prebiotic microsystems (the second group); and specific nonequilibrium processes providing cooperative behavior of molecules and self-organization (the third group). Necessity of nonequilibrium conditions is remarkable. This requirement connects the origin-of-life process with wide range of the specific events that take place in a course of nonequilibrium bifurcate transitions and formation of dissipative structures. These aspects will be considered in the next chapters.

2.4 Specificity of Biological Information

The broad classification of information was offered by Shannon (1948) in his information theory. “Information” by Shannon is inversely related to uncertainty; the highest possible uncertainty characterizes a random sequence. Informational systems operate only in nonequilibrium states (Volkenstein and Chernavsky 1979; Ebeling et al. 1990). Therefore, the exchange of information takes place in both self-organizing physical/chemical systems and living systems.

In both physical (non-biological) and biological worlds, the information inflow decreases entropy in systems. However, information in cosmic or geological systems ("physical" information) principally differs from information in biological systems (bioinformation). Their methods of organization described above are thermodynamically different: Non-biological systems develop in accordance with the second law of thermodynamics (entropy rises in them), while the biological evolution has the negentropy direction (entropy in biological systems rises as well, but it is immediately compensated—with excess—by free energy and information contributions).

Both physicists and biologists recognize the difference between physical and biological information. Quoting Feistel and Ebeling (2011), "We underline that biological just as socio-economic processes can be investigated with the help of the theory of self-organization because they obey the valid physical and chemical laws. However, processes, which include real life (biological and socio-economic systems) also obey additional rules and laws that are not determined by physics alone" (p. 27). In the coevolution theory of the genetic code origin, Wong stated that bioinformation in heteropolymeric sequences (nucleic acids and proteins) is similar to alphabetic, non-alphabetic, and computer languages (Wong 1988; Wong and Xue 2002).

According to the author's opinion, a principal distinction of information in biological systems (bioinformation) from information in non-biological systems (physical or proper information) follows of their different thermodynamic nature. Information in non-biological systems is entirely compensated by means of the informational entropy contribution; i.e., it is bound by entropy. In biological systems, a part of the information contribution is bound by entropy, while another part is *over-entropy* (Fig. 2.4). Over-entropy information is free in a sense that it is not limited to freely circulate throughout an organism and form an integrated reflection of the environment. The reflection is helpful to execute expedient behavior of a living being. In this way, bioinformation acquires new quality in comparison with physical information.

Taking into consideration this approach, three unique characteristics of biological information have been distinguished (Kompanichenko 2014).

2.4.1 First Unique Characteristic of Bioinformation: Functionality

Functional bioinformation is considered as "an encoded network of functions in living organisms—from molecular signaling pathways to an organism's behavior" (Sharov 2009), or as a measure of a biological system complexity (Hazen et al. 2007). Functional information has meaning (such as in coded information). In a living organism, a sequence (gene or protein) is functional and meaningful, unlike a polynucleotide or polyamino acid chain, spontaneously synthesized in vitro. A semiotic system is necessarily made of three distinct entities: signs, meanings, and code. Signs (set of symbols) and meaning are connected by the conventional rules of a code (Barbieri 2008; Abel 2009; Johnson 2013). A code is a precise mapping from a set of symbols to specified meanings, actions, and objects. The best-known biological code is the codon-to-amino acid translation during protein construction that uses tRNAs to translate one codon from the 64-codon alphabet (a sign) into one amino acid in the 20 amino acid alphabet (meaning). There is no chemical or other deterministic link between the opposite ends of a tRNA that causes a particular amino acid to be associated with a particular codon. They are associated with an arbitrary rule determined by a code (Johnson 2013; Seaman 2013). Shortly, a semiotic system can be expressed as follows:

“Signs → Code → Function” (Scheme 2.1)

The values of functional bioinformation can be obtained with the method, developed and applied to 35 protein families (Durston et al. 2007), allowing to measure the functional sequence complexity.

2.4.2 *Second Unique Characteristic of Bioinformation: Purposefulness*

This characteristic emphasizes that bioinformation is goal-oriented, aimed to perspective. Bioinformation is not only functional/meaningful, but also prescriptive and algorithmic—that is substantiated in the framework of the “prescriptive information” concept (Abel 2009; Durston et al. 2007; Abel and Trevors 2005; Abel 2011). Prescriptive information is *purposeful,* and it includes any form of programming, either instructing or directly producing a non-trivial function at its destination. Thus, the prescriptive information in a DNA sequence is a recipe or algorithm *to accomplish a desired task*. A biological system produces prescriptive information by means of some purposeful (perspective) choices at *bona fide* decision nodes. It is emphasized that purposeful choices can be produced neither by chance nor by necessity (Johnson 2013; Abel 2011).

The considered feature of bioinformation allows expanding the succession (Scheme 2.1) in the previous paragraph:

Purpose → [“Signs → Code → Function”] → Action, the achieved result (Scheme 2.2)

The general succession (Scheme 2.2) can be interpreted as follows: a living organism or community sets a goal and achieves it through the biosemiotic system that includes signs, functions, and a code.

2.4.3 *Third Unique Characteristic of Bioinformation: Control Over Life's Processes*

Life's hardware and software systems control the chemistry and physics of all of life's processes, including metabolism, manufacturing, control, and feedback. These systems use digital processing of information to control, integrate, and maintain life's processes. A prescriptive algorithm can be implemented in either hardware or software (Johnson 2013). Life is basically the result of the information "software" process. Our genetic code is our software (Venter 2010). For the last several years, the significant experimental confirmations of the fact that life has "hardware/software" organization have been published (Johnson 2013; Seaman 2013; Venter 2010; Seaman and Sanford 2009; Gibson et al. 2010). One proof is a computer-generated artificial genome. Venter's team placed life-synthesized pieces of the target DNA into yeast, where they were assembled into the target genome. The assembled genome was transplanted into a different organism and "booted up" to create a new synthetic version of the target. The "operating systems" and the interacting "computers" in the cell with the replaced genome remained intact, and they were able to function by using the replacement "software." This research evidently demonstrates (at least for the two organisms involved) that life can use general "operating systems," "programming languages," and "devices" (Venter 2010; Gibson et al. 2010).

In the next chapter, the arising of biological information from physical one, including the appearance of the most essential characteristics of bioinformation (such as functionality, purposefulness, and control over the life's processes), is considered in the framework of the author's approach to the origin of life.

2.5 Integrated View on the Thermodynamic Method of Biological Organization

From the thermodynamic point of view, essence of a biological system can be expressed as follows. It is an ambivalent system. On the one hand, spontaneous (basic) processes proceed in biological systems, like in non-biological ones (for instance, diffusion). They obey the second law of thermodynamics. On the other hand, the opposite non-spontaneous (coupled) processes proceed more efficiently in them. This is a key point of the biological organization: intensity of the coupled processes exceeds intensity of the basic ones. As a result, energy gradients rise in a living system (at least at the ascending branch of its existence), and free energy and bioinformation accumulate. Internal entropy rises as well, because entropy never decreases in a natural system that is in compliance with the second law of thermodynamics. But free energy and information increase faster than entropy. Due to this reason, a (viable) biological system is characterized with persistent deficit of entropy; i.e., its entropy is negative. In this way, the excessive over-entropy free energy and information organize the entire system providing by means of the acquired fundamental properties its active existence in the environment (that we call *life*). This quality is reflected in the negentropy trend of biological evolution. In fact, at the expense of such organization, biological systems are able to develop in the thermodynamic direction that is opposite to the development of the rest (i.e., non-living) of the systems of the Universe.

A paradox of such organization of a biological system consists in the following: Any coupled process proceeds at the expense of the corresponding basic process taking *a part* of its energy only. That means energy of the basic processes (and correspondingly entropy) should also rise in the course of biological evolution providing additional energy source for the coupled processes. Such energy non-compensated organization of biotic systems (organisms or communities) is maintained through the exchange of energy, matter, and information with the environment. By using the unique fundamental properties, living organisms actively extract high-energy substance (i.e., free energy) from the environment, reorganize it inside (release energy), and actively remove low-energy substance (i.e., entropy) outside. Unlike other natural systems, *biotic* systems (organisms, communities, and species) energetically exist at the expense of the environment. This emphasizes the well-known fact that a biological system (ecosystem and biosphere) is the inseparable pair system inclusive of proper biotic systems and their environment. So, the ability for active extraction of free energy (and information) and entropy export must appear in a prebiotic chemical system in order to launch the biological processes. Besides, the prebiotic system must be in a process of the incessant exchange with the surroundings.

One more consequence follows of the thermodynamic method of biological organization. As entropy inevitably rises in a biological system, it must all the time reorganize own structure, functions, and behavior to compensate growing internal entropy in plenty. So, it is always in the face of choice: either to advance or to be eliminated with the natural selection. The trend to the degradation of a biological system that appears due to fast entropy growth may not be irreversible. Having the latent surplus of free energy and information accumulated during the whole biological evolution, living beings, communities, species, and ecosystems possesses huge potential for self-reorganization at any moment of own existence.

This subsection expresses the author's understanding of the principal gap separating non-living systems (including prebiotic models) and living cells indicated as FACTOR L in the Chap. 1. Proper chemical evolution (complication) is insufficient condition for the transition of prebiotic microsystems into primary living units. The described above great difference between non-living (chemical) systems and living cells implies necessity to search specific requirements that would make such transition possible.

Below, the author gives his answer to the question designated in the Chap. 1.

The question: Why the initial signs of transformations in laboratory protocells cannot reach self-maintained level and to be converted into biochemical processes?

The answer: Because laboratory protocells do not possess the surplus over-entropy free energy and (bio)information, as well as the corresponding mechanism of entropy export, that may organize a chemical matrix into a living unit.

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