

Self-organizing dynamic stability of far-from-equilibrium biological systems

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Abstract. One indication of the stability of a living system is the variation of the system’s characteristic time scales. Underlying the stability mechanism are the structural hierarchy and self-organization of systems, factors that give rise to a positive (accelerating) feedback and a negative (braking) feedback. Information processing in the brain cortex plays a special role in highly organized living organisms.

Keywords: biosystems, characteristic times, stability, metamorphosis

Dynamic stability is temporary equilibrium burdened with a fall

1. Introduction. The multifaceted notion of stability

A few years ago, I published the article “21st century: what is life from the perspective of physics” [1] at the request of

V L Ginzburg. The manuscript submitted to *Uspekhi Fizicheskikh Nauk (Physics–Uspekhi)* was reviewed by D S Chernavskii [2], who was himself interested in the problem. The reviewer noticed some flaws and advised one to consider, for completeness, *mechanisms underlying the stability of biosystems*. However, this recommendation could not be met in full measure in view of the large volume of Ref. [1]. With the present publication designed to address the concept of *stability inherent in biological systems*, I wish to pay my respect to the recently deceased Dmitry Sergeevich Chernavskii, a wonderful person and prominent scientist.

Stability is a multifaceted term interpreted in a variety of ways.

In a broad sense, *by stability is meant the ability of a system to maintain its current state under the influence of external factors*. In mechanics, stability is characterized by the response of an initially equilibrium system to a perturbation (Le Chatelier’s principle [3]). Stability is categorized into Lyapunov’s asymptotic stability [4], local stability, and asymptotic stability in its entirety [5].

In engineering, stability is defined as the capacity of technological systems to retain their design and kinetic parameters within prescribed limits [6]. The theory of probability treats statistical stability as the convergence of probability measures to some limit [7]. In computer simulation and quantitative calculations, so-called numerical stability, e.g., the relationship between the algorithm of calculations and errors in rounding off numerical values of variables, needs to be considered [8].

The definition of stability in complex systems is closely related to the transfer of energy fluxes inside a system. Living

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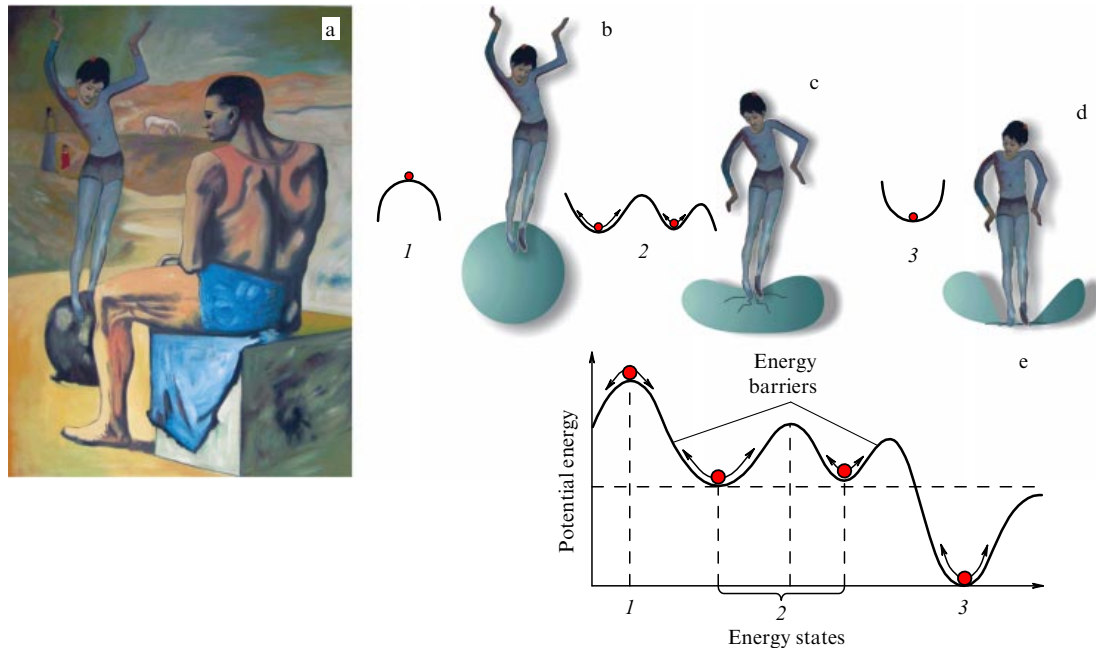


Figure 1. Vivid image of self-organizing dynamic stability of lumped-parameter systems (ball gymnastics). (a) Picasso's painting *Acrobate à la Boule*. (b) An unstable position (stability can be achieved only by *continuous correction* of body position by the neuromuscular apparatus of the gymnast), and (c) the quasi-stable position. To reach stability, an adequate position on the base must be found with help of the muscular nervous system. (d) The stable position. The shape of the energy relief is shown on the left in figures b, c, and d (the ball indicates the energy state). The shape of the platform is determined by the bulk modulus of compressibility of its material under the weight of the gymnast, which accounts for different energy states. (e) Potential energy plotted in correspondence to the energy states separated by energy barriers.

matter constituting the biosphere gradually tended toward stability as it was becoming increasingly more complicated in the course of evolution. At the dawn of evolution, competition and symbiosis played a key role in this process. With increasing biodiversity, the formation of species was accompanied by their division into predators and prey. The processes of differentiation within individual organisms themselves gave rise to two systems, the brain and the body, that evolved to co-exist as information and power worlds. Such differentiation is intrinsic in any living entity (from bacteria to the biosphere on the whole), regardless of its place in the hierarchy of evolutionary development. Interaction between these systems maintains the stability of life in its entirety.

This problem as applied to economics has been addressed in research work by D S Chernavskii and his colleagues and disciples over the past few years [9, 10]. References [9, 10] and other studies by these authors have demonstrated, by modeling *competition* between two manufacturers of functionally identical articles, the instability of such systems, resulting in the long run in ousting one of the producers from the market as the other swallows up its business or drives it into bankruptcy, despite the initially equal starting conditions of work for the two competitors. However, stability can persist for an arbitrarily long time in the *presence of an additional regulator*, e.g., an antimonopoly law and/or a law-enforcement agency responsible for supervising compliance with legislation. In higher organisms with a central nervous system, the role of such regulator is played by the brain cortex.

No general theory of stability for living matter has thus far been proposed, and it can hardly be created in the near future. There are too many factors contributing to the loss and restoration of stability. Nevertheless, the theory of stability

does exist for many special cases, e.g., balancing on a ball, as illustrated in Pablo Picasso's painting *Acrobate à la Boule*.

Stability depends on variations of the contact surface in time and the adaptability of a living organism to them. Figures 1b, c, d show different variants of stability.

In what follows, selected examples and lines of research into the stability of dynamic far-from-equilibrium biological systems are considered, including *restoration of their broken symmetries with the use of gauge invariants*.

To recall, a gauge invariant is a measurable physical quantity (or combination of such quantities) essential for the concrete problem of the search for stability. This quantity remains unaltered under certain transformations in a local region. The physical quantity considered in the present article is first and foremost the *characteristic time scale of the processes in a system open to energy fluxes*. The characteristic time is the time of a transient process in the search for stability. Alterations of the characteristic time range can be utilized to elucidate the origin of different variants of stability.

The presentation that follows is intentionally designed to be comprehensible to specialists from different disciplines. It has two main purposes: to draw the attention of young physicists and biophysicists to the theory of stability of biological systems, and to demonstrate the crucial importance of a systemic physical approach to the analysis of biological processes.

2. Parallel worlds in living systems

2.1 What Darwin missed in his theory of evolution

The formation of the central nervous system in living organisms did not interrupt their connection with the micro-

world of bacteria and viruses. However, they acquired a new property of existing in two worlds at the same time, viz. the world of information processing (fast processes) and the world of force-driven spatial movements (slow mobility processes). The information world is highly diverse.

To begin with, the world of information is the world of parents and tutors teaching a new generation of living organisms how to survive. Second, it is the individual world of positive and negative emotions (stresses) arising from memories of the past teaching and the discrepancy between model vision and real-time events. Third, it is the world of self-tuition by trial and error method. Fourth, it is the world of satisfying subsistence needs (nutrition, reproduction, and curiosity). Fifth, it is the social world based on the interaction between individuals (friends or enemies). The existence of these worlds does not require evidence. Let us consider only the last one.

It would seem at first sight that Darwin's theory of evolution via *competition* is closed and self-consistent, since it covers all aspects of the development process [11]. P A Kropotkin was the first in Europe to criticize it from the sound scientific perspective. His book [12] was translated into many European languages, but its arguments were disregarded and had no appreciable influence on refining Darwin's theory at that time. In Asia, similar ideas were formulated by the Japanese natural scientist Kinji Imanichi, but his work was published in Japanese and became available to European researchers only in the late 20th century [13]. Moreover, the hypothesis of Lamarck [14] (a predecessor of Darwin) contained, for all its faults, a rational kernel, e.g., the idea of cooperation in animate nature [15].

It came to be increasingly better understood at the beginning of the 21st century that Darwin's theory reflects only one aspect of the evolution of living matter, namely competition. Two new terms were coined, Holobionts and Hologenomes, to describe its second aspect, i.e., symbiosis (Greek *syμβioun* 'a living together', from *sym-* 'together' + *-bios* 'life'). In fact, a new *holobiontic concept* (from the Ancient Greek word *hólos* for 'whole') [16–19] formed itself at the intersection of different branches of evolutionary biology. At first, it was concerned only with processes proceeding in microbiological communities [20–22]. However, it soon became evident that it must be extended to all levels of development of living matter, bearing in mind common food chains of individual organisms and the biosphere.

For example, the surface and the interior of the human body provide a home to some 10^{12} – 10^{15} microorganisms (bacteria and helminthes) whose total mass in an adult normally amounts to 1.5 kg (practically the weight of the human brain), whereas a variety of species counts between hundreds and a few thousand. Such biotas of various microbiological compositions are specific for each host organism. To put it differently both its normal functioning and life span depend not only on its own genome but also on the cumulative set of genes of its symbiotes (allies). In this way apart from the own genome our development and behavior are subjected to biota's genome [23–26]. At the social level of human society, this instance of information influence is described by the saying "a man is known by the company he keeps."

Systemic investigations of living communities began only in the late 20th—early 21st centuries. The *problem of stability in biological systems taking account of the existence of*

microbiological biota is central in applied biology and biophysics for addressing both environmental issues at large and specific problems facing biomedicine, agriculture, demography, nanorobotics, and biological safety. It needs to be taken into consideration when planning the development of new territories and space exploration, exploitation of renewable energy resources, and designing artificial intelligence systems.

The biota is highly inhomogeneous. It may consist of both the allies and conformists and even of enemies (parasites). Imbalance in their composition can lead to a diversity of deviations in the behavior of host organism and may even influence its psychics. It is therefore an important factor responsible for the opposition of predator's strategy towards the victim and vice versa when it comes to victim's strategy towards the predator. We confine ourselves to one example.

Herbivorous animals, e.g., sheep, happen to be affected by a disease called *stagger* that makes them walk in a peculiar staggering vacillating way, perform circular motions, and eventually stray from the flock. This pathology is caused by larvae of dog tapeworms (*Taenia multiceps*) migrating via blood to the brain and spinal cord. The next hosts are either wolves or wild dogs killing the stray animals. As a rule, these parasites do not induce a new type of behavior in the predators; rather, they transform their routine behavior so that the brain cortex of the affected animals fails to adequately respond to environmental changes, which ends in their death [27]. Not infrequently, what is regarded as a disease is actually a result of pathological modification of the biota and the struggle at this hierarchical level between commensals and parasites in the host organism.

What is it that attracts commensal bacteria to a host? It is the possibility of mutually beneficial utilization of information and energy, called *symbiosis*. Both partners or only one of them take advantage of such information–energy partnership or alternatively one uses energy and the other information. In the third case, the exchange of information benefits takes place, whereby one partner receives necessary information from the other, while the latter in turn obtains information from the former.

Actions of symbiotic partners or the substances they produce are essential for each of them to maintain stability of their mutual survival. Generally speaking, these processes are intermediary between remote interaction and complete merging. The fusion of dissimilar organisms is a limiting case of symbiosis when partners make up a single body and have a common genetic code read out as organs are formed through cell differentiation (see Table 1) [28, 29].

A rough classification distinguishes three types of exchange underlying symbiosis.

Energy exchange is self-evident and needs no comment. Suffice it to say that digestion in animals and humans would be impossible without gastric and intestinal bacteria. Another example is symbiosis of fungi and algae in lichens. Photosynthetic algae produce organic matter (carbohydrates) [30] utilized by the fungi, which in turn supply the algae with water and minerals.

Energy-information exchange provides the ordered transfer of genetic information essential for a given species in a predetermined direction in exchange for food, as exemplified by insect–plant symbiosis. Some orchids are pollinated by a single insect species. Other flowering plants can be pollinated by different species. Some insects eat plant products, such as nectar, (nectarivores) and help spread pollen (genetic information), thereby contributing to plant reproduction. Certain

Table 1. Quantitative parameters at different organizational levels of the human body as a medium for symbiotic bacteria.

Parameter	Value
Body volume of adult subject, m ³	~ (0.03–0.05)
Body surface of adult subject, m ²	~ (1.6–2)
Body density, kg m ⁻³	~ (1050–1100)
Number of neurons in brain	~ (10 ⁹ –10 ¹⁰)
Amount of brain neuroglia	~ (10 ¹⁰ –10 ¹²)
Maximum number of synaptic connections	~ (10 ¹² –10 ¹⁴)
Number of human cells	~ (10 ¹³ –10 ¹⁵)
Number of symbiotic bacteria	~ 0.7 × (10 ¹³ –10 ¹⁵)
Number of different cell types	~ 210
Number of water molecules	~ 10 ¹⁴
Number of sugar molecules	~ 5 × 10 ¹²
Number of fat molecules	~ 2 × 10 ¹²
Amount of RNA	~ 6 × 10 ¹⁰
Number of different types of proteins	~ 10 ⁶
Amount of low-molecular-weight metabolites	~ (2–3) × 10 ³
Number of genes	(25–35) × 10 ³
DNA length, m	~ 2

Note. The human organism can be described as a condensate of one-celled organisms formed in the course of evolution. In other words, the cells and organoids make up a giant integrated colony having the volume ~ (0.03–0.05) m³. This colony evolved into an information–energy complex with its own internal communication language and thereby acquired stability, i.e., a relatively long lifespan, at the expense of reproduction rate.

birds also distribute the seeds of the plants on which they feed in their excrement over large territories. Some plants grow together to protect each other. For example, young South American cactuses are subject to overheating in direct sunlight and can grow only if shaded by drought-resistant shrubs. Being spiny plants, cactuses in turn protect symbiotic plants from consumption by herbivorous animals. Triple symbiotic systems formed by birds and herbivorous and carnivorous animals have been described. Certain birds eating seeds contained in the manure of herbivores warn them of an approaching predator. Such symbiotic relationships are based on the ability of animals to respond to a change in information they receive from the environment.

Information exchange. Psychic activity has for a long time been considered unamenable to direct observation for want of relevant methods necessary in studying the underlying processes. In so doing, zoopsychology evolved not to the examination of the *psychic activity as such, but to studying only its observed external manifestations*. Systematic investigations into the mechanisms of psychic activity became possible only with the advent of differential electric encephalography and dynamic magnetic resonance imaging in the late 20th–early 21st centuries. Our brain works on the same principles of competition and symbiosis modified by peculiarities of information storage and processing [31, 32].

The limiting statement of the problem reads: how stable in time are the processes of interaction in predator–prey systems? Can competition lead to self-destruction of living matter? Can mutual interference between predators and their prey result in the disappearance of both?

Answers to these questions should be sought through the evaluation of stability of competitive and symbiotic relationships with due regard for the role of the intellect of the animals. It would seem that negative feedback-based mutually detrimental interactions must converge to zero as a decreasing function $\langle \exp(-t/\tau) \rangle$, where t is real time, and τ is

the characteristic lifetime of the biological system. However, life does not merely exist; it continues to develop, ascending the hierarchical ladder step by step as it becomes increasingly more complicated. Therefore, any set of decreasing functions $\langle \exp(-t/\tau) \rangle$ determined by competition must correspond to a set of increasing or slowly decreasing functions $\langle \exp(\pm t/\theta) \rangle$ arising from symbiotic relationships, where θ is the characteristic time of information perception and processing by an organism. In such a case, the growth of one function hampers by negative feedback the decay of the other. As a result, the system comes into an equilibrium once the equation

$$\ln \sum \theta_i = \ln \sum \tau_j \quad (1)$$

holds true. Sustainable development and complication occur if the inequality

$$\ln \sum \theta_i > \ln \sum \tau_j \quad (2)$$

is satisfied. Dynamic selection of stabilities in the course of evolution was effected by virtue of the periodically manifested weak asymmetry of local competition processes in favor of symbiosis [13]. Thus, *presence of a weak local asymmetry is the motivating force of biosystem evolution*. Weak asymmetry of interactions has the form

$$0 \leq \sum (\theta_i - \tau_j) \leq 1. \quad (3)$$

When this relation is disrupted for a given species, it dies off, to be replaced by another for which this rule continues to hold.

Similar processes proceed in highly organized organisms. *Such organisms are composed of hard and soft components. For an individual, they involve the skeleton and the adjacent muscle tissue, as well as a liquid substrate or liquor* (such as blood plasma, lymph, an intercellular substance, cerebrospinal fluid, various colloids, gels, and mucus). *These two components maintain the structural plasticity of a system as a whole, and enhance its stability, i.e., prolong the lifespan.*

In social (in a broad sense) *biological systems capable of information exchange* (regardless of the language of communication: chemical, acoustic, or tactile) *the role of the skeleton is played by dominant organisms, i.e., superpredators and supervictims (ardent passionarians or attractors) [33], while that of soft tissue by subordinate ones (symbiotes, conformists, and parasites).*

Importantly, a social biological system that happens to go beyond stability boundaries does not necessarily die off but undergoes metamorphosis, i.e., transition into a qualitatively new state. Here are two examples of such a transition.

2.2 Biological system outside the stability boundary

Stability is disrupted as soon as the population density of a carnivorous species reaches a critical value in the period of limited abundance of prey. This may lead to extinction of the carnivore population but usually results in its metamorphosis. A commonly known example of metamorphosis is the fate of a locust (*Acrididae*) population as it reaches critical density. Locusts are known to exist in two phases (solitary and gregarious) differing in morphology and behavior. When the population density of the species occupying a certain territory exceeds a critical level, each insect forms wings and changes color. They gather in a swarm, and the ‘flying cloud’ leaves the former habitat in search of new areas rich in food. The

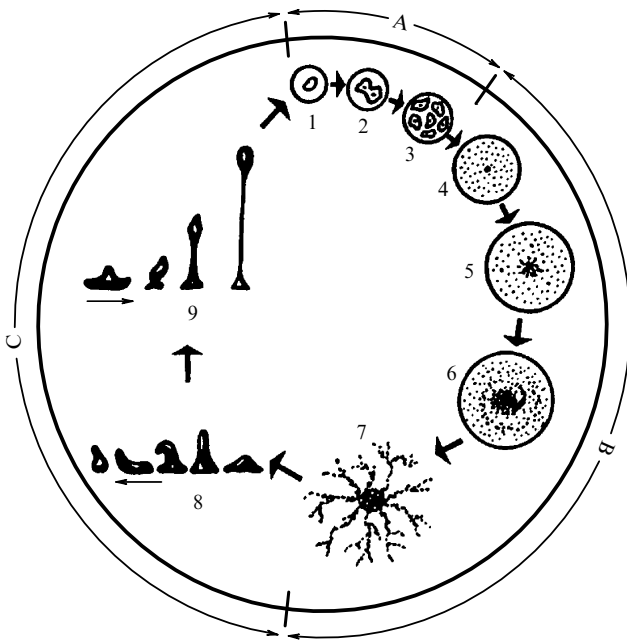


Figure 2. Phases of *Dictyostelium discoideum* metamorphosis. A phases stand for reproducing spores: A-1 (a spore), A-2 (spore disconservation in a nutritive medium and transformation into an amoeba), A-3 (mobile and dividing amoebas). B phases—aggregation of amoebas in a nutrient-depleted medium: B-4 (SOS signal secreted by a starving leader cell), B-5 (spatial response of amoebas to the alarm signal), B-6 (propagation of the signal over the population and movements of amoebas toward the signal substance), B-7 (end of aggregation preceding plasmodium formation). C phases—development of plasmodium and fungus: C-8 (plasmodium migrating in search for food), C-9 (formation of spore-carrying fruiting body from the plasmodium).

metamorphosis is triggered by a signal in the form of mutual tactile stimulation of the insects rubbing continuously over one another, i.e., a reduction in the critical space available for individual insects in the course of their reproduction, which is being provoked by reaching the critical population density within a limited territory [34].

Another interesting example is the slime mold (*Dictyostelium discoideum*) [35] that exists, depending on the environmental conditions, either as an assembly of individual amoeboid cells or as an integrated multicellular organism (Fig. 2).

In a nutrient-rich environment, the cells live and feed independently of one another and do not fuse into a single organism. As food resources become exhausted, certain cells secrete SOS signals suggesting starvation (see Fig. 2, B5 phase) and release cyclic adenosine monophosphate (cAMP). This chemical signal is received by specific receptors of other individual cells, which turn around and move along the gradient to the sites of high cAMP concentration (B6–7 phases). Eventually, all single-cells gather in one place and merge to form a single multicellular organism—plasmodium (B8 phase) capable of traveling in search of food faster than individual cells. If it fails to find food, the plasmodium forms the stalk of a fruiting body having a sac with small spores at the top (see Fig. 2, C9 phase). The mature fruiting body collapses and the spores catapult themselves into the air, sometimes as far away as 12 m. Certain spores ‘gone with the wind’ find themselves in a food-rich environment and give rise to new fungi (otherwise, the clone dies). Metamorphoses are underlain by epigenetic mechanisms, i.e.,

blocking the expression of certain genes and deblocking others [35].

2.3 Limitations of the Lotka–Volterra model

Because all biological systems, on the one hand, are energetically open nonlinear systems, while a totality of them, on the other hand, develops as they interact with one another, this allows them to be considered in terms of dynamic stability. In inanimate nature, the notion of dynamic stability is applicable, for example, to air and water flows associated with the displacement of air and water masses under the influence of temperature and pressure gradients in Earth’s gravitational field.

If nutrition is unrestricted, any biological system exists due to exponential chain type reproduction up to exhaustion of energy and available territory. Predators kill their victims and thereby limit their reproduction, while victims, in turn, affect the reproduction of carnivores that experience food shortage as they reduce the abundance of prey. This leads to suppression of reproduction and a decline in the carnivore population or its extinction. This long-known fact was described mathematically by Alfred Lotka and Vito Volterra [36, 37]. Such a model implies an oscillatory process in which variations in the numbers of predators and their prey occur with a phase shift along the time axis in relatively constant steps referred to as characteristic reproduction time [38–40].

However, this model fails to take account of two additional features of biological systems: the formation of social symbiotic communities, and intercourse among symbiots, in which transmitted information plays an essential role.

2.4 Symmetry ↔ asymmetries

Intrinsic in any biological system is a large set of characteristic times. The largest of them for an individual is its lifespan. It provides a scale on which all other characteristic times (childhood, youth, etc.) are plotted. Let us denote the lifetime as τ_i , and regard it as the sum of all other characteristic times:

$$\tau = \sum \tau_i. \quad (4)$$

Cybernetics of the 1950s [4] gave rise to synergetics (Greek *synergētikós* ‘working together’, from *syn-* ‘together’ + *-ergētikos* from *ergon* ‘work’)[42]. In terms of the stated goals, this new science as an approach to the description of nonlinear systems stands very close to the theory of stability in predator–prey food chains. It is based on the principle of symbiosis and related effects. A major advantage of this science consists in providing a set of more or less concrete methods for the analysis of special problems, even if with the loss of universality.

Morphogenetic studies proceed from the principle treating morphology as a reflection of kinetics on a different (larger) time scale. A variant of this approach is consideration of riverbed formation as a result of water stream–bank interaction. In this case, variation of stability can be estimated from changes in the bed configuration during the long life of the river. However, configuration of the riverbed does not adequately reflect the kinetics of the water flow. Mathematically, the bed is the integral of the flow with boundary conditions dictated by the bank composition, i.e., a kinetic model. The knowledge of bed morphology alone is insufficient for characterizing the dynamics of structure formation

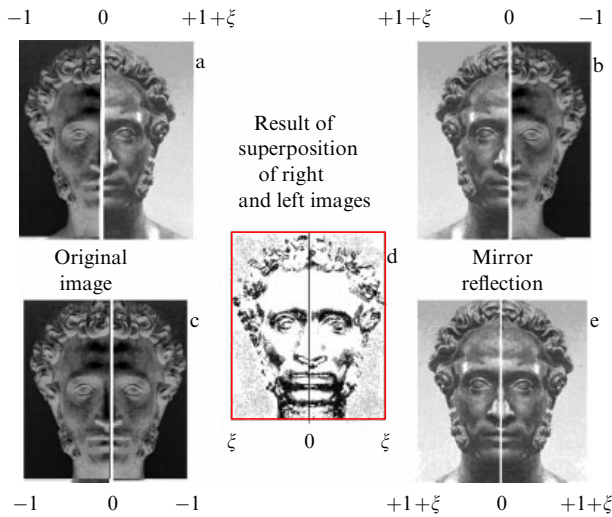


Figure 3. Two images—negative (c) and positive (e) made up of right halves of the original (a) and right halves of its mirror reflection (b), respectively. When the image is perfectly mirror-symmetric, it disappears after the superposition of the negative and positive plates. In the case of broken symmetry, the superposition produces a contour image. (d) The contour image obtained by superposition of images shown in figures c and e. Quantity ξ characterizes mirror asymmetry of human face: $\xi = \xi_0 \exp(-S_1/S_2)$, where S_1 is the area of dark regions on the facial image, S_2 is the area of light regions, and $S = S_1 + S_2$ is the total area of the facial image [13].

inside the flow. Integration over time is known to inevitably destroy part of the information.

To avoid the loss of information, it is of primary importance to observe over time for the symmetry violations and search for gauge invariants to restore symmetry. Morphological asymmetry never disappears. Figure 3 shows a variant of mirror symmetry of a dummy organism exemplified by the plastic image of an adult human face.

A degree of axial asymmetry is inherent not only in the human face but also in the human body. Matrix thermovision [43] made it possible to reveal an asymmetry of noncoincident temperature reliefs (e.g., right and left halves of the face or the body) where the system formerly seemed to possess mirror symmetry [13, 44–48]. It is worthy of note that living face asymmetry is much more apparent than that of its plastic image, because morphology reflects only specific spatial features but fails to provide information about changes resulting from small-scale temporal variations of blood flow and muscle contractions in the living face (Fig. 4) [46].

We are used to seeing minor morphological asymmetries with our vision apparatus in visible light and therefore simply overlook them. Marked facial asymmetry apparent in the visible electromagnetic wave range is initially perceived as a turn of the head (Fig. 5). Usually, pronounced asymmetry is associated with pathological conditions (tumors or gingival abscesses).

Mirror symmetry is the simplest form of symmetry. It is rare in predator–prey systems, where attack and protection strategies improved continuously in the course of evolution. The evolution finds asymmetric variants in terms of specularity, which restore equilibrium.

Drawing an analogy with a formal description of nonlinear equations in the quantum theory implies the necessity of searching for equations satisfying the principle of asym-

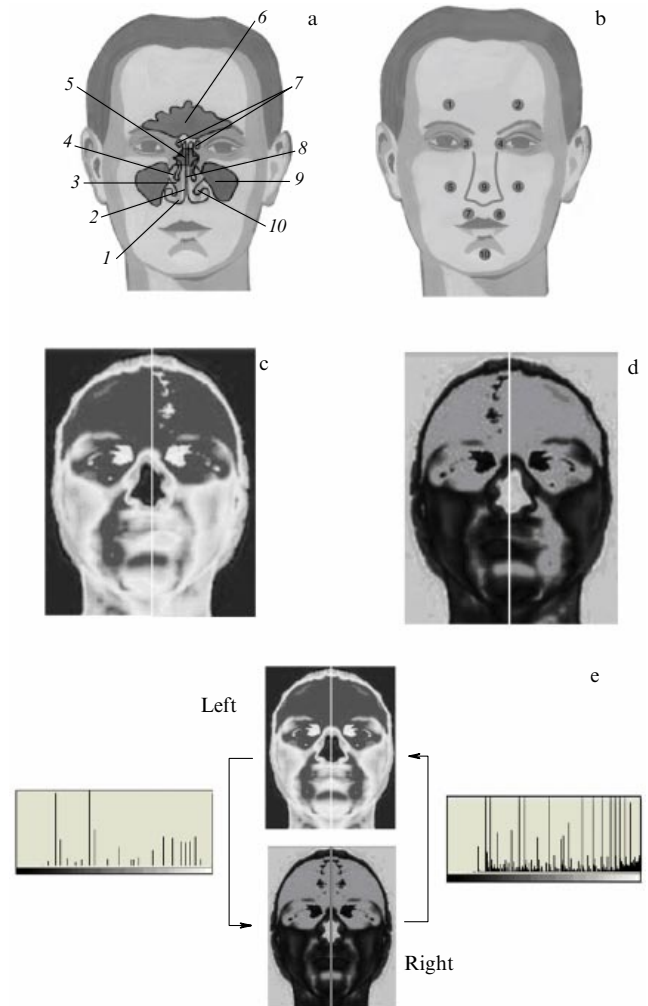


Figure 4. Distinguished points on a human face: (a) paranasal sinuses (front view): 1—*Meatus nasi inferior*, 2—*Septum nasi*, 3—*Meatus nasi medius*, 4—*Concha nasalis media*, 5—*Sinus sphenoidalis*, 6—*Sinus frontalis*, 7—*Cellulae ethmoidales*, 8—*Meatus nasi communis*, 9—*Sinus maxillaris*, 10—*Concha nasalis inferior*, and (b) 10 distinguished points to measure temperature with a thermovisor. (c) The thermal portrait of a normal human subject in a range of 8–12 μm , (d) its mirrored negative, and (e) dynamic stability with broken mirror symmetry. Temperature histograms of warm and cool parts of left and right halves of the face do not coincide.

metry and symmetry restoration, such as Einstein and Young–Mills equations, i.e., the symmetry of a two-dimensional sigma-model [49, 50]. In classical mechanics, such models are of the reaction–diffusion type, where nonlinear terms describe the kinetics, while transfer and displacement processes are represented by diffusion [51–56].

However, more intricate diffusion type mechanisms (e.g., nonlinear, anisotropic, and cross-diffusion) operate in various systems. In many cases, modeling of distributed population systems like a predator–prey system requires taking account of cross-diffusion [57–60]. Cross-diffusion mechanisms are of primary importance for mathematical simulation not only of pigmentation in animals [61–63] or aggregation in *Dictyostelium discoideum* [64–67]; they equally well describe various social events, such as swarming. It is a very important form of the search for stability during directional motion induced by alterations of the spatial distribution of information-carrying stimuli [68–71], such as environmental factors

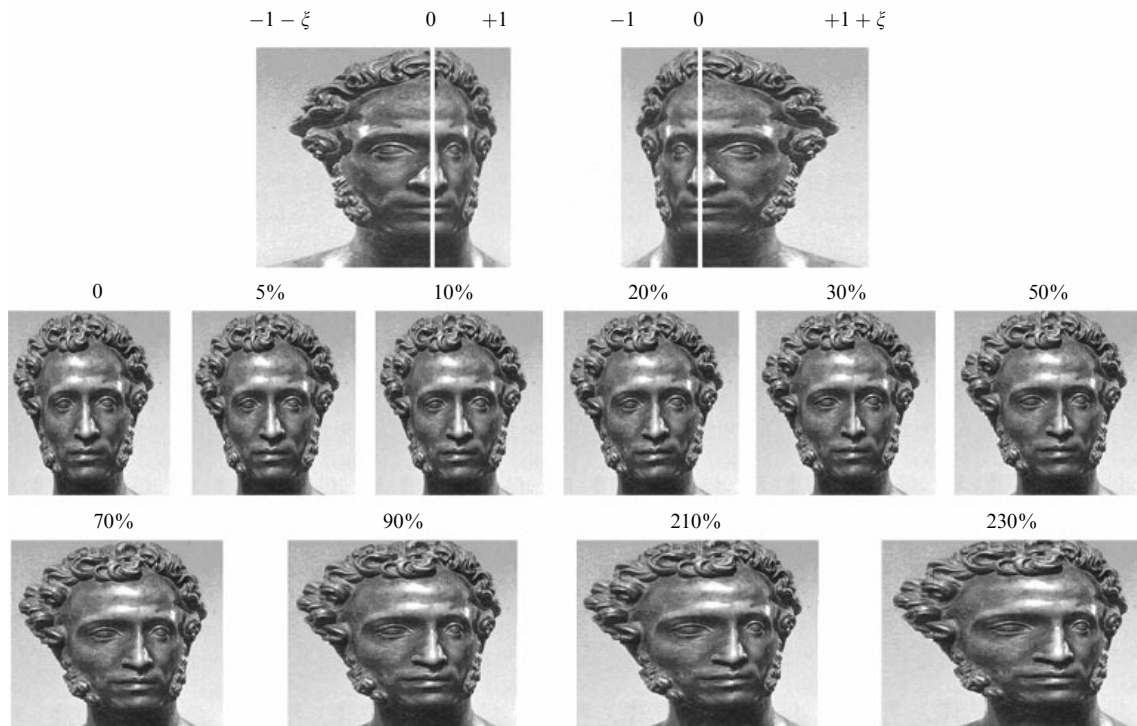


Figure 5. Introduction of marked asymmetry of facial morphology by means of horizontal expansion of one of its halves (in percent) [13]. Symmetry breaking ($> 200\%$) produces illusion of head turning.

(temperature, salinity, illumination, sounds, food, etc.) and population density itself.

As early as the 19th century, Michel Chasles proposed categorizing isometric transformations into those occurring on a plane and in space [72]; he appears to have been the first to prove the similarity transformation theorem. In the early 20th century, Felix Christian Klein developed the theory of geometric group transformations [73]. Such a description allows the evaluation of the temporal evolution of biological systems from symmetry violations [13, Ch. 2].

Projection of the shape of a solid body traveling in the Euclidean space onto a plane is conducive to maintaining the equality of angles such that the scalar products are conserved. For a two-dimensional case, any orientation-preserving motion is either a straight-line movement or a turning movement with abrupt braking or acceleration. It *may be supplemented with a screw motion or various jumps*.

A carnivore may be capable of extremely fast movements in straight lines; still, its prey, lacking such ability, can escape from falling victim by making sudden turns or jumping over obstacles. The search for gauge invariants describing the equilibrium restoration mechanism often (although not always) helps to solve nonlinear equations, e.g., based on the theory of system integrability [74–78]. In other cases, the result is nothing but a fresh view allowing us to identify common features of different problems and emergence of new stability criteria.

It appears that the main result of the future general *predator–prey* theory could be the concept of universality classes with the *catastrophe theory* [79–81] as one of its components or the classification of different forms of phase transitions [82]. Classification of phase transitions in multi-dimensional systems makes it possible to formulate two important parts of the theory of many-dimensional confor-

mal models and calculi of the shapes of the phase space surfaces on which symmetry-restoring interactions take place.

As far as strong linkages in predator–prey systems are concerned, it is appropriate to mention ‘naïve’ relationships between them. A link can be interpreted as a set of one-dimensional strings stretched with different forces and signs. Such a description of the process is akin to the string theory for strong interactions in the microworld [83]. Moreover, such a situation is very common in our *macroworld* due to its spatial *three-dimensionality*. Quantum chromodynamics provides the most remarkable example of this kind in the microworld of many-dimensional space.

The existence of a strong linkage in a situation with a single predator species and a single prey species enabled V. Volterra to build a special theory based on the coupled pendulums model [37]. The string theory also arose from the search for a description based on strong interactions [83, 85–90]. Such attempts applied to the description of biological systems have a long history; they resulted in the introduction of the notion of the *ecological niche*. At first, this term was used to designate a place in the space where interactions among predators, prey, and their symbiotes occur [91]. Thereafter, it served to describe a totality of factors indispensable for the existence of a given species as a component of a hierarchical food chain [92]. Finally, it was proposed to relate a network of food chains (food web) to space and time [93, 94]. In the end, the model of interactions among all food chains came to be represented as a many-dimensional space encompassing a variety of ecological niches.

A specific ecological niche was assigned to each species in which it can exist together with its symbiotes. The number of ecological factors essential for a given species can also be represented as a graph. Such an approach to the description

of predator–prey relationships has both advantages and disadvantages. A disadvantage common to all conceptual models is that the description makes the process explicit but precludes quantitative evaluations of the system’s behavior due to the infinite number of niche topologies in the many-dimensional space of parameters, which are responsible for multiple uncertainties arising from their projection onto the plane.

2.5 Diversity of stable forms and transitions between them in terms of phases

Nature is integrated and indivisible, while classification of sciences reflects discipline-specific description languages. The choice of the language is based on the search for correspondence between microscopic (atomic-molecular) and macroscopic (cells, organs, whole organisms, and their social systems) levels of description [95], taking into consideration different variants of hypotheses and respective gauge invariants not only in the framework of classical mechanics but also in related theories (quantum mechanics and the general theory of relativity) (Fig. 6).

Here is an example considered by Ya B Zel’dovich in the paper published in the jubilee issue of *Uspekhi Fizicheskikh Nauk* dedicated to A A Friedmann on the occasion of the 75th anniversary of his birth [96].

A A Friedmann proposed extending Einstein’s general theory of relativity based on two postulates. First, the Universe is in the average uniform and isotropic, despite the presence of bunches of mass (planets and stars), because each galaxy has other galaxies in its vicinity, which accounts for a certain mean density of matter such that physical conditions are in the average identical over the entire Universe. Our Galaxy is neither unique nor central; the same is true of the Sun and Earth. Second, the motion of galaxies has to be such that it does not break the uniformity and isotropy of the Universe, with the physical conditions being identical at all points and in all directions. Based on such a minimal number of postulates, Friedmann arrived at the conclusion that *galaxies cannot be at rest relative to one another*. In principle, their collective velocity at a given moment can be zero, but *acceleration will be always nonzero*. Such vanishing of velocity is experienced by a stone thrown up vertically at the uppermost point of its trajectory in Earth’s gravitational field. Therefore, in accordance with Newton’s second law of motion, the relative discrepancy between the velocities of two different objects increases in proportion to the distance between them. The forces applied to thrown stones being

equal, the lighter the stone, the higher it goes. At present, the maximum recession velocity of distant galaxies is estimated at $(0.3–0.4)c$, where c is the speed of light, namely it is on the order of $100,000 \text{ km s}^{-1}$. In other words, mean density of matter can vary with the Universe’s expansion, but gauge invariants remain unaltered at all points in space, because all spatial directions are equivalent.

A similar conclusion holds true for Earth’s biosphere. Observations with low spatial and temporal resolutions show that the biosphere is on the average uniform and isotropic in space and time. The Sun serves as the source of energy, and all living creatures inhabiting our planet are in a sense carnivores consuming products of its activity. However, observations with increasing resolution reveal marked inhomogeneity in biosphere density in the direction from tropical regions to the poles and from expanses of green vegetation to deserts, meaning that the flux of solar energy is insufficient for the formation of food chains. Living matter (at least a carbon-based one) forms and develops under the protection of the atmosphere and magnetic and gravitational fields of Earth in the presence of water and soil of definite chemical composition.

The description of any system, regardless of the language used, must yield an identical conclusion. Otherwise, the description in the chosen language proves incomplete. Such a situation is frequently encountered in mathematical linguistics (machine translation) [97].

On the one hand, a method is needed to limit the number of variables. The absence of such a reduction is fraught with such robust resulting expressions that their practical application makes no sense whatsoever.

On the other hand, ‘overcompression’ of the number of variables is likely to produce an effect of ‘throwing the baby out with the bath water.’ There is nothing new in this thought. It dates back to antiquity, the theologist of the 14th century W Occam (Occam’s razor), and Einstein’s aphorism “Everything should be as simple as possible, but not simpler” [13]. The problem is how to reach a compromise on simplification?

Let us assume that we managed to capture all wolves hunting hares in a given territory, placed them in an enclosure, and release them back into the wild after a period of time τ_1 . The Volterra model [37] suggests that the number of hares to be available as prey increased during this time. Therefore, the number of wolves must also increase during time τ_2 after release (needed for reproduction and replenishment of the population). Does the increase actually take place? If all the wolves are captured again and counted, three scenarios are conceivable:

(1) the number of wolves increased, which means that the reproduction conditions were consistent with the Volterra model;

(2) the number of wolves remained unaltered;

(3) the number of wolves decreased.

The last two situations are very real and deserve special consideration since they lie outside the Volterra model. They are feasible given that the theory of predator–prey food chains in the Volterra model has proven to be incomplete.

The stability of biological systems varies in space and time and is measured in arbitrary units upon displacement of one dynamic system (predators) with respect to the other (prey). Here is a simple example. Let us assume that two elastic balls, white and black, are placed in a chamber with two compartments separated by a partition. Let us then raise the partition, shake the chamber, and put the partition back into the initial

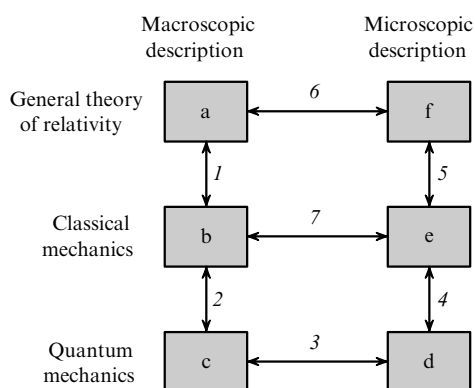


Figure 6. Methodology of description of processes in living systems.

Table 2. Possible combinations of balls in the two sections.

Section 1, open	Section 2, closed
White	Black
White + black	Empty
Black	White
Empty	White + black

position. We do not know how the balls of different colors are distributed between the sections. In the classical case, there is a hidden parameter, the color and number of balls in a section. One section may contain the black, and the other the white balls. What we know with certainty is that neither the color nor the number of balls changes. On opening the first section, we can see one of four possible combinations of white and black balls (Table 2). Hence, it is possible to say what the second section contains.

In this case, there are no long-range or nonlocal links: we just remembered the starting information and this *a priori* knowledge enabled us, after we came to know the hidden parameter of one section, to deduce the hidden parameters of the other. This logical operation was performed in our brain. The probability of finding one combination or another or its absence in the open section was initially 1/4, while the *a priori* information about the presence of only two balls of different colors and two sections allowed us to avoid uncertainty after opening one of them, because it became possible to predict with a probability equal to unity what the other section holds. Such a system in time is a fully determinate reversible Newtonian system.

Let us turn to a more intricate problem. Suppose that white and black balls can be reproduced by division and assume that the energy flux needed for reproduction is unlimited. Let white balls be reproduced at a rate of $\omega_w(t)$, and black ones at a rate of $\omega_b(t)$, where t is time. This gives rise to a temporal component in addition to the spatial one. After the sections are separated and their contents mixed up, open one of them and count the balls it contains. Can we unambiguously predict their combination in the second section? Given that rapid and ideal intermixing produced an entangled state, the resulting system must be uniform and isotropic on average in terms of color, i.e., the answer is yes. In reality, however, errors are inevitable for two reasons.

First, it is necessary to take into account the dynamic characteristics of the observer (or the instrument) counting the balls. Even if they were counted correctly and quickly at a rate ω_0 much higher than the maximum division rates ω_w and ω_b , the resulting ratio between black and white balls in one section does not provide adequate information about their combination in the other for the second reason. The spread of reproduction rates affects the spatial-temporal density of the number of balls.

Let us assume that time τ_i elapsed from the onset of division till the opening of section 1 was recorded by the chronometer with a round dial. We then get frequency ω_i and phase φ_i for each moment of time

$$t = \left(m + \frac{\varphi_i}{2\pi}\right)\tau_i = \left(m + \frac{\varphi_i}{2\pi}\right)\frac{1}{\omega_i}, \tag{5}$$

where m is the integer number of hand revolutions around the dial, and τ_i is the value of the scale division on the dial. Expression (5) yields

$$\varphi_i = 2\pi(\omega_i t - m), \tag{6}$$

and expression (6) gives the phase value $\xi_i = \varphi_i$ within the last incomplete revolution:

$$\frac{\xi_i}{\omega_i t} = 2\pi = \text{const}. \tag{7}$$

The right-hand side of Eqn (7) contains the length of the circumference with a unit radius, expressed in radians. Because

$$\xi_i = 2\pi \frac{t}{\tau_i}, \tag{8}$$

the smaller the characteristic interval τ_i of values of the scale division, the higher the accuracy of phase measurement of the running watch hand as an addition to the integer-valued number of revolutions.

Let us make our system with the chamber more complicated by allowing the balls with a low division rate (with large characteristic periods) to use for food the balls dividing at a higher rate (with short characteristic periods). In this case, we shall have to consider the motion of one set $\langle N_1 \rangle$ with respect to the other $\langle N_2 \rangle$, i.e., rotation of a hand and the dial relative to each other at different speeds. This process is known as synchronization of auto-oscillating networks with time-delayed coupling [98]. The idea of the synchronization effect is very old [99, 100] and has been repeated in different variations by mathematicians since the 17th century (see Huygens [101], Rayleigh [102], Appleton [103], Van der Pol [104], Andronow and Witt [6]). Synchronization is of primary importance for biological systems, because all processes in them, from cellular to social, proceed with a variable time delay [105–108].

From the geometric standpoint, the phase value $2\pi/l$ at constant rotation rates, depending on how many times arc $l \sim \varphi_i$ falls on the length of the circumference $L = 2\pi$, can be both an integer and a rational or irrational fraction:

$$\varphi = \frac{2\pi}{l} = m + \xi, \tag{9}$$

where m is the integer number of revolutions preceding the arrival of the l -long arc at the starting point, and ξ is the fractional part. To recall, the notion of irrational fraction is a geometrical notion, when the value of the scale division on the dial is $\tau_i = 0$, which is practically impossible, because τ_i always has a finite nonzero value. Therefore, ξ must fall into the interval $0 \leq \xi < 1$. Phase coincidence in integer-valued revolutions results in a circle with an inscribed star polygon indicating phase coincidence points over the circumference length. At small τ_i , the number of such points is finite but large enough to cover the entire length (Fig. 7).

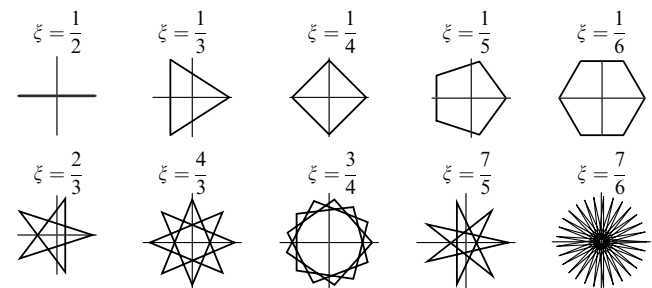


Figure 7. Geometric patterns of phase deviation. ξ is the rational fraction at any integer number of revolutions $m = 1, 2, 3, \dots$

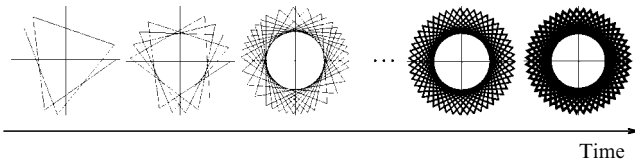


Figure 8. Time course of polygon formation at $\varphi = 3.14$.

When trajectories are not smeared out, the system exhibits absolute dynamic stability and is completely time-reversible. If ratio (9) gives integer-valued phases supplemented by rational fractions, for example, $m + \zeta = 2.5, 3.5, 3.6, 4.5 \dots$, etc., i.e., $\zeta = 0.5$ or 0.6 , the measuring arc l will rotate many times around the circumference $L = 2\pi$ of the dial before it eventually returns to the starting point. Such a system is stable as well, but stable dynamically with the large characteristic time of the search for the stable state θ .

At very small values of the scale division on the dial, the characteristic time of the search for the stable state θ becomes finite, whereas on the scale of small divisions it remains very large. In fact, the shape of the figure tells us about the characteristic time of system's arrival to a stable state.

A polygon formed by stable trajectories is a *generative figure* creating a given class of phase stabilities. For example, the emergence of a star polygon proceeds by rotating a tetragon when the integer-valued m is close to 4, rotating a triangle when m is close to 3, etc. Figure 8 shows by way of example the sequence of trajectory pattern formation at $\varphi = 2\pi t/\theta = m + \zeta = 3 + 0.14$, i.e., when $t/\theta = 1/2$.

A star polygon can be formed by means of both clockwise and counterclockwise rotation. If perturbation $\zeta = \pm\lambda$ is introduced in the vicinity of integer-valued m , rotation would be either clockwise or counterclockwise, depending on the perturbation sign. For example, at $m = 3$ and perturbation $\lambda_1 = 0.0333$, one obtains $n = m + \lambda_1 = 3 + 0.0333 = 3.0333$ (counterclockwise rotation); at negative λ_2 , $n = m - \lambda_2 = 3 - 0.0333 = 2.9667$ (clockwise rotation). The generative figure appears as the attractor, i.e., a compact subset of a certain set of regular polygon shapes. All trajectories from the vicinity of the phase space of a dynamic system tend to have a regular shape, because they correspond to equilibrium states. Similar geometric structures underlie principles of dynamic crystallography, namely, the presence of regular shapes of crystal cells and their distortions as a result of the impact of dislocations [13, Ch. 2]. An example is presented in Fig. 9.

The evaluation of stability in the analysis of planar projections (see Fig. 9) in terms of phase kinetics and corresponding regular polygons reduces to routine vector calculus in three-dimensional space with two spatial coordinates plotted in the plane, and with time as the third coordinate. In this case, the real four-dimensional world of H Minkowski loses one spatial dimension and therefore some information.

The International Stereological Society that existed in the 1960s–1970s held congresses with such issues on their regular agenda as information compression methods for the purpose of anatomical studies, e.g., the dimensional reduction of spacetime in the chain of $4D \rightarrow 3D \rightarrow 2D \rightarrow 1D$ transitions [109]. I participated in the work of several such congresses (Fig. 10).

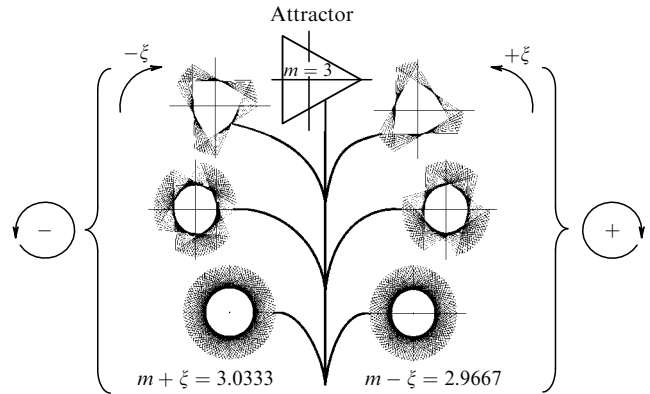


Figure 9. Example of computer simulation of transitional forms. Occurrence of arrest at $m = 3$ (stable state–attractor), counterclockwise rotation at $m + \zeta = 3.0333$ (subtraction), and clockwise rotation at $m - \zeta = 2.9667$ (addition).



Figure 10. Switzerland, August 1969. From right to left: the Swiss anatomist Prof. E R Weibel, the designer of the morphometric model of the human lung and President of the International Stereological Society, the author of the present article, and Prof. Weibel's wife.

Paradoxically, attempts to reduce the outside world were not infrequently ridiculed. Not only scientific articles but also science fiction novels were devoted to this topic. As early as 1884, Edwin Abbott, mathematician and physiologist, published in London the satirical novel *Flatland. A Romance of Many Dimensions* (under the pseudonym 'A Square') [110]. Abbott's story describes a fictional two-dimensional world occupied by geometric figures, of which women are simple line segments while men are polygons inhabiting higher organizational levels. Seventy years later, the book got a new lease on life as a genre depicting the primitive perception of the world by our computer-based society in the epoch of the contemporary technological revolution. This paradox is known as cyberpunkism (*cyber-* + *punk*). For all that, scientific model construction is impossible without reducing the number of invoked variables. Historical examples give evidence that a reduction in the number of variables has both merits and disadvantages but is absolutely necessary to conduct physical and biophysical research. At the same time, one should not totally rely on the choice of gauge invariants, because it is highly subjective and may prove incorrect. It needs to be kept in mind that a gauge invariant

chosen based on the results of reduction has very limited applications [13].

If a dynamic system possesses large characteristic times of the search for stability, the dynamics of the search process may lead to increased diversity of figures. This principle equally well holds in biology. N I Vavilov's homological series are a set of wild forms giving rise to various agricultural plants mediated through attractor metamorphoses. Certain transitional forms suffer impaired resistance to environmental perturbations, such as changes in weather conditions [111]. A A Ukhtomskii's dominant idea [112] can also be interpreted as a pathological attractor in the work of the brain. It exemplifies one of the forms of pathological dynamic stability.

2.6 Characteristic times \leftrightarrow frequency modes and information \leftrightarrow entropy transitions

One may try to restrict the parameter space in a different way, for example, by distinguishing essential variables and excluding unessential ones [113]. This, however, poses the question: *Who are the judges? Who can a priori find differences between essential and unessential variables? And how can they be found?*

The rise of the modern information world relying on the intelligence capabilities of the human brain initiated a process, the main function of which was the search for answers to these questions under conditions of a time deficit. A peculiar feature of biological systems is that they are involved in six complementary interactions of living matter, which have different energies and characteristic times of realizing their functions, viz. *reception, communication, mobility, reproduction, memory, and information consolidation (processing) into blocks by forming links*. These interactions are crucial for the survival of organisms under conditions of competition and symbiosis with each other.

In most cases, *receptors* are spatially localized in an organism. The function of reception is to transfer *small masses or low amounts of energy* from the outside to the inside of the organism. These signals *carry information* about environmental conditions and make the organism capable of long-range information perception.

Communication inside and among organisms at different organizational levels is also mediated through small mass or energy transfer in the form of chemically meaningful molecules (smell), mechanical contact impacts (touch), remote acoustic signals (hearing), and changes in electrical and magnetic fields (sight, etc.). Interactions among them lead to the formation of various semantic patterns in the organism. In the figurative sense, all living cells 'talk' to one

another in their specific language, most frequently, the chemical one. It is safe to say that interactions among living organisms in predator-prey or consumer-resource systems occur not only via energy exchange but also through the exchange of vitally significant information.

Mobility is a means of development of energy-rich territories. This process makes an organism spend much of its own energy for movements in space. The energy is stored preliminarily in the form of adenosine triphosphoric acid (ATP) or fat [114] and is replenished as the organism consumes nutrients (food) to nourish and fuel its body. Both the organism and its progeny are involved in territory development. This principle is inherent in all organizational levels of living systems, from molecular intracellular structures to social interactions inside the biosphere as a whole.

Reproduction is a chain reaction, with characteristic times and, correspondingly, frequencies specific to each species. The time interval of this chain reaction depends on the length of the reproductive period in a given organism.

Memory (memorization) is a process whereby stable connections between nerve cells are formed in an organism. In most cases, the process at first involves the entire brain cortex and thereafter becomes localized in the vicinity of specialized target structures in the course of intercellular communication.

Information processing through block assembly and disassembly is also an energy-consuming process, even if the organism has to spend much less of its own energy than for moving in space. In this context, two savings conveying opposite meanings can be mentioned, one of which applies to predators ("all brawn and no brains"), the other to prey ("need makes the old wife trot").

A brain at rest consumes 4–5% of the energy that muscular work does (Table 3). Moreover, it operates within a tighter timescale.

There is still no generally accepted term in biology to describe block transformation of information on a time scale, although the presently used time grading (seconds, minutes, hours, days, etc.) seems to be suitable for the purpose.

The point is that the range of the timescale in the virtual inner space of the brain varies, depending on the environmental conditions (emotions and stress accelerate the timescale compression) and the skills acquired in the process of learning, i.e., memory of the past. As applied to living systems, this time should be considered the projection of past time onto the present timescale, because memory stores past experience and thereby influences current events. These characteristic time intervals θ set the scale in the brain's

Table 3. Distribution of the per-minute blood flow of left ventriculus over human organs at rest [115].

Organ	Organ mass, kg	Blood flow		Effective resistance to blood flow*
		ml min ⁻¹	ml (100 g min) ⁻¹	
Porta hepatis	2.6	1500	57.7	1.56
Kidneys	0.3	1260	420.0	0.214
Brain	1.4	750	53.6	1.67
Skin	3.6	462	12.8	7
Skeletal muscles	31	840	2.7	33.3
Myocardium	0.3	252	84	1
Remaining tissues	23.8	336	1.4	64.3
Whole body	63	5400	8.6	10.6

* Effective resistance is the ratio of mean arterial pressure [mmHg] to the blood flow rate [ml (100 g min)⁻¹].

virtual space and ‘live by themselves’. For example, a nerve impulse travels through the neuronal network of our brain at a speed of $20 \leq v \leq 200 \text{ m s}^{-1}$, which means that the impulse covers the distance l up to 2 m for $\tau_{\max} = 0.1 \text{ s}$. The characteristic time itself can vary in a person exposed to stress within a range of $0.01 \leq \theta \leq 0.1 \text{ s}$.

When classical Newtonian mechanics is applied to describe nervous processes, its time reversibility is limited by entropy. Erwin Schrödinger [116] coined the term *negentropy* as the opposite of entropy to characterize diminishing system entropy. It was used by Schrödinger and other authors in thermodynamics. Moreover, Schrödinger supposed that an *organism feeds on negative entropy and thereby inhibits the growth of entropy*. This figurative expression does not reflect reality, because organisms actually consume energy rather than entropy and themselves generate information essential for their survival. The effectiveness of brain work is estimated from a decrease in the characteristic time needed for achieving stability after excitation (see Section 4).

As a result, information in living organisms undergoes changes as they acquire new skills and knowledge; specifically, it is assembled in blocks or transferred from higher to lower organizational levels, e.g., from brain to spinal cord, to facilitate performance of motor functions and relieve the upper levels of routine work [117]. This helps additionally save energy and diminishes entropy for a relatively short time. In social systems, information transfer in brain tissues may affect individual behavior in such a way that a person adapts his (her) behavior to that of a crowd [33], and an animal to the behavior of a swarm or a herd [68–71]. To describe this process, various interpretations and terms have been proposed by different authors (Table 4).

This table only partly reflects the chronology of the appearance of new terms in biology. It contains no more than 0.003% of their total number encountered in relevant dictionaries [131–134]. Such a diversity indicates that we are not yet fully aware of how to perform hierarchical blockwise selection [13, 135], nor we have learned how to create a whole from a large number of special rules based on a limited set of terms. It explains why we see the outside world as being so complicated and multifaceted. Possibly, the laws will prove simpler, despite their visible complexity after we fully understand biological mechanisms operating in this world. However, to expect it is almost the same as to believe that “this will happen and that will never happen,” simply because *one likes this but dislikes that*. Nevertheless, one can regard with great probability alterations in the range of characteristic timescales in various living organisms as a principal parameter.

The time unit for information transfer can be arbitrarily termed the instant, the information time quantum, or otherwise. Researchers tend to avoid operations with characteristic time in virtual space and prefer to transfer it to reciprocal space, i.e., the frequency domain. In this space, its temporal changes are replaced by frequency–phase changes.

Characteristic time in the inverse Fourier transform frequency domain is defined by the term *frequency modes* [136]. *Natural oscillations or eigenmodes make up a set of various types of harmonic oscillations characteristic of an oscillatory system*. Each normal oscillation in a physical system, i.e., oscillations of atoms in molecules, is characterized by its *own normal frequency or eigenfrequency* (analogous to the eigenvalue and eigenvector in linear algebra). The set of normal oscillation frequencies makes up an oscillation spectrum. Arbitrary oscillations of a physical

Table 4. The list of formerly and presently used terms in describing brain activity (in chronological order).

No.	Terms and time of their appearance
1	Entelechy —Greek ἐντελής—complete and <i>echein</i> —actuality. Aristotle, 4th century BC [118, 119]
2	Monad —Greek μονάδος—unity. Leibnitz, 17th century [120]
3	Coherence —Latin <i>cohaerens</i> —coupling. Thomas Young, 1801
4	Qualia —Latin <i>qualia</i> (plural)—properties, qualities. C I Lewis, early 20th century [121]
5	Entropy —Ancient Greek ἐντροπία—turning towards. Term introduced in thermodynamics by Clausius (1865)
6	Negentropy —Latin <i>negativus</i> , opposite of entropy. Schrödinger, mid-20th century [116]
7	Syntropy —Greek σύνθεση— <i>together</i> , and τροπισμού— <i>turning, tendency</i> . Luigi Fantappie, mid-20th century [122]
8	Information —Latin <i>informatio</i> — <i>explanation, familiarization</i> . C E Shannon, mid-20th century [123]
9	Holographic concept of brain activity formulated by Karl Pribram in the second half of 20th century: “... <i>our brains mathematically construct ‘hard’ reality by relying on input from a frequency domain...</i> ” [124]
10	Autowaves . V I Krinskii and G R Ivanitskii, mid-20th century [125, 126]
11	Dissipative structures —Latin <i>dissipatio</i> — <i>dissipate, destroy</i> . I R Prigogine, second half of 20th century [127]
12	Synergetics — <i>cooperative behavior from ancient Greek συν—<i>together</i> and ἔργον—<i>activity</i></i> . Hermann Haken, second half of 20th century and Charles Scott Sherrington, early 20th century [128–130]

system can be represented as superposition of normal oscillations, while its forced oscillations have resonance at frequencies coincident with normal oscillation frequencies. In this case, characteristic time coincides the interval between jumps, i.e., δ -functions in spacetime, when frequency modes are coherent. Characteristic times lend themselves to transformations like real particles, but on a timescale.

The space of δ -function jumps should be regarded as an imaginary space (where the behavioral skills are accumulated as they are acquired in the course of mental development). The problem of searching for optimal trajectories in real space (running, jumping, resting) depends on the interaction of δ -functions in the virtual spacetime of the brain). They can either slow down or accelerate processes in real space in the form of phase synchronization in auto-oscillatory networks with delayed couplings. Changes in the dynamics of frequency spectrum in such situations as sleeping, acquisition of skills (learning), or their loss (amnesia) require special consideration.

Pairwise interactions like those between *predators* and their *prey*, when one carnivorous species hunts a single prey species, are an exception rather than the rule. First, different variants of predator–prey interaction are feasible. Different prey can be consumed by one species of a carnivorous animal, which leads to *competition* over prey. Second, prey species must have own food sources to exist. In this sense, they also comprise predators (and competitors) with respect to their food source hampering its replenishment. Third, there are sets of carnivores and their victims with competitive cross-links.

An energy-converting food chain starts with phototrophs (plants) that utilize solar light quanta, minerals formed on prehistoric Earth, and water. These resources are still unlimited. However, there are other limiting factors, such as the territory size and population density. In all cases, it is necessary to consider the dynamics of a cyclic system consisting of at least three interacting systems: *reproduction of phototrophs–reproduction of prey species–reproduction of predators*.

3. From equilibrium to nonequilibrium thermodynamics

3.1 Heterogeneity of systems and the ‘curse’ of large numbers

Thermodynamics seems to provide the most efficient tool for reducing the number of variables. If brain work is evaluated based only on three parameters (signal energy and noise energy + size of local information perception zones), a variety of signal-to-noise ratio gradations accounts for a wide choice of combined strategies for further information processing and decision making about the mode of behavior (in both men and animals) for the simple reason that, according to the information theory, the quantity of information in the receptor space can be estimated using the Shannon formula

$$I = \sqrt{1 + k \frac{W_s}{W_n}} \ln m = n \ln m, \tag{10}$$

where I is the quantity of information in the space of variables, W_s and W_n are signal and noise energies, respectively, n is the maximum number of points (pixels) in the plane, m is the maximum number of amplitude gradations at each point in the plane, k is the safety factor determined by the statistical properties of the signal and noise.

This means that the number of variants from which information for making a decision must be chosen grows rather quickly, as m^n . Even if the signal-to-noise ratio is very low, e.g., 8 at $k = 1$ and a limited area (e.g., 128×128 pixels), the information choice space becomes equal to

$$m^n = (128 \times 128)^3 = 4 \times 10^{12}. \tag{11}$$

With such a wide range of options available to each carnivore and prey species, they may use various combinations affecting their behavior.

The most common form of the prey’s response reduces to its reproduction. The smaller the size of an organism, the higher its reproduction rate (Table 5).

Hence, there are numerous ways to achieve parity in the means of survival that can restore equilibrium. Evidently, one of them is symbiosis.

To estimate the influence of symbiosis, the total enumeration space needs to be reduced, i.e., one should move from the total enumeration system ($I!$) to the block enumeration system $[i_1!i_2! \dots (I - i_1 - i_2 \dots)!]$; in other words, it is necessary to find links limiting total enumeration. The links are formed via hierarchical blockwise selection and memory mechanisms (genetic, symbiotic, or intellectual) [13, 135]. There are three ways to avoid the enormous numbers encountered in combinatorial theory.

First, natural selection is governed by variations of the environmental conditions. All organisms on this planet live

Table 5. Examples of biomass and reproduction rate doubling time [137].

No.	Species	Mass doubling time	Mass doubling rate/human mass doubling rate ω_1
1	Human at birth	180 days	$\omega_1 = 1$
2	Horse at birth	60 days	$\omega_2 = 3$
3	Guinea pig at birth	18 days	$\omega_3 = 10$
4	Sheep at birth	10 days	$\omega_4 = 18$
5	Pig at birth	6.5 days	$\omega_5 = 27.7$
6	Rabbit at birth	6 days	$\omega_6 = 30$
7	Silkworm	68 h	$\omega_7 = 63.5$
8	Human HeLa cells	24 h	$\omega_8 = 180$
9	House fly larva	13 h	$\omega_9 = 332$
10	<i>Paramecium aurelia</i> infusoria	5 h	$\omega_{10} = 864$
11	<i>Saccharomyces cerevisiae</i> yeast	1 h	$\omega_{11} = 4320$
12	<i>Escherichia coli</i> bacteria	20 min	$\omega_{12} = 12,960$

under relatively constant conditions due to the stability of rotation trajectories of Earth, the Sun, and the Moon and the presence of the atmosphere. By way of example, such a vitally important parameter as temperature in different regions of the planet housing life, from the North Pole and Antarctica to the equator, varies in the range from -80 to $+70$ °C, i.e., a difference of only 150 °C. Strong magnetic storms, earthquakes, floods, eruptions of huge volcanos, and falls of large meteorites occur but rarely.

Such relative stability of the environmental conditions through the geological history of Earth, from the protoplanetary state to our time, i.e., for $\sim 3-4$ billion years, enabled living systems to find, *by the trail-and-error method, stable interaction trajectories based on stable food webs* [13]. The extinction of certain species was compensated for by the appearance and multiplication of others.

Second, nature is not wasteful: it stored and multiplied in its genetic memory the lucky findings it had happened to make at the early stages of evolution (e.g., development of protozoans) by parallel transfer of genomic information. The analysis of food chains from the bottom to the top permits following up on the formation of relatively stable developmental strategies [1, 25, 26].

Third, gradual complication of food webs was governed not only by mechanisms underlying interactions of living organisms with the environment but also by social interactions within communities of small and big organisms.

The last assertion needs to be clarified before turning to the definition of stable trajectories in view of its special current interest. It is actually based on the concept of *long-range information attraction*.

3.2 Price of action in systems disturbed from equilibrium conditions

At a biophysical seminar held in the 1960s to discuss the laws of thermodynamics in application to biological systems, the outstanding biophysicist and radiobiologist N V Timofeev-Resovskii was asked: “What is the meaning of life?” The answer was: “Shameless death.” From the thermodynamic

standpoint, there is only a grain of joke in this joke. Any closed macroscopic system tends toward the state of stable equilibrium upon achieving maximum entropy. After passing into this state, the system exists in it for a rather long period, because all its macroscopic characteristics remain unaltered. Is it true of living systems? No, it is not. Memories of the dead (either human or animal) are preserved for some time in the information space of surrounding society (community) or in the inherited genome of the offspring; they continue to influence the real-life behavior of living individuals, while the residual potential energy of dead bodies is consumed by microorganisms and becomes re-involved in the energy turnover of the biosphere.

This brings up the question: can the law of energy conservation serve as an invariant for the description of the stability of living systems?

The balance of energy in an energetically open system can be represented only in terms of its flow by introducing an additional variable, such as characteristic time of energy utilization, τ_e . In this case, the energy balance has the form

$$\begin{aligned} (W_{\text{in}} - W_{\text{out}}) &\geq \Delta W, \\ W_{\text{in}}t - W_{\text{out}}\tau_e &= \Delta W\tau_e, \\ \tau_e &= \frac{W_{\text{in}}}{\Delta W + W_{\text{out}}} t, \end{aligned} \quad (12)$$

where W_{in} and W_{out} are incoming and outgoing energies in the same wavelength range, respectively, t is time, ΔW is the utilized energy, and τ_e is the characteristic time of energy utilization. In terms of dimension, $\Delta W\tau_e = H$ is a macro-quantum of energy or the price of action [138–140].

The quantity H in any organism stands for an analog of a bank account replenished at any time in energy units; how the energy is spent depends on the competition and the strength of connections among the organism elements.

Science seeks to elucidate the range of changes in the relationships among parameters. Such changes in complicated systems can be described either by extending the set of terms or linkage variants. The links are characterized by changes in strength and number. In either case, an operation method for measuring both sets is needed.

A diagram of three phase states (solid, liquid, and gas) of matter in a living tissue undergoes continuous transformation (Fig. 11a). Simultaneously, various phase transitions occur.

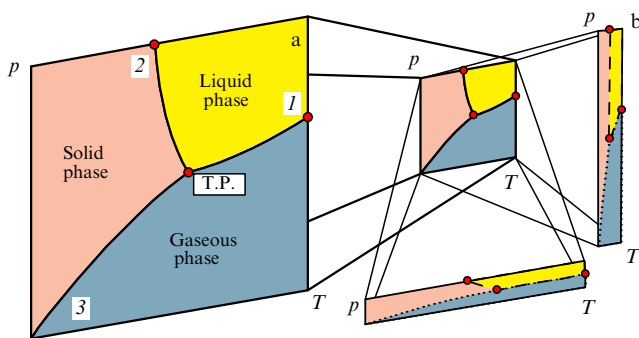


Figure 11. (Color online.) Transformation of the phase space of thermodynamic variables (second-order phase transitions) associated with the loss of stability near the triple point (T.P.): (a) diagram of stability at the triple point, and (b) transformation of the diagram upon a jumpwise change in thermal capacity C_p , pressure p , temperature T , and volume V .

Such a process can be described using partial derivatives of volume V with respect to pressure p and temperature T . Figure 11b presents only one example of phase space transformation. Such changes of the phase space occurring without heat absorption or release and alteration of the specific volume are interpreted as second-order phase transitions associated with jumpwise changes of thermal capacity C_p , isothermal compressibility factor

$$\beta_T = -\frac{1}{V} \left(\frac{\partial V}{\partial p} \right)_T,$$

and volumetric expansion coefficient

$$\alpha = -\frac{1}{V} \left(\frac{\partial V}{\partial T} \right)_p.$$

Entropy and the Gibbs thermodynamic potential are continuously altered, too. Paul Ehrenfest's equation describes the relationship among jumps of C_p , β_T , and α and the slope of the equilibrium curve near the second-order phase transition point:

$$\begin{aligned} \Delta C_p &= -T \left(\frac{\partial p}{\partial T} \right)^2 \Delta \left(\frac{\partial V}{\partial p} \right)_T, \\ \Delta \left(\frac{\partial V}{\partial T} \right)_p &= \frac{\partial p}{\partial T} \Delta \left(\frac{\partial V}{\partial p} \right)_T. \end{aligned} \quad (13)$$

Given that all the parameters C_p , β_T , α , V , T , and p are subject to alteration, a variety of their combinations can arise.

Body temperature in cold-blooded reptilians¹ is an alternating quantity and the total volume of their body changes but slowly. In insects, it changes too. Practically any combination of thermodynamic quantities is likely to be reflected in the animal kingdom, including the general case in which all of them change with time.

Warm-blooded animals (and humans) have a practically constant body temperature, $\sim 37^\circ\text{C}$, unrelated to broad-range variations of environmental temperature. Uniformly stable temperature is distributed within the body by the flow of internal fluids (blood and lymph) regulated by the heart. Overheating and overcooling of the body surface bordering the external medium are compensated for by excessive sweating and shivering, respectively, under control of the nervous system [43]. This allows internal processes to be considered isothermal. On the whole, the body volume changes slowly with the growth of the organism, and these short-term alterations can be disregarded. A change in pressure with each heart contraction results in little more than a redistribution of changes in internal volumes that reverse themselves between contractions. Evidently, the type of equilibrium in an isothermal process will depend on the sign of the derivative of the difference, with due regard for bulk compressibility modulus K of individual body elements. Then, elastic tissues contract to a greater extent than rigid

¹ Cold-blooded or poikilothermic animals are all invertebrates (insects) and such vertebrate forms as fish, amphibians, and reptiles. All mammals had for a long time been called warm-blooded till at least one exception was recently discovered. This small animal, the naked mole-rat (*Heterocephalus glaber*), is a very long-lived creature insensitive to pain and resistant to carcinogenesis. The naked mole-rat is a cold-blooded mammal [141].

ones. For such a heterogeneous system composed of r phases and n components, the condition of constancy of entropy s , volume V , and masses m is satisfied, namely

$$\sum s = \text{const}, \quad \sum_n V_n = \text{const}, \quad \sum_r m_r = \text{const}. \quad (14)$$

Any deviation from this equality leads to departure from equilibrium, suggesting instability of the system which, however, becomes dynamically stable in the presence of a regulator ensuring fulfillment of condition (14).

If a system consists of two parts differing in bulk compression moduli K , then

$$\partial \left(\frac{K_1}{\rho_1} - \frac{K_2}{\rho_2} \right)_T = \frac{\rho_1 \partial K_1 - K_1 \partial \rho_1}{\rho_1^2} - \frac{\rho_2 \partial K_2 - K_2 \partial \rho_2}{\rho_2^2} \quad (15)$$

in accordance with Newton’s third law. It follows from formula (15) for a system having two parts differing in densities ρ_1 and ρ_2 and in bulk compression moduli K_1 and K_2 that static equilibrium occurs when the numerator vanishes.

However, a description of stability like this excludes from consideration such an important characteristic as *time*. Nevertheless, the integral thermodynamic characteristics can be extended with the help of other conservation laws.

3.3 Conservation laws

Let us turn to equilibrium thermodynamics. The total energy ΔW of any equilibrium thermodynamic system is the sum of its kinetic energy W_k , potential energy W_p exerted by an external force field, and internal (pre-accumulated) energy U [142]:

$$\Delta W = W_k + W_p + U. \quad (16)$$

The internal accumulated energy U is composed of intrinsic energies of separate parts of the system; it is independent of the system’s motion as a whole or the presence of external force fields. The internal accumulated energy U is itself the sum of kinetic (U_k) and potential (U_p) energies:

$$U = U_k + U_p. \quad (17)$$

The assumption that two different values of internal energy, e.g., U_k and U_p , correspond to one and the same state of the system contradicts the law of conservation of energy, because it suggests that the system can be in two identical states with different energies. Therefore, the difference between them, viz.

$$\Delta U = |U_k - U_p| \quad (18)$$

could be used in the absence of any changes, i.e., to create a perpetual motion machine of the first kind. This is absurd. However, if such a system is placed in an external force field, it can absorb its energy and accumulate it, thereby changing U with its own characteristic time. In this case, Eqn (17) can be rewritten by introducing the characteristic energy storage time:

$$Ut = U_k \tau + U_p \tau, \quad (19)$$

or written in the standard form of a transient process:

$$U = U_0 \exp \left(-\frac{t}{\tau} \right). \quad (20)$$

The predator–prey relationship represents such a variant of a thermodynamic situation, i.e., the thermodynamics of a nonequilibrium process. In the next section, we shall consider the case of a cat controlling its fall from a certain height without violation of physical laws.

Classical thermodynamics provides a complete quantitative description of *equilibrium* reversible processes, and establishes inequalities for nonequilibrium processes, which characterize the possibility and directions of reversible processes. In these cases, at least six special conservation laws can manifest themselves [143–146]:

- law of conservation of energy for volume elements (introduction of specific values of energy with respect to the volume in the force field with the expansion of the total specific energy into dispersion of the particles’ thermal motion and the mean energy of interaction among them);
- law of conservation of mass (Lavoisier–Lomonosov law);
- law of conservation of momentum (Navier–Stokes hydrodynamic equations);
- entropy balance equation (when local entropy s is assumed to be the same function of internal energy U and specific volume V , as in the state of complete equilibrium, i.e., when conventional thermodynamic equalities hold true);

• phenomenological equations with continuous coefficients. In this case, fluxes associated with minor departures from thermodynamic equilibrium show the linear dependence on thermodynamic forces and are described by equations for the sums of transport coefficients (diffusion, resistance, viscosity) or strain coefficients (like Ohm, Fourier, or Fick equations). Cross-impacts or interacting effects (cross diffusion, cope effect, thermal diffusion) frequently arise in many-component systems [146]. In such cases, a stationary process at given external effects impeding equilibrium is characterized by minimum standard deviation (hence, minimum entropy) (Onsager theorem and Prigogine theorem);

• phenomenological equations with abruptly changing coefficients (heterogeneous systems, such as gases or fluids in containers connected by capillaries or a membrane, with valve-shaped channels operating by virtue of thermomolecular pressure difference). Variants (scalar, vector, or tensor) of these processes are feasible. According to the P Curie symmetry principle for isotropic media, there is a linear relationship between thermodynamic forces in a flow in the case of equal tensor dimension.

A system open to incoming external energy can take as much energy as necessary for its functioning.

4. Interaction between the brain’s virtual world and the real world of the body as exemplified by a falling cat

4.1 Characteristic times in the brain’s world

How do cats falling from a height upside down manage to turn over in the air and land on their feet with a minimal risk of injury? The answer to this question is of interest because, at first sight, such a fall seems to be in conflict with the conservation laws. A few stages can be distinguished in the fall with a flip and landing. The work of the cat’s brain plays the key role in this process, with the characteristic time it takes to make a decision being of primary importance.

Because all processes in the brain space proceed with short characteristic times and small energy expenditures in compar-

ison with those in power processes needed to turn the body, one has to recognize that the brain and the body are two different interconnected worlds [147].

Newton's laws of classical mechanics are formulated with respect to inertial reference frames [148]. Any frame of reference is called inertial with respect to which the space is both uniform and isotropic and time is homogeneous.

To recall, absolutely inertial systems in their pure form are nothing but a mathematical abstraction nonexistent in Nature, because our entire Galaxy is moving in space. Nevertheless, we can see rotation of the cat, while remaining in the same local coordinate system related to Earth's center of gravity, i.e., in the geocentric inertial system. The cat's brain is also related to the geocentric inertial system through its vestibular apparatus and visual analyzer. Therefore, the laws of classical mechanics must be satisfied in full measure.

The cat's visual analyzer receives information about distances at a speed close to the speed of light. The brain processes it more slowly depending on its bandwidth Δf . The relationship between the rate of transmission of the incoming data and the receiver bandwidth can be estimated from V A Kotel'nikov's theorem. If the upper frequency of the brain bandwidth is f_{br} , the characteristic time of information perception τ_{perc} will be as follows:

$$\tau_{perc} = \frac{1}{2f_{br}}. \quad (21)$$

To process any message as long as t , it is necessary to transmit n discrete values τ_{perc} apart from one another; therefore, one finds

$$n = \frac{t}{\tau_{perc}} = 2f_{br}t. \quad (22)$$

In accordance with Newton's laws, the value of t is, in turn, related to height h from which the cat falls by the expression

$$t = \sqrt{\frac{2h}{g}}, \quad (23)$$

where g is the free-fall acceleration. Therefore, $t = 0.247$ s at $h = 0.3$ m. Experience shows that this time is enough for the cat's brain to estimate the situation in the environment and order the body to turn by 180° .

The sense of equilibrium in cats is controlled by the well-developed vestibular apparatus located in the inner ear. Cats have a fantastic head for heights and can walk on the peak of a roof, fences, and tree branches. When falling, they *reflexively acquire a position in the air needed to land on their feet*. The characteristic time of this reaction equals

$$\tau = \tau_{perc} + \tau_r, \quad (24)$$

where τ_{perc} and τ_r are characteristic times of information perception and response of the body to the information-carrying signal, respectively. Cats appear to reflexively control the position of their bodies when falling, which suggests the involvement of the spinal cord.

The speed of a simple motor reaction in cats is an order of magnitude faster than in humans due to the difference in the basal metabolic rate in the two species. The normal body temperature in a cat is $38-39.5^\circ\text{C}$, compared with 37°C in people, the pulse ranges 120–220 and 50–90 beats/min, and

the respiration rate is 20–40 and 16–18 breaths/min, depending on physical and psychic activity, respectively. A cat's body weight is roughly 1/15–1/10 that of a person. The reaction time in humans is no less than $\tau_{perc} = 0.15$ s, even under the most favorable conditions. A person needs at least $\tau_r = 0.4$ s to recognize a visual image; hence, the total time reaches $\tau = 0.55$ s, i.e., almost 15 times that in a cat reflexively performing these operations ($\tau_{perc} = 0.01$ s, total time $\tau = 0.03-0.04$ s). This means that, in accordance with expression (23), it takes a cat falling from a height of 30 cm less than 0.25 s to turn over in the air; some 0.2 s remains to turn a body of 7 kg.

The falling cat phenomenon raises a number of questions. Does a cat have any fixed point of support when in the air? How much does the cat need the air for its turn-over in free falling? Does it use its tail to flip itself around? Is the momentum conservation law violated in the cat's fall? Can a cat turn over in a weightless environment? What mechanism is necessary and sufficient to enable a cat to quickly turn round in the air as it falls upside down? Does the cat's fur play a role in its ability to spin itself around mid-air?

On the one hand, the phenomenon of a cat's fall helps to understand one of the fundamental principles of stability in living matter: *genetic memory and memory acquired through the learning process promote knowledge acquisition and thereby increase the survival chances of any highly organized living creature* [1]. On the other hand, it illustrates one more attribute of living matter, namely, the *ability to purposely enhance instability in a critical situation in order to restore stability after coming out alive*.

4.2 Preconditions for the cat's flight

The cat's fall from height h with its legs straight up in the air consists of three stages:

- (1) quick turn about the axis passing through the body's center of gravity;
- (2) stabilization of position after the turn with stretching the legs out to create a sort of parachuting effect;
- (3) landing, with the hind legs touching down first, followed quickly by the front legs.

The initial stage is of special interest. The first high-speed photographs of a cat flipping over in mid-air were done as early as 1894 by Étienne Jules Marey, the French physiologist and pioneer of animal locomotion photography, who was one of the first to use the multiple exposure technique [149]. The falling cat problem remained a prominent focus of interest long after that and is still discussed on the Internet.

The rotation of a falling cat is initiated and maintained by the systems of its own body totally devoid of any external support. The hypothesis that two different values of the internal energy, U_1 and U_2 , correspond to one and the same state of the system is at variance with the law of conservation of energy, because it suggests two identical states with different internal energies [see formula (17)]. As is known, a body cannot move directionally by virtue of its inner forces alone in the absence of external support. Otherwise, it would be akin to pulling oneself out of a mire by one's own hair in the manner of famed Baron von Münchhausen. Nevertheless, the falling cat's ability to quickly turn over in the air and land on its feet is an experimental fact. What is behind it?

First, the body of any mammal is a combination of at least three systems: two power systems, and one controlling system. The former two encompass the anterior part of the body from head to the lumbar region and the remaining posterior part.

The entire spine (*columna vertebralis*) is made up of 24–34 vertebrae held together by cartilaginous intervertebral disks, joints, and ligaments. The lumbar spine usually consists of 2–9 (mean 7) asymphytous vertebrae providing a hinge joint near the center of gravity, allowing the lower and upper parts of the body to be rotated by muscular contractions in different directions relative to and independently of each other at an angle up to $\pm 35^\circ$ (even in humans, this angle can be quite large during childhood and further increased by means of special exercises). The cat’s back is remarkably flexible because the vertebrae of these animals are connected chiefly by muscles and not tendons, as in people.

Second, the leading actors in the event of a cat’s fall are the brain monitoring the direction of Earth’s gravitational field through the vestibular apparatus and the eyes measuring the distance to the landing surface. The brain is responsible for spatial orientation, while reflexively contracting muscles turn the body. The brain triggers the process of oppositely directed rotation of two body parts and ensures its timely arrest.

4.3 Turning without violating angular momentum

Richard Montgomery, who considered a cat’s free fall in the 1990s, showed that a cat falling under gravity upside down is able to turn over while maintaining zero total angular momentum [150]. Figure 12 demonstrates the sequence of events taking place as the cat flips itself in mid-air.

The total angular momentum \mathbf{L} of the whole body is constant by force of the angular momentum conservation law:

$$\mathbf{L} = \mathbf{r} \times \mathbf{p}, \tag{25}$$

where \mathbf{r} is the radius vector drawn from the body center of gravity to the center of gravity of a moving element of its separate part, and \mathbf{p} is the momentum of the element of this

separate part. To overturn itself in a free fall, the cat spends previously accumulated and stored energy for muscle contraction needed to sharply turn the head about 180° in order to see the landing surface. The cat spreads the hind legs and presses the fore ones to the body, the angular momentum \mathbf{L}_1 of its front part being

$$L_1 = rm_1v_1 = rm_1(\omega_1r) = m_1\omega_1r^2, \tag{26}$$

where r is the projection of the radius vector of the pressed legs onto the vertical z -axis orthogonal to the landing surface or (which is the same thing) parallel to the force of gravity detected by the vestibular apparatus and corrected by the visual analyzer (see Fig. 12), m_1 is the mass of the anterior part of the body, v_1 is the rate of turn, and $v_1 = \omega_1r$, where ω_1 is the rotation frequency.

The rear part transfers the torque moment to the front one as they rotate in different directions. The momentum of the rear part (Fig. 12c) is given by

$$L_2 = Rm_2v_2 = Rm_2(\omega_2R) = m_2\omega_2R^2. \tag{27}$$

Hence, the expression for the sum of momenta \mathbf{L} :

$$L = L_1 + L_2 = m_1\omega_1r^2 + m_2\omega_2R^2. \tag{28}$$

Three conservation laws are applicable to expression (28) [151]. For the law of mass conservation,

$$m = m_1 + m_2. \tag{29}$$

Because all turns of the cat’s body occur around the center of gravity,

$$m_1 = m_2 = \frac{1}{2} m. \tag{30}$$

For the law of momentum conservation,

$$L = L_1 + L_2 = \text{const}. \tag{31}$$

The cat’s body being a whole entity, all its components obey Newton’s second law which means that *gravitation acts equally on all parts of the body*, i.e.,

$$g = \frac{F}{m} = \text{const}, \tag{32}$$

where g is the acceleration of gravity, and m is the cat’s mass.

Finally, Newton’s third law states that for every action, there is an equal and opposite reaction,² i.e., the forces of interaction between the two parts of the cat’s body are equal and opposite; it follows, taking into consideration Eqn (31), that

$$L_1 = L_2. \tag{33}$$

Bearing in mind formulas (29), (30), and (32), from expression (33) follows

$$\omega_1r = -\omega_2R. \tag{34}$$

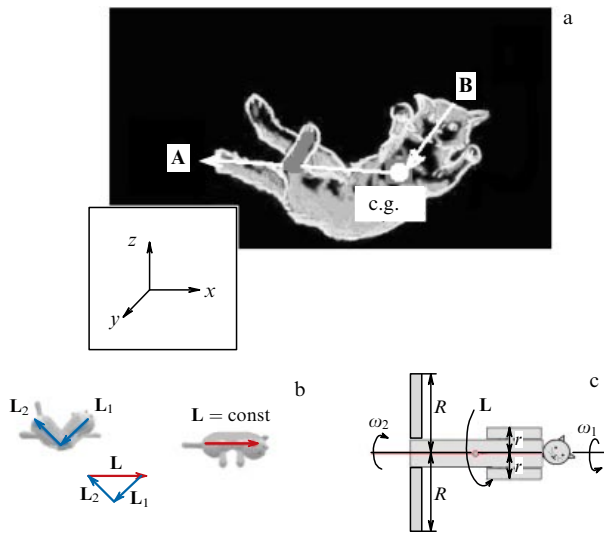


Figure 12. (Color online.) Sequence of movements of a cat flipping over in the air: (a) photograph of vectors \mathbf{A} and \mathbf{B} rotating round the center of gravity (c.g.); (b) the cat rotates the front and rear parts of its body in opposite directions by spine bending and muscular contractions (\mathbf{L}_1 and \mathbf{L}_2 are the angular momenta of the anterior and posterior parts of the body, \mathbf{L} is the total angular momentum), and (c) the angular momentum value is the difference between the radii of spread of the fore and hind limbs, the radius of which changes the rate (characteristic time) of clockwise rotation of the front part of the body and counterclockwise rotation of its rear part.

² Relativistic effects should be ignored even if they can give rise to noncentral forces. However, the time-averaged result will be the same as for the central forces. Because quantity r has the same value for any pair of interaction forces, their momenta are equal and opposite [151].

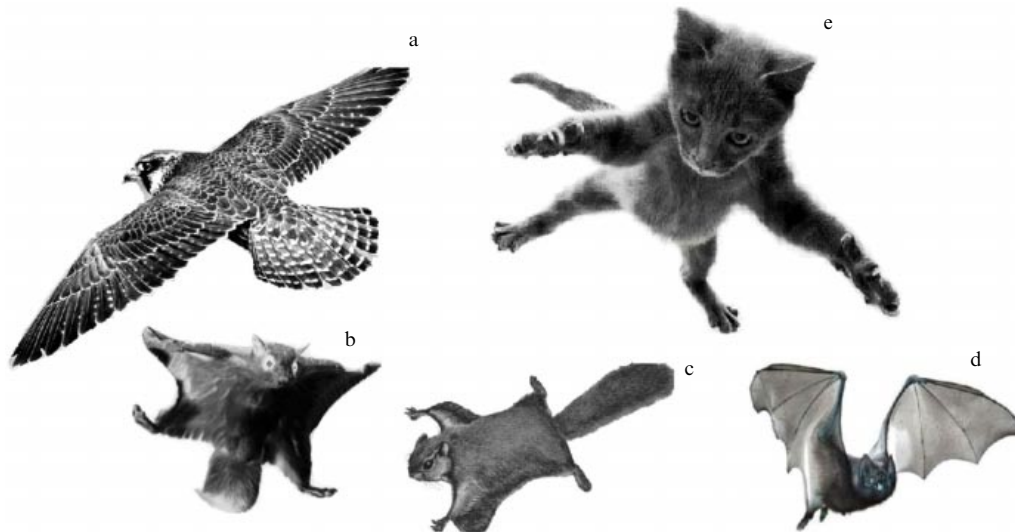


Figure 13. Gliding: (a) hawk, (b) red squirrel, (c) flying squirrel, (d) bat, and (e) cat.

Taking account of

$$\omega_1 = \frac{2\pi}{\tau_1}, \quad \omega_2 = \frac{2\pi}{\tau_2}, \quad (35)$$

one arrives at

$$-\frac{\tau_1}{\tau_2} = \frac{R^2}{r^2}. \quad (36)$$

It follows from Eqns (29)–(33) that the cat's flipping does not violate conservation laws. These expressions do not contain terms designating support, tail swinging, viscosity of the medium, and the cat's fur. What they do reflect is opposite changes in the direction of rotation with different characteristic times due to the alteration of the torque moments of the two body parts with respect to the center of gravity and the influence of the brain as a controlling device. The cat's brain, interacting with the vestibular apparatus that determines spatial coordinates and the visual analyzer that links the three-dimensional coordinates to the vector of Earth's gravitational field, generates signals to stop rotation.

It was shown in experiment that a cat with the vestibular apparatus switched off for a short time under conditions of weightlessness in a diving plane tends toward the nearest wall by turning its body parts and relying on the visual analyzer alone. The vestibular apparatus switches on upon restoration of gravity, and it takes the cat some 100 ms to correct its behavior in order to fall onto the plane orthogonal to the gravitational field. Fear is not the sole cause for why a blind cat cries as it is falling; in all probability, sonic detection also assists it to be oriented in space. Cats have exceptionally keen hearing that enables them to sense with closed eyes a squeak and rustle of mice around them using the Doppler effect. The human brain and organs of hearing cannot respond so quickly and precisely to an object's movements in space.³

³ In 2007, John O'Keefe, May-Britt Moser, and Edward I Moser were awarded the Nobel Prize in Physiology or Medicine "for the discovery of the navigation system in mammals based on grid cells creating a kind of internal GPS in the brain". These researchers demonstrated the presence of a neuronal network in the mammalian brain, including that of humans, which builds a mental map and helps its carrier track where it is in space. The same navigation system is responsible for the formation of memories (see, for instance, Ref. [152]).

For all that, a 'blind' cat needs much more time to turn its body than does one able to see.

All other parameters (tail swing, fur, air density) are important not so much for turning the body as for stabilizing the 'parachute' flight understood as assuming a vertical position with respect to the gravitational field and self-maintaining this position during the flight.

A cat falling from a small height, e.g., from a handbag or a child's hands, may have too short a time to turn over in the air and land safely; hence there is some risk of injury. However, a fall from a roughly 30-cm height gives the animal quite enough time to turn over.

4.4 Parachuting

Adherents of the widely discussed 'high-rise syndrome in cats' argue that cats falling short distances are likely to suffer greater injury than those falling from mid-range or higher altitudes, because the velocity of a free-falling object in the air is limited. Let us consider the cause of this limitation.

Humans are capable of developing all attributes of the behavior of a falling cat, other than gliding, because we cannot increase our body area in a cat-like manner by spreading our limbs; in fact, we need a parachute to soar safely in the air. Humans are too heavy and have very few means to enlarge the body surface area. Gliding is readily available for observation and analysis by cinematographic techniques. Various forms of gliding and soaring are inherent in many living organisms mastered a third dimension, viz. birds, bats, squirrels, etc. (Fig. 13).

It is easy to show what factors are responsible for the limiting free-fall velocity [153]. Let us first consider a feline dummy made of wool and shaped like a sphere falling from a relatively small height in comparison with Earth's radius with a velocity below the speed of sound (300 m s^{-1}). The model has surface S and weight P equivalent to the shape and weight of a cat's body. Naturally, its behavior is not controlled by a brain. Gravity \mathbf{P} and air density ρ are assumed to be constant. Rectilinear motion of the dummy under the force of gravity is characterized by two differently directed vectors applied to its center of gravity: one being drag \mathbf{F}_a orthogonal to Earth's plane and directed upward, and the other gravity \mathbf{P} is also orthogonal to Earth's plane but directed downward. The

modulus of the former is given by

$$F_a = 0.5c_z\rho Sv^2, \tag{37}$$

where S is the body surface, c_z is the specific friction between the air and the body surface, and v is the rate of fall. It may be assumed that quantities c_z , ρ , and S remain constant during the fall. Then, the modulus of the vector of the resultant force F_{res} acting on the body is written as

$$F_{res} = P - \sum F_{a,z} = P - F_a = P - 0.5c_z\rho Sv^2, \tag{38}$$

where S is the frontal area of the body experiencing braking by the air counterflow. The differential equation of motion has the form

$$\frac{P}{g} v \frac{dv}{dz} = P - \frac{1}{2} c_z\rho Sv^2, \tag{39}$$

bearing in mind that the flight path is equal to z , and the rate of fall $v = v_z$. Let us introduce the notation

$$\frac{2P}{c_z\rho S} = a^2. \tag{40}$$

Then, one obtains

$$v \frac{dv}{dz} = g \left(1 - \frac{v^2}{a^2} \right), \tag{41}$$

or, after separation of variables, the equation assumes the form

$$-\frac{v dv}{a^2 - v^2} = -\frac{g}{a^2} dz. \tag{42}$$

Performing integration of both parts of the equality yields

$$\ln(a^2 - v^2) = -2 \frac{g}{a^2} z + C. \tag{43}$$

The initial conditions for the flight path $z = 0$ and the rate of fall $v = 0$ give integration constant $C = \ln a^2$. Substituting this value into expression (43) yields

$$\frac{a^2 - v^2}{a^2} = \exp\left(-2 \frac{g}{a^2} z\right). \tag{44}$$

Finally, the following resultant expression for the rate of fall derived from equation (44) is given by

$$v = a \left[1 - \exp\left(-2 \frac{g}{a^2} z\right) \right]^{1/2}. \tag{45}$$

Formula (45) gives the dependence of variations of the falling body speed in the air on the distance it covers. Quantity $\exp[-2(g/a^2)z]$ decreases with increasing z and tends to vanish when $z \rightarrow \infty$. This means that the rate of fall v increases with z and tends in the limit towards a . In accordance with formula (40), this quantity equals

$$\lim_{z \rightarrow \infty} v = a = \sqrt{\frac{2P}{c_z\rho S}}. \tag{46}$$

It is the *limiting rate of fall* v_{lim} . Consequently, a body falling in the air with the initial rate $v_0 = 0$ cannot fall faster than $v_{lim} = a$ given by expression (40). The limiting rate of fall grows with increasing body weight and decreasing c_z , ρ , and S . It is possible to estimate the minimum characteristic time τ_{min} of the fall from height h taking into account that the maximum attainable velocity v_{max} is limited in accordance with Eqn (45). As a result, one obtains

$$\tau_{min} = \frac{h}{v_{max}(h)} = \frac{h}{\sqrt{2P/c_z\rho S}} = bh \frac{S^{0.5}}{P^{0.5}}, \tag{47}$$

where

$$b = \frac{1}{\sqrt{2}} \sqrt{c_z\rho}.$$

Quantity b is constant for a falling body, because air density ρ and the specific friction of the body against the air remain practically unaltered. In the limit, one finds

$$\tau \sim h \frac{S^{0.5}}{P^{0.5}}. \tag{48}$$

The greater the height h , the larger the active stretched body area S , and the smaller the body weight P , the longer the characteristic time τ of the fall. This means that the real cat has certain characteristic time τ in reserve to perform all maneuvers needed to stabilize its position in the air and prepare itself for landing.

The sequence of brain-controlled movements performed by a falling cat as captured by Marey's chronophotographic gun is shown in Fig. 14.

Turning now to the principles on which living systems are organized, it should be noted that any dynamic system consists of components moving relative one another. These components differing in matter package density are *skeleton and soft tissues*. The skeleton is not necessarily made from bones. For example, its function in the membrane of unicellular organisms is performed by a polysaccharide net, while the soft tissue is represented by lipids that fill up meshes

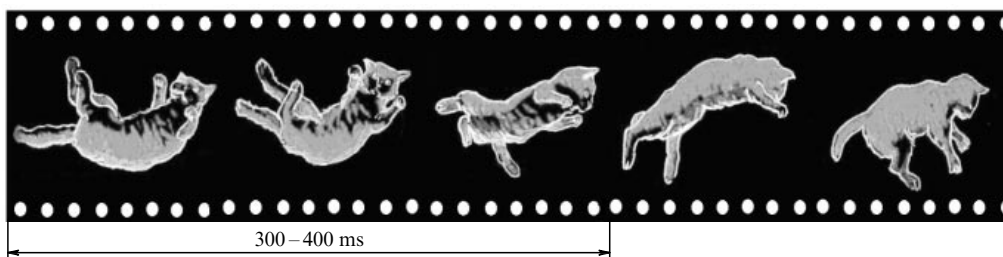


Figure 14. (Color online.) Chronophotograph of cat's fall and landing (E J Marey, 1894) [149].

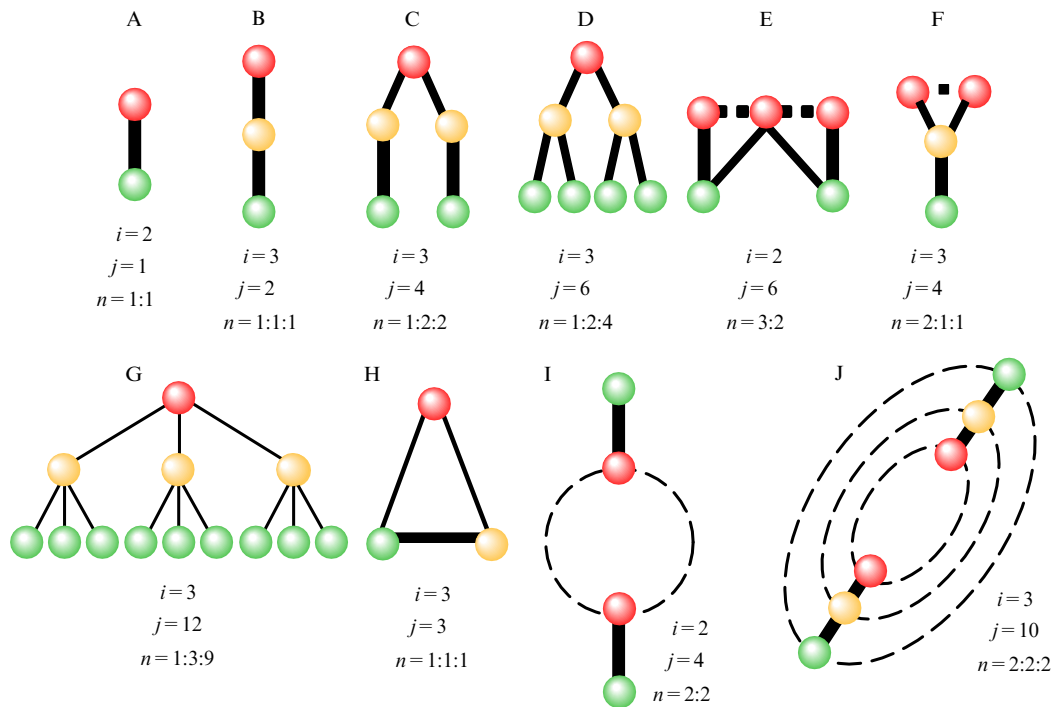


Figure 15. (Color online.) Ten graphs disclosing food chains: i is the number of hierarchical levels in food web topology, j is the number of links in them, n is the number of species at each hierarchical level from the highest to the lowest ones. Predators are denoted by dark balls (red online), prey by gray balls (green online), and intermediate species of symbiotes by lightest balls (yellow online).

in the net pierced by protein channels [154, 155]. T-series bacteriophages have a skeleton in the form of a dense rod-shaped protein structure and the soft tissue surrounding it as a less compact protein sheath [156]. The difference between skeletal and soft tissue densities can be estimated from a change in adiabatic compressibility measured by an ultrasonic device. Characteristics of the structural organization of living systems at the molecular level were obtained in experiments as early as the 1980s [156, 157].

5. Some other modes of describing the stable biological systems

5.1 Alphabetical description

Let us consider at least briefly another version of the description of the mechanisms of sustaining stability in biosystems. The alphabetical description comprises an alternative way of describing such mechanisms. Figure 15 shows the alphabet consisting of ten trophic links. The top level represents superpredators, the middle one oligopredators, and the bottom one micropredators. Branching links characterize the degree of pantophagy among the predators, i.e., one link denotes a strictly stenovorous predator, two links a moderately stenovorous one, etc. Link thickness reflects its strength, which equals 1 in the absence of branching, $1/2$ for each of two branches, $1/3$ for each of three branches, etc. In the case of cyclic competition between predators, the link strength is -1 , $-1/2$, $-1/3$, etc. In Fig. 15, such links are shown by dashed lines.

This is actually biochemical language [105, Ch. 1]. The strength of the links is an analog of valence, and competition in the biochemical language implies enzymes catalyzing or inhibiting equilibration.

Entangled predator–prey food chains correspond to the vertices of graphs (hubs), and the edges serve as paths for traffic of energy flows. The construction of the sequence of all food traffic flows is analogous to finding in such an oriented graph a path (Eulerian trail) which visits every edge exactly once. In terms of the graph theory, the solution to the interaction problem can be interpreted as the substitution of the Eulerian problem for the Hamiltonian problem. Such a problem is easy to solve for the case of binary relations, when a set of edges is partitioned into nonintersecting subsets. The necessary and sufficient condition for the existence of a Hamiltonian cycle in any oriented graph is the presence of a sugraph (a graph that lacks some edges or vertices or both). Such a conjugate graph represents the Eulerian trail, i.e., a graph with the Eulerian cycle [158]. However, the method for finding such a sugraphs for the general case remains to be proposed.

There is nothing new in the application of alphabetical language and the graph theory that have for a long time been employed in biophysics and biochemistry, e.g., to describe chemical kinetics in enzymology [159]. Moreover, such a description is used to formalize other processes, starting with those in living cells [105] to interactions in social systems of human populations. It finds application in the studies of demographic processes [160], the evolution of living matter [161], and even competition for information transfer in the fine arts, e.g., competition between cinematographic, TV, and other image transfer techniques [162].

To overcome uncertainty of response, information needs to be continuously compressed as it is transferred in the cycle of mutual influence of the upper and bottom levels: *predators + their symbiotes* graph \leftrightarrow *prey + symbiotes* graph. In this case, the set of prey graph vertices will be a subset of predator graph vertices and, due to the feedback, the

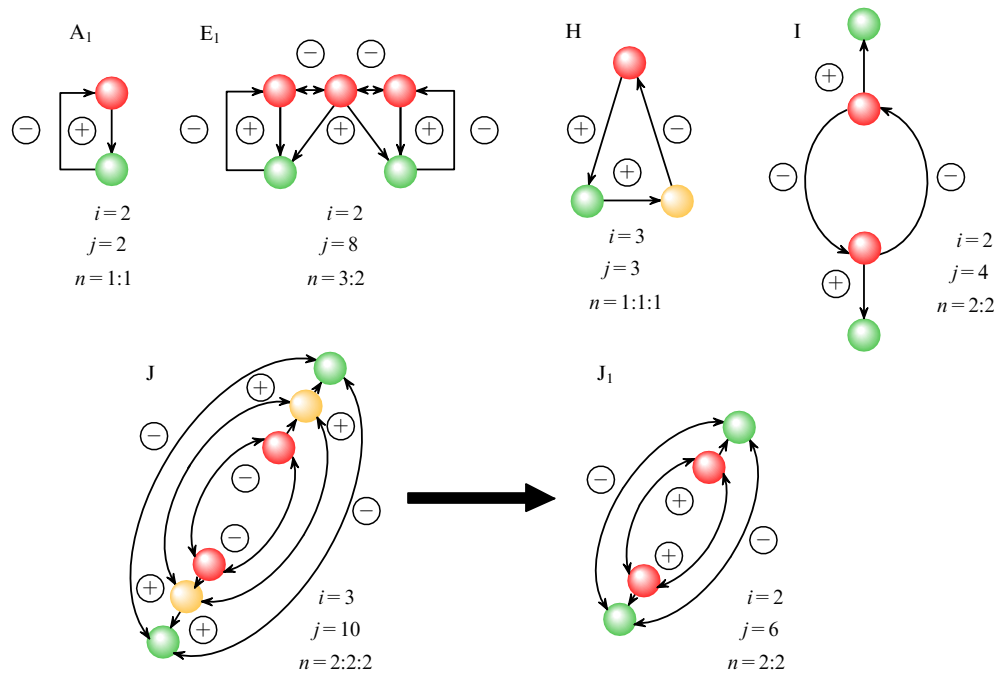


Figure 16. (Color online.) Models of graphs with cyclic interactions. See Fig. 15 for the notations used.

set of prey graph edges will be, in turn, a subset of predator graph edges. The sought Hamiltonian trail must pass only those edges that come into or go out of the vertices common to these graphs. Formally, it is attainable by overlapping common prey and predator graph vertices, while deleting those edges coming in or going out of these vertices that are not common to both graphs. We earlier utilized such an algorithm to reconstruct words from their parts and deduce the primary sequence of heteropolymer structures [105, pp. 270–277].

A link graph demonstrates the strength of links among chain elements but does not provide any information about characteristic times. The graphs shown in Fig. 15 can be transformed, taking account of feedback direction and sign, into cyclic models. The limited volume of this article precludes enumeration of all variants of such graph alphabet models, since their number amounts to $\sim 10^{10}$ even for a 10-letter alphabet. Therefore, we confine ourselves here to the stability definition principle as exemplified by graphs taking account of link number and signs. Negative and positive signs denote the slowdown and acceleration of the process, respectively.

A predator eating prey should be designated (from the former's standpoint) through positive links. Cooperation among predators (symbiosis) give them additional advantages and facilitates the search for prey. Therefore, it must also be viewed as having a positive sign. True, sign designation is a matter of the subjective choice of a researcher, depending on whose view (predator's or prey's) they share. Competition for food among predators slows down the process, which accounts for the negative sign of the links. Examples of such graphs with feedback signs are presented in Fig. 16.

From the prey's perspective, the sign should be reversed. Systems A_1 , I , and J in Fig. 16 should be considered as equilibrium systems having an equal number of positive and

negative links. All trophic chains with links of the same sign can be integrated into a single weighted chain to simplify the analysis (e.g., graph J is reduced to J_1). To sustain stability, energy flux moduli must be identical. For example, systems E_1 and H have different numbers of positive and negative links, which suggests the necessity of an additional analysis of the link strength. The links would be stable only under condition that $|\sum j_+| = |\sum j_-|$, i.e., if the sums of energy fluxes along positive and negative links coincide in terms of moduli, even though they may differ in number. A change of the sign corresponds to the appearance of so-called negative acceleration parameters (negative resistances, negative inductiveness, negative refractivities [163–167]).

5.2 Description in terms of interphase fluctuations

This class of problems is rooted in formal statistical physics dealing with the relationships between micro- and macroscopic descriptions. It is closely related to the array of problems and issues discussed in preceding paragraphs and reduces to the search for variants in which the system of interest looks like a weakly interacting one. In the physical context, it implies distinguishing rather weakly interacting collective states (groups of excited and decelerated particles). Formally, it means replacement of variables turning a system of equations into a linear (the 'integrable' case) or weakly nonlinear one [74, 75].

Classical statistical physics is confined to simple situations in which a system has a few phase states and transitions among them are quite apparent. In the case under consideration, the situation is different, because the number of phases is unrestricted and fluctuations among them are strong enough. The most thoroughly explored systems of this kind are spin glasses in engineering [168, 169] and neuronal networks in neurophysiology [170]. The limiting case of amorphous entangled quantum states [171] and various forms of chaos belong to the same class of phenomena [172]. The evolution of

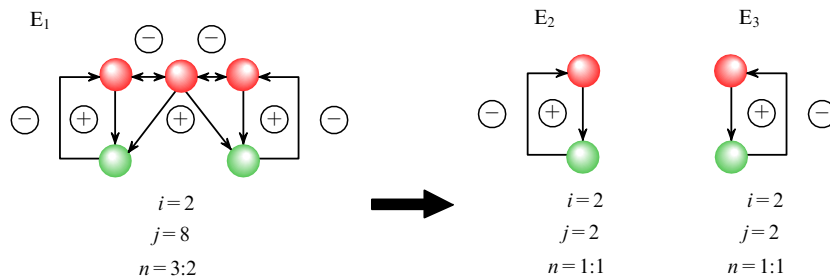


Figure 17. (Color online.) Splitting of a three-predator graph into two after removal of the central predator.

an amorphous medium can be regarded as the passage through a sequence of practically identical metastable phases that are not separated by potential barriers, differences in symmetries, or other qualitative thresholds. The ‘amorphous phase’ and the ‘spin glass phase’ are frequently considered to be single entities, since each is a set of an infinite number of phases with different configurations of background fields.

Of course, the notion of phases is a typically statistical approximate notion. A phase always exhibit fluctuations (either quantum or integral ones in the form of temperature or pressure jumps), representing a permanent feature of any phase associated with virtual nucleation of other phases. Therefore, any *accurately* determined quantity in one phase contains information about all other phases; it can be ignored only in a certain approximation. Discussions of the role and importance of such information are periodically provoked under various pretexts.

For example, the approach to multiphase systems in the string theory [83] is based on equations of state of various phases, with essential differences between them being smoothed. The number of variables, the order and number of equations, and even the dimension of space in which they find themselves *remain to be elucidated*.

5.3 Paradox of the plankton

Graph E_1 (see Fig. 16) is worthy of special attention because it has for a long time been believed to serve as a source of the so-called paradox of the plankton or the *competitor exclusion principle* that was widely discussed in the past and still remains the focus of interest for certain authors [173]. However, the paradox of the plankton arises from a mere misunderstanding.

It was originally described by G F Gause who maintained that *each species has its own ecological niche* [174]. In other words, two different organisms cannot occupy the same ecological niche at the same time because the more aggressive and fecund one inevitably forces the other out via the mechanism of competition.⁴ However, relevant experimental verification of this principle gave rise to the paradox presently known as the paradox of the plankton. The crux of the paradox is as follows.

G F Gause studied three infusorian species: *Paramecium caudatum*, *P. aurelia*, and *P. bursaria*. They co-existed and seemingly thrived on a nutrient medium making high-density populations *in vitro*. Infusoria fed on bacterial and yeast cells grown on oatmeal regularly added to the nutrient medium. The food was abundant and did not limit infusorian growth.

However, after the population was reduced to two species by the removal of predacious *P. bursaria*, the remaining *P. aurelia* and *P. caudatum* changed their behavior. Their spatial distribution in the test tube underwent differentiation such that the former went down to the bottom to eat yeasts, while the latter was localized at the surface and fed on bacteria. It turned out that the two species co-existed *under conditions of a lower reproduction rate than in the presence of the third one before its elimination*. What is behind this paradoxical situation?

Let us turn to Fig. 16 plotting graph E_1 with the interaction among three predators in the presence of two prey species. The removal of the central predator capable of feeding on any of the two substrates resulted in graph disintegration into two independent food chains (Fig. 17).

Paramecium bursaria, being able to eat both bacteria and yeasts, competed with *P. aurelia* for yeasts and with *P. caudatum* for bacteria. *Competition always promotes the growth of competing organisms by decreasing characteristic times of their reproduction*—it is a law of Nature. Division of all the three infusorian forms occurred with specific characteristic times τ_i and they were randomly distributed in space. After the graph split into two independent food chains following the removal of *P. bursaria*, the two remaining species no longer competed between themselves. Therefore, the volumetric problem posed by the presence of three species transformed into a layer problem in the presence of two. Each of the remaining predators obtained its own territory and prey (food) in the absence of competition. Moreover, the time of their reproduction increased and came to be limited by the territory size. In economics, the role of such limiting factor is played by the size of the market.

Such a variant of interaction in which the mobility of one species has a positive or negative effect on the mobility of another and thereby enhances the efficiency of development of the entire available space was considered in Ref. [175] for a system with cross-diffusion and a variety of motions in space and time, including soliton-like movements and reflections [176].

Intermixing of the medium by an omnivorous super-predator having an unlimited source of food leads, via competition, to the growth of all populations with which it shares the niche. But it is not only such a superpredator that is capable of intermixing nutrients. The same function may be performed by environmental factors, such as wind, solar heat, flows, convection, etc. In social systems, wars and famine promote reproduction and migration from affected to prosperous countries, i.e., medium intermixing. Therefore, there is actually no such phenomenon as Gause’s paradox of the plankton suggesting *obligatory competitor exclusion principle*.

⁴ Recall the problem addressed by D S Chernavskii and co-workers in application to economics [9, 10], mentioned in the Introduction.

6. Conclusions

Analyzing the currently available information on the theory of stability in living systems leads to the conclusion that there is still no general theory of this phenomenon; instead, we have a *set of experimental data and use the model-based approach to their interpretation*. The observed specific behavioral regimes may provide a basis for future mathematical generalizations.

In practical terms, elaboration of the general predator–prey theory from the perspective of biophysics requires the uniform description of various models and their introduction into an integrated ‘configuration’ space, such as Earth’s field at ‘low energies’ or even better the ‘cosmic field’, taking into account widely debated hypotheses of technogenic panspermia or lithopanspermia as mechanisms of origination and extension of living matter throughout the Universe and its delivery to planets [177, 178].

In other words, such a scenario implies the creation of a ‘theory’ with a complicated phase mobile structure and interpretation of the known concrete properties of life as a consequence of dynamic selection of special variants of the general theory. True, realization of this scenario is a matter for the distant future bearing in mind a great variety of mechanisms responsible for the achievement and maintenance of stability in complex dynamic systems.

Special attention should be given to the factors involved in mixing processes (in quantum and cosmic systems). In biological systems, these factors contribute to the establishment of dynamic equilibrium under conditions of their complication (see references to Gause’s paradox in preceding paragraphs). Also worthy of consideration in this context is the theory of strings tending to give rise to knots. As mentioned above, there is indirect evidence that ecological considerations are consistent with string theory formalism.

Pessimistic estimation. Humankind appears to be on the threshold of a new and very dangerous phase of development in which the virtual world begins to substitute the real one and the borderline between the two disappears. This situation can be referred to as ‘*information psychosis*’. It is fraught with destabilization arising not only from extensive drug use but also from the wide-scale implementation of socially oriented computer technologies.

Long ago, humans separated themselves from the animal kingdom by creating new information carriers with large characteristic lifetimes much in excess of the lifespan of a single generation. We invented writing, created arts, developed methods to reproduce information in printed form, and came to the utilization of new forms of computer and Internet-based long-term memory.

All these innovative options greatly promoted further development of human society. At the same time, the younger generation tends to be increasingly more exposed to the risk of lopsided development as a result of videogame addiction, which leads to consciousness transformation by substituting the virtual world for reality. It may lead to the loss of stability (cyberpunkism effect) and eventually to a change in the species *Homo sapiens*.

Optimistic estimation. The spectacular effects of mathematics inspire optimism since they give ample evidence that all special physical laws, no matter how diverse, have some common features. Integrating physical laws into a unified theory is the realm of basic science. It is now recognized that the division of Nature into animate and inanimate matter is wholly arbitrary. Nature is indivisible and its two forms differ

only in characteristic times and lifespan duration. The development of animate and inanimate nature represents two aspects of one process [1, 13]. In the framework of this paradigm, the elucidation of mechanisms of brainwork and its influence on the choice of alternative strategies for further development of human civilization are becoming the main goals of such synthetic sciences as *biophysics* or, if you will, *biopsychophysics*. It seems opportune to recall that those applications of mathematical formalism sometimes prove to be especially fruitful of which nobody thought at the time when they were first proposed. Nevertheless, one should not overemphasize the value of currently popular physical ideas or scenarios, including the generalized predator–prey theory, bearing in mind that they are sure to be modified at best many times and even replaced in the worst case by more plausible ones. It is an ordinary situation regarded as such in the past and periodically arising at present.

The importance of the diversity of such scenarios is that they stimulate the brain’s work and provide a basis for the assessment of the relative efficiency of different approaches to a formalized description of the surrounding world and serve as a source of new ideas about its conservation (and that of our lives) and determination of permissible limits of human impact on the environment.

As the science of biophysics is bounded by the general theory of relativity from above and by quantum mechanics from below, their development is crucial not only for addressing many practical problems facing biomedicine and ecology but also for the further development of the entire spectrum of basic sciences.

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