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The closed-loop coding-decoding concept as the general principle of functional organization in living systems

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The principal paradigmatic and structural schemes of the functional organization of life (organisms and their systems) are constructed on the basis of systemic analysis and synthesis of the main phenomenological features of the living world. Life is based on functional elements that implement engineering procedures of closed-loop coding-decoding control (CL-CDC). In this approach, living systems are technological systems that naturally emerged on the Earth 3–4 bln years ago as a result of chemical and, later on, biological evolution. Generalized schemes of functional organization on the levels of cell, organism and brain neocortex (as the highest one with CL-CDC) are presented. The CL-CDC concept expands the understanding of bioinformatics as informatic technologies in life sciences by showing information as the key player in natural processes.

Key words: coding-decoding, informational control, constructive biology, synthetic system biology, living systems

INTRODUCTION

Biology has not yet found out a general principle of the functional organization of living systems [1]. The life on the Earth is a complex system consisting of various functionally closely interconnected components such as biomolecular clusters, organelles, and organs, which undergo continual changes in order to adapt to the varying environment. It is supposed that the general principle of the functional organization of life does exist. But experimental research, which is the dominant method of biology, floods up the information sphere with the diverse data which more often play as noise in the search for the essential understanding of life. Therefore, other methods of scientific research that could enable us to look at the alive from above are required.

The method of choice might be the method of theoretical synthesis of a hypothetical functional system, with the subsequent application of a synthesized theoretical system for interpretation of experimental facts. In search of the general principle of life organization, H. Maturana and F. Varela [2] raised the concept of autopoiesis (self-production) as an initial functional hypothesis. From this point of view, life is a self-producing or technological system. Technology is a broad concept that deals with tools and techniques as a whole for purposive mass serial transformations and production of matter (chemical or material technologies), energy (physical or energy technologies) and information (information technologies). Life is a natural technology, a system of different organized complex technologies.

The biosphere and human society (noosphere) may be represented as systems of natural and artificial technologies. The biological species may be regarded as a natural technological system that lives, adapts and self-reproduces using the existing environmental resources. In biosystems of all hierarchical levels starting from cells, it is possible to allocate two, essentially different, but functionally closely interconnected natural biotechnologies: (a) material-power transformations (controlled) subsystem and (b) informational control (controlling) subsystem. Technology as a phenomenon appeared on the Earth 3–4 bln years ago when life, information, control and adaptivity originated. The first technology was formed when material-power transformations and information control merged to purposeful closed-loop coding-decoding. The initial technology was based on genetic informational control and enzymatic material converting principles. This point of view allows to interpret biological evolution as natural engineering, natural technical and technological development of biosphere. Parallelism of natural (biological) and artificial (technical) technologies is seen in such field as bionics / biomimetics.

Here, a new concept of life as natural technology organized on the principle of Closed-Loop Coding-Decoding Control (CL-CDC) is presented. The CL-CDC concept is based on the following theories: living systems (LST) [3], self-reproducing automata [4], self-referring automata [2], eigenbehavior and self-organization [5], perceptual control (PCT) [6, 7], and the concept of modeling relations [8, 9]. The aim of the study was to reveal and formulate the general principle of the functional organization of living systems and present the biological data in graphic schemes. Attention was focused on the information control concept as the essence of natural and artificial technological control procedures.

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METHODS

The paradigmatic, functional and structural schemes of living systems, presented in this study, have been synthesized by holistic systemic [9], projective constructivistic [10], and systemic bio-engineering [11] methods on the constructivistic foundation [12].

RESULTS AND DISCUSSION

Methods

Nowadays, new theoretical methods of biological research are being developed. Methods of synthetic biology [13], analytic (or bioinformatic) biology [14], constructive biology [15], complex systems biology [12, 14, 16, 17], based on engineering thinking [18], are targeted to integration of different areas of research in order to create a more holistic understanding of life. Recently, the terms of synthetic systems biology have been used in a sense of science and engineering combination in order to design and build novel virtual or real biological functions and systems. In this study, thinking in terms of synthetic systems biology has been used for designing graphic schemes representing the essential functional organization of living systems.

The paradigmatic closed-loop coding-decoding (CL-CD) conceptual scheme that reflects the essence of the functional organization of living systems and facilitates the holistic understanding of life as a complex technological system has been synthesized on the basis of modeling relation [7] and mathematical modeling [8]. The CL-CD scheme has been applied to explain activities of biological, psychological and social organizations.

Life as a closed-loop coding-decoding system

According to the CL-CD scheme, a natural system **N** of the real world may be represented by encoding (coding) procedure on the formal (abstract, mathematical, virtual, computer, symbolic or information) world sphere **F** as a technological model (program) for the production of **N**. The model (technological program) or a formal system **F** operates according to special rules (Fig.1).

Respectively, the decoding procedure is de-reflection or synthesis of natural system **N** under control of the model in the formal system **F**. The decoding accompanies procedures of interpretation, control, prediction, synthesis and anticipation.

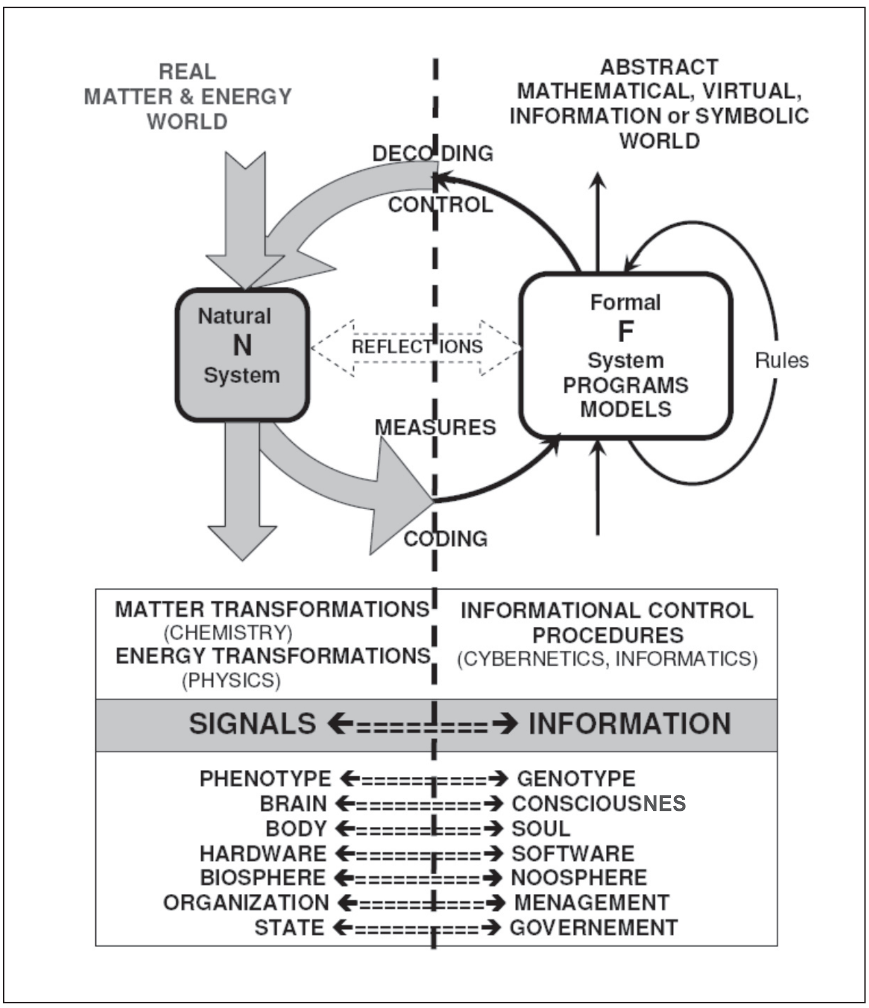

Fig. 1. Paradigmic scheme of closed-loop coding-decoding control (CL-CDC) procedures in an organizationally closed but matter-energy-information open living system

Coding (*encoding*) should be understood as a reflection of a real system (nature or technological procedures) in an abstract virtual form on ***memory*** structures (DNA, hormones, neural networks, programs, books, computers, *etc.*) in such a way that reversion from the abstract to the real would by possible. The coding procedure corresponds to observations, measurements, analysis, representations or reflections. The coded reflection in the memory is a model or a technological project of a real system. This model or a coded symbolic representation for controling the technological procedures is the essence of information.

Decoding is the technological realization of such a project or control of biotechnological procedures according to information. In the process of decoding, the activated coded states of the memory structures or the informational projects for synthesis of reality are reflected in the dynamic states of the real world, by matter, energy transformations in controlled structures and informational signaling flows in the controlling structures of cells, body, populations, etc.

A full closed-loop coding-decoding structure consists of partially autonomous complex organized systems. There are genetic, hormonal, neural, psychical, social, robotic organized systems in the world. The dualistic material↔informational equivalence is manifested in these organized systems: signal↔information; phenotype↔genotype; body↔soul; brain↔thought; hardware↔software; social group↔management; state↔government, biopshere↔noosphere.

The systems constructed according to these principles are organizationally closed, but materially, energetically and informationally open. Organizational closeness causes the functional compatibility of coding-decoding and functional sense (semantics) of coded reflections. Informational openness means ability to uptake additional information on the environment into a pool of existing world models ("informational metabolism" in analogy of matter and energy conversion).

No doubt, functional structures of biological organisms are the most elaborated control systems, because they are the result of natural evolution which refined these technologies during billions of years of life history. The systems developed by man are much simpler in comparison with biological systems. So, it is interesting to sketch the structure of the functional organization of biological organisms as technological systems.

A living being as an organized system includes two functionally different subsystems: the controlling one, which has memory and carries out information processing, and the controlled one, which carries out transformations of matter and energy, i. e. biotechnologies for goal-oriented actions. The subsystems are interconnected reversibly by receptors-coders and effectors-decoders (Fig. 2). The scheme presented in Fig. 2 is different from the classical Shannon's coding-decoding system since the latter would be open, without the execution subsystem, without the real matter and energy transformation subsystem, e. g., the nerve system without muscles. The closed-loop coding-decoding process may by represented as a mathematical procedure of integral transformations that it is especially important in the application of effective methods of orthogonal coding. Coding-decoding procedures are essential for reproduction of an organism, since the stability of functional structures can be ensured by multiplication of discretely coded genetic projects of the organism. Biotechnology of reproduction becomes a rather steady bioinformation technology.

Living systems of different complexity could be described in the best way by using the terms of biological closed-loop coding-decoding technologies.

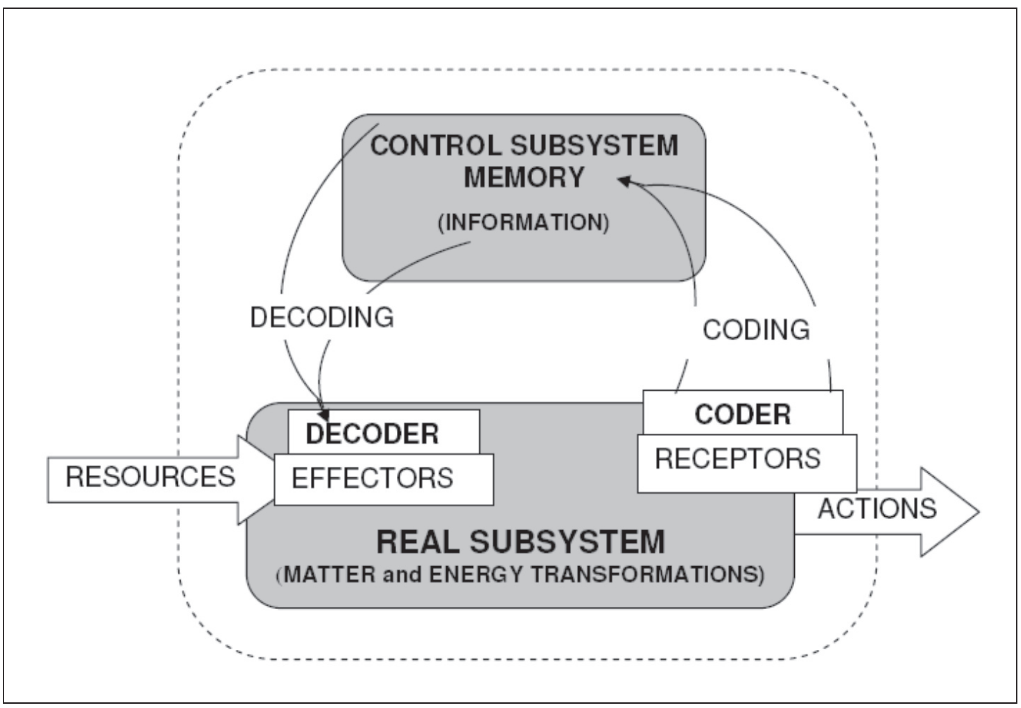

Fig. 2. Closed-loop coding-decoding informational system. Classical Shannon's coding-decoding system is open, without real subsystem

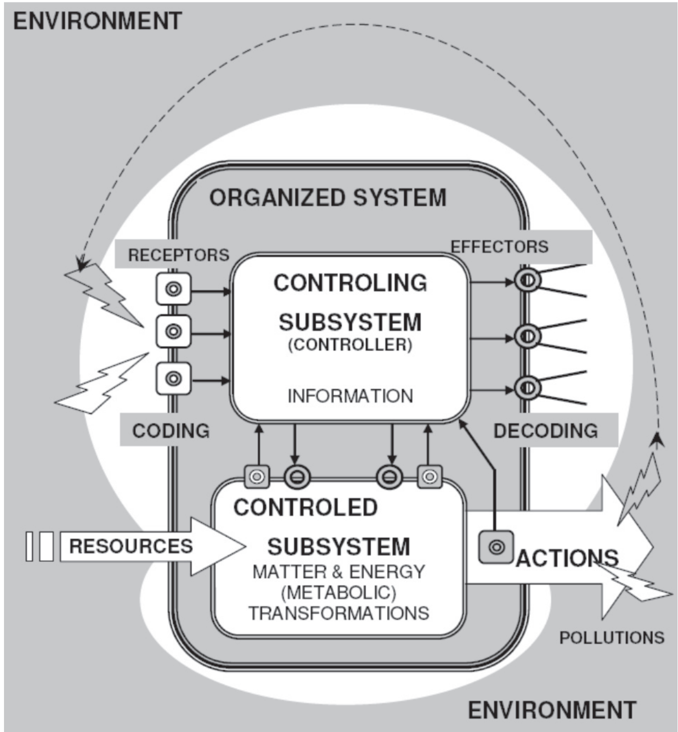

Fig. 3. Functional structure of cells as organized systems with combined feedforward and feedback informational control or external and internal closed-loop coding-decoding – receptors (elementary coders), – (elementary decoders) effectors

Organisms as closed-loop coding-decoding systems

The cell as an organized system also includes two functionally different subsystems: the controlling one (controller) which processes information, and the controlled one, which carries out biochemical metabolic transformations for goal-oriented actions. The functional organization of the cells consists of two CL-CD loops: internal and external coding-decoding loops informationally conjugated by the controling subsystem (Fig. 3).

A multicellular organism as an organized system also consists of two functional subsystems, as in the case of the cell. However, in the multicellular organism, the controller is augmented by hormonal regulation (and the animal's controller has a nervous system, in addition). Animals have three structures of control: genes, hormones and nerves. They are linked to the environment by internal and external feedbacks. Together, they form a hierarchically organized closed-loop coding-decoding system.

Many phenomena of living nature could be explained in terms of information technologies, since in essence they are coding-decoding procedures.

1. Spores and seeds are carriers of biotechnological programs or projects of future organisms loaded with an initial supply of necessary substances and energy. The essence of the existence of plants, fungi and animals are replication, improvement and spreading of these projects.

2. Sexual reproduction (recombination) is the diversification of these programs or projects.

3. Adaptive modifications are alternatives of realization of these programs.

4. Gene engineering is a purposeful insertion of new individual components into genetic programs.

5. Apoptosis is programmed cell disintegration necessary for the most effective dismantling of some parts of the organism.

6. Organism morphogenesis is carried out under the informational control that uses hormonal signals.

7. The influence of pheromones on the behaviour of insects is an example of the action of informational programs by special extra-organismal signal molecules.

8. Activities of the nerve system that determine the behaviour of animals are obvious products of information technologies.

9. Repetition of phylogenesis in ontogenesis (biogenetic law or theory of recapitulation) is an example of persistence of evolutionary old programs (an illustration of the evolution of information coding-decoding procedures).

Hormonal coordination of activities of a multicellular organism can be explained in terms of agent theory as selective receiving of molecular signals, processing of their information, and decision-making for action. It is the activity of the coding-decoding systems. The more dynamic control of a multicellular animal is carried out by complexes of nerve cells, neural nets which receive, process and send information. Undoubtedly, the neural control of a multicellular organism is a network of coding-decoding procedures.

The nerve system is a typical information coding-decoding system which reflects and codes not only the environment of the animal, but also its inner state. Animals control their activities according to this information and select the optimal behaviour.

Informational control as the organizing factor of living systems

Cybernetics as control and information theory states that information is a factor that organizes functional activity of purposeful systems including the living ones. Perceptual control theory (PCT) is inseparable from functional organization of living systems and it complements the CL-CD system [6, 7]. The functional organization of living systems presented in Figs. 2 and 3 is based on the principle of a closed loop, which is part of PCT, and on the principle of coding-decoding, which is part of Shannon's theory of open information channel (or memory). It results in the structure of closed-loop coding-decoding control (CL-CDC). Such CL-CDC association gives the system a property of organization because combinations of the symbols (coded signals in the memory of the controller) get a functional sense, i. e. semantic information. Furthermore, such a structure evidently shows that the coded signals determine the functional organization and the necessary states of the system, i. e. they carry out information control.

Even the simplest organized systems based on the CL-CDC principle must have at least two closely connected CL-CDC circuits in the controlling structure: external and internal. The external CL-CDC circuit i) reflects information on the environment using receptor structures, ii) constructs the environment models, iii) develops and creates the action models that encode the necessary states of interactions between the environment and the body (organized system). Decoding of these models is the control of environment-targeted actions of the body by means of effectors. The internal circuit collects information on the inner environment and develops action models to control the inner environment by means of inner effectors. Usually these two circuits work in tandem. They correspond to a cybernetic system of combined feedforward and feedback control. An organized system is a case of complex systems that have features of a cybernetic system (a purposeful system), especially if it has features of the second-order cybernetic system [5]. Here, the controlling subsystem stores, collects, and processes internal and external information, constructs plans-programs for actions and by these means handles the actions, i. e. material and energy transformations.

Evolutionary cybernetic analysis of the functional organization of animal nerve systems and behaviour identifies five levels of CD-CDC [19]. In the mammalian visual analyser, five levels of CL-CD control can be seen:

- simple reflection (on-off motoric reactions of the jellyfish or of human eyelids to light);
- multireflex coordination and programmed control (coordination of earthworm motion or control of the human head turning to light);
- regulation and homeostasis (regulation of the eye pupils and lenticuli in reptiles and man);
- simple perceptronic analysis (simple perceptronic analysis and motoric response to the visual situation in frog or control of the human eyes' look at a light spot);
- analysis by synthesis (A-by-S) without or with sensory screens (visual A-by-S in the sensory structures of neocortex Area Striata of the mammals and particularly man).

The understanding of the scientific value of information as a factor of control needs a discussion of the concepts of bioinformation, bioinformatics and the relation of these concepts to information and informatics in general.

Bioinformation and bioinformatics, information and informatics at large

The present concept of the CL-CDC allows to expand and generalize the understanding of both bioinformation and bioinformatics as well as of information and informatics. From the technological viewpoint, each organism needs the ability to control and coordinate the purposive transformations of matter, energy, and information flow using various technological tools. These transformations must be controlled by information structures of controlling subsystems (controllers).

The first controlling information technologies, which emerged on the Earth by way of biological evolution and still keep operating in each cell, are the genetic ones, i. e. bioinformational control by genes and proteins (Fig. 4). In metaphytes, bioinformational controlling, in addition, is carried out by hormones. On the level of metazoa, nervous networks are added. On the biosocial level, control has been improved by occurrence of communication agents, i. e. pheromones and speech, and on the level of human society, an important and increasing controlling role is played by information transmitted by symbols (e. g., letters in printing), electronic technologies, different modeling representations. Thus, it is possible to regard information as a specific property of the organized matter arisen during biological evolution for the management and coordination of technologies. In the beginning these were natural biotechnologies. Along with the development of human society, human reason kept creating and introducing new technologies, starting with application of fire and arriving at information technologies.

Therefore, the substance of information theory and informatics as branches of science is methods of the quantitative estimation of information, its functional value and importance for management. Undoubtedly, information and bioinformation in essence have common roots and differ only in the level of life organization, the level of management technologies: biological or social. Informatics should be a general science both for bioinformational and informational control-managing procedures in any organized system.

Special interest from the technological point of view, on analogy with the processing or manufacture of matter and energy, should be given to understanding the generation of information. The copying (copy) of information is an informational procedure, but it creates no new information. Clearly, generation of information is important for creating projects of new technologies. Only two bioinformational technologies producing new information exist in living nature: i) genetic natural biotechnology, which implements stochastic testing in living

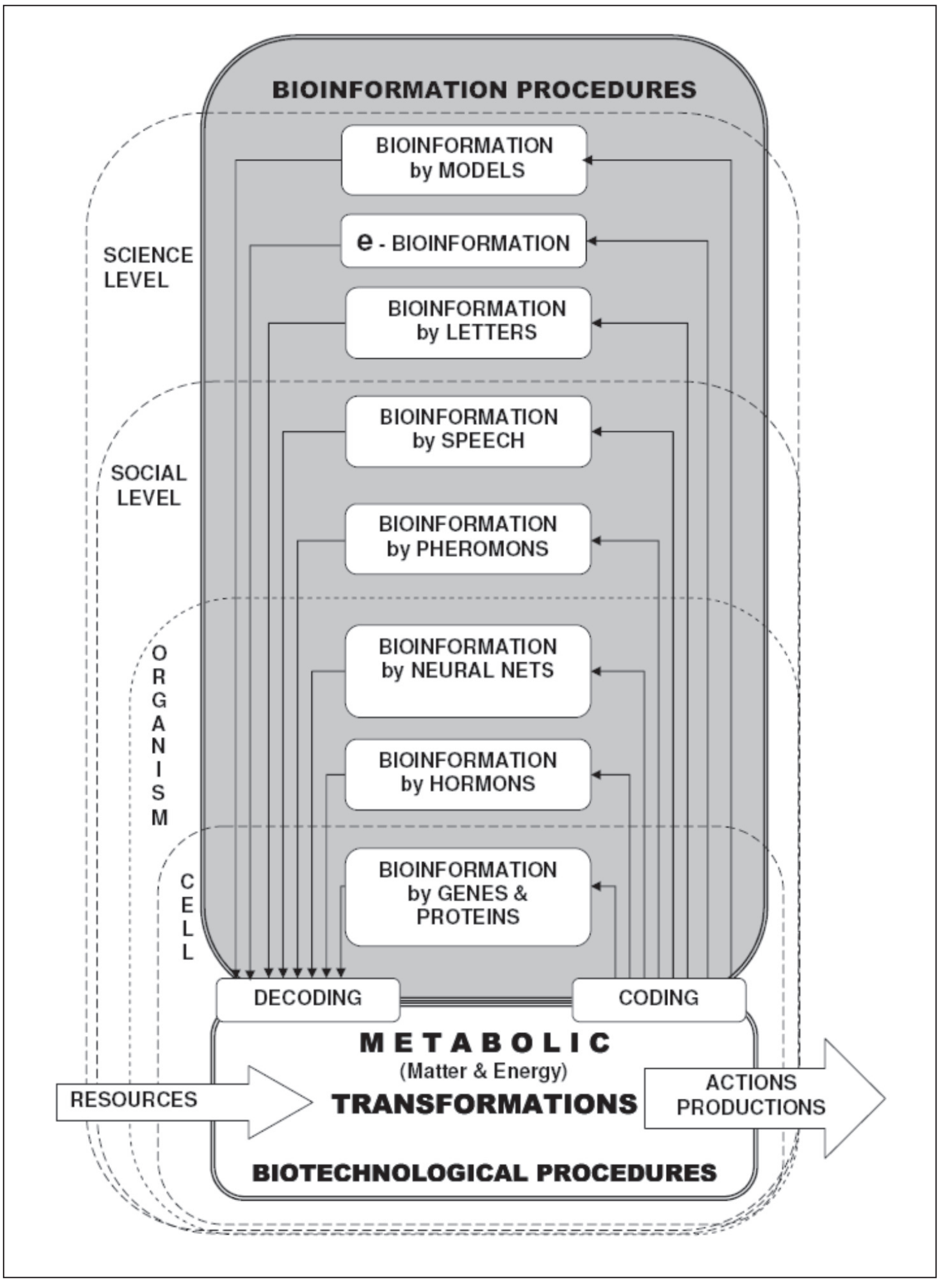

Fig. 4. Different levels of closed-loop coding-decoding or bioinformational and informational-knowledge procedures in living (biological, humanitarian and social) systems

populations with the subsequent natural selection (genetic algorithms), and ii) mental natural biotechnology, which implements a motivated search, creation of virtual imitatory projects aimed at the achievement of purposes with the subsequent checks, rejection or acceptance for action. The mental natural biotechnology is carried out by special zones of the brain (neocortex) of mammals and birds. The name of such mental manufacture-generation of information is "creative work".

Sensory neocortex as perceptual controller or subsystem analysis by synthesis

To reveal the functional organization of the neocortex, the visual analyser has been explored as an example [19–21]. A general scheme of the functional organization of information processing by the visual analyzer has been constructed on the basis of interpretation of visual perception, the anatomic and morphological structure of visual subsystems of animals, as well as neuro-physiological, psychological, and psycho-physiological data, in the light of theoretical solutions of image recognition and simulation of visual perception processes (Fig. 5). The scheme reflects the active information processing. The activities in special areas of the neocortex are as follows: focused attention, analysis of visual scenes with prediction, synthesis of predictive mental images, and comparison of visual scenes with predictive mental images.

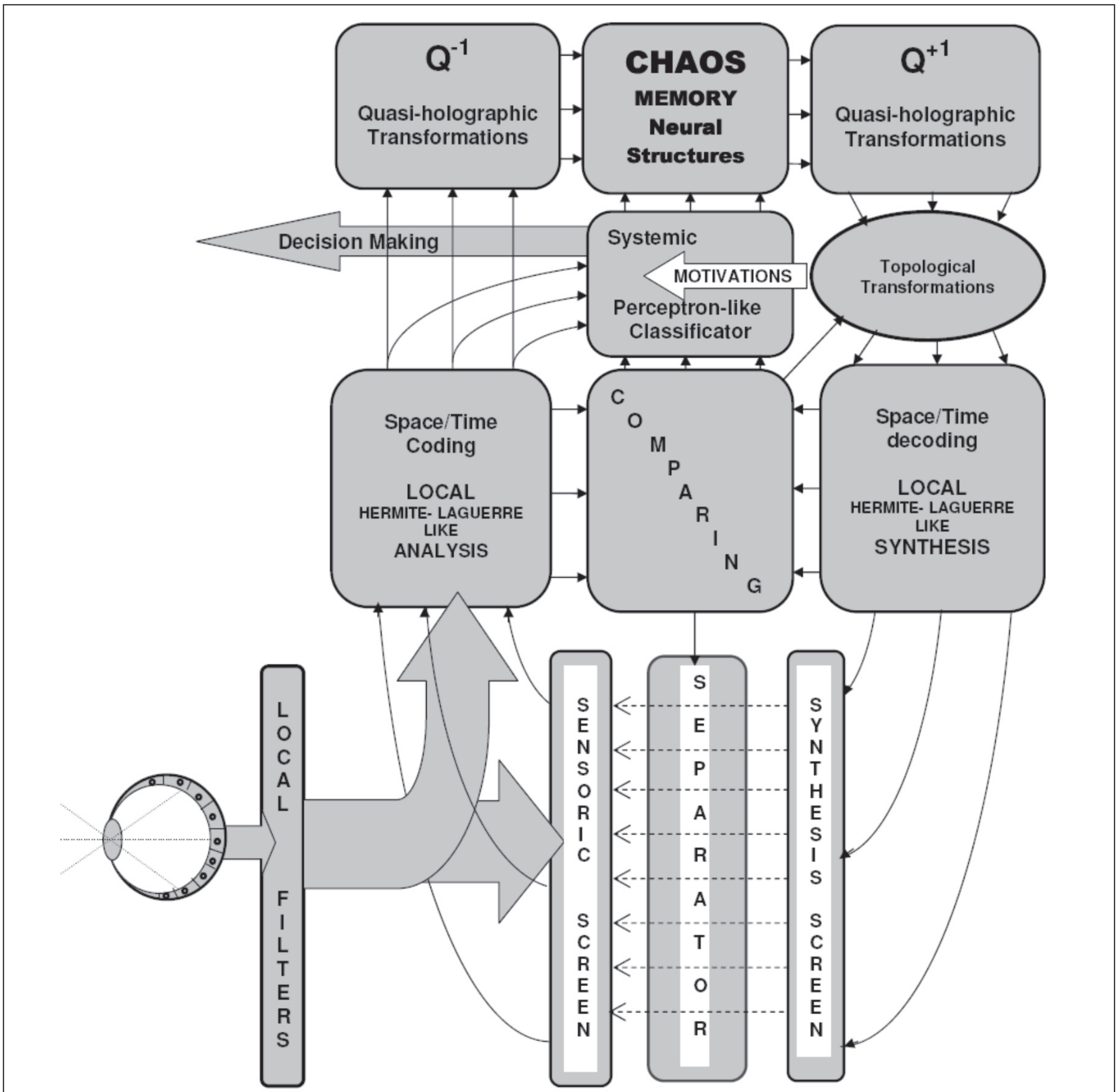

Fig. 5. Functional structure of sensory neocortex as Analysis by Synthesis (A-by-S) or imitative Closed-Loop Coding-Decoding (CL-CD) with Neural CHAOS Memory

The functional organization of neuron layers of the Brodmann area 16 in the primary visual zone V1 of mammals is especially interesting from a viewpoint of information processing. Morphological, neurophysiologic and computational research have generated a great amount of experimental data and have created many theoretical models, but the principles of organization and functioning of the area 16 are still very hazy. Interpretations of the functioning of *Area Striata* might elucidate the CL-CDC principles of the neocortex in visual thinking and in the general thinking procedure as information processing [20, 22].

In the projection zone of the visual cortex *Area Striata* or V1, a "sensory" screen (SS) and "reconstruction" or synthesis screen (RS) are supposed to exist. The functional structure of the visual analyser consists of the analysis of visual scenes projected onto SS, "tracing" of images, preliminary recognition, reversive image reconstruction onto RS, comparison of images projected onto SS with images reconstructed onto RS, and "correction" of preliminary recognition. The closed procedure of A-by-S corresponds to mental image vision procedures. It is supposed that the quasi-holographical principles of the neuronal organization within the brain of the image "tracing" and the reverse image reconstruction lie in the background of the periodical procedures of coding-decoding. Receptoric structures code the environmental images and their changes and after local filtering send coded information to primary visual zones of the neocortex. Here, the properties of visual images are analysed in detail. The results of analysis are used for the primary perceptronic recognition, for comparison with the image reconstructed from memory, and for registering in memory structures. An essential trait of the visual neocortex is that it continually analyses images transferred from the retina and compares them with anticipated images that are collected from memory on the basis of the environmental situation and motivations. This cyclic A-by-S or internal distinctly anticipatory CL-CD control procedure carries out the imitative cognitive modeling. The results are used in generating pragmatic behaviour models for current and future actions. All these activities are used for the following purposes:

1) to generate cognitive models which must correspond to reality as exactly as possible. The role of motivation here is to shorten the search of the most corresponding models in memory;

2) to generate pragmatic models which are used to change the reality. The reality is changed in such a way that it would correspond to more or less strategic plans generated in mind. The latter feature is especially characteristic of human mind.

A full dynamical perceptual control system of coding-decoding in the visual analyser is a closed loop because an actual image is compared with the one reconstructed from memory (Fig. 5). This system consists of closed-loop space / time coding-decoding structures which correspond to the reflective local Hermite–Laguerre-like coder and the Hermite–Laguerre-like decoder structures. This property gives a functional sense to information in the visual perception system.

We propose that the neuronal structure implementing the quasi-holographic analysis-by-synthesis ought to possess at least ten functional layered complexes: (1) the receptor layer where the retinal image is projected; (2) the layer of local filtering; (3) a local Hermite–Laguerre-like analyser, and (4) a local Hermite–Laguerre like synthesizer with (5) a comparator between them. These structures are looped by quasi-holographic memory layered complexes $\mathbf{Q}^{-1}$ and $\mathbf{Q}^{+1}$ (6, 7) with (8) a CHAOS memory neural structure controlled by a systemic perceptron-like classificator (9) between them. Memory traces are extracted by means of the topological transformations structure (10) controlled by signals from the comparator. The comparison block collates an actual signal of local analysis and the mental image of local synthesis. The synthesis may be accomplished by dedicated predictive structures driven by arbitrary motivations or preliminary expectations of events in the environment. Note here, that the system described above resembles the closed-loop coding-decoding similar to a classic non-loop communication system of the Shannon information theory whereby analysis/decomposition and $\mathbf{Q}^{-1}$ are equivalent to the encoding step, and the reconstruction/synthesis with $\mathbf{Q}^{+1}$ corresponds to decoding.

This model is based on both visual psychophysical and neurobiological data interpreted in the light of the theoretical solutions of image recognition. According to this model, the functioning of the visual analyser consists of the following stages:

- projection of the retinal image (image arriving from the retina) to the local Hermite–Laguerre-like analyser. This projection is related with the analysis of an image. The actual images are guasi-holographically transformed and recorded to the chronological searchable CHAOS memory (with systemic search catalogue);
- projection of the mental image from the CHAOS memory (searched in the catalogue, extracted, decoded by inverse quasi-holographic transformations and topologically transformed) to the local Hermit–Laguerre-like synthesis structure;
- comparison of the real image and the hypothetic mental images and detection of mismatching features. Additional rotation, shift and other topological transformations are used in comparison;
- decision or recognition is based on the preliminary recognition and involves an iterative formulation of image identity hypothesis, which leads to a synthesis of an image of the new object. The iterative procedures last until the correspondence between the actual object and its retrieved hypothetical image is achieved.

It could be suggested that this imitative A-by-S with CL-CD feedbacks is the essence of thinking, because thinking is a mental creation of schemes (point of view of cognitive psychology) which is possibly implemented in the structures of the neocortex [23].

A similar functional structure is characteristic of biological and social systems. The possible prospects and problems of information, knowledge and creative society (IKCS) can be analysed indirectly through analysis of the functional evolution of biological and neural systems. Such analysis can be valuable as a prognostic instrument of the development of IKCS and finding the most promising directions in the development of IKCS. We can expect that the biological evolution has found many valuable ways of information processing and functional organization that can be implemented in human technical and social creative technologies.

CONCLUSIONS

1. The closed-loop coding-decoding control concept is a potential basis for complex living systems theory.
2. The living systems could be regarded as complex technological systems.
3. Biological information implements control on vital technological procedures in the living systems.
4. Organizational coding-decoding closeness determines the functional compatibility and functional sense (semantics) of coded technological reflections.
5. Analysis by synthesis or imitatory closed-loop coding-decoding of the sensory neocortex of the mammals and avifauna permits thinking, generates information, and constructs (creates) projects for actions.

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UŽDAROJO KODAVIMO-DEKODAVIMO KONCEPCIJA KAIP PAGRINDINIS GYVŲJŲ SISTEMŲ FUNKCINĖS ORGANIZACIJOS PRINCIPAS

Santrauka

Remiantis pagrindinėmis gyvojo pasaulio fenomenologinėmis savybėmis, sisteminės analizės ir sintezės metodais sudarytos gyvybės (organizmų ir jų sistemų) funkcinės organizacijos paradigminė ir struktūrinė schemos. Šių schemų, atspindinčių gyvojo pasaulio esmę, pamatas – uždaruoju cikliniu kodavimu-dekodavimu veikiantys funkciniai elementai, vykdantys biotechnologines procedūras. Pagal šį požiūrį gyvosios sistemos yra technologinės sistemos, natūraliai atsiradusios prieš 3–4 mlrd. metų Žemėje cheminės evoliucijos dėka ir nulėmusios tolimesnę ne tik biologinę, bet ir dirbtinę technologinę evoliuciją. Pagrindžiamas informacijos būtinumas gyvybės technologijų, kaip ir bet kokių sudėtingų sistemų, valdymui. Pateikiamos apibendrintos ląstelių, organizmų ir aukščiausios informacinės uždarojo kodavimo-dekodavimo veiklos lygio – smegenų žievės – funkcinės organizacijos schemos. Iš šių schemų seka platesnė bioinformatikos samprata, jungianti ne tik gyvybės mokslinio pažinimo informacines technologijas (bioinformatiką siaurąja prasme), bet ir dėl biologinės evoliucijos susiformavusias informacines technologijas (genetines, hormonines, nervines, feromonines bei kitas signalines) – bioinformatiką plačiąja prasme. Informacijos gamyba „genetinėmis priemonėmis" vyksta per populiaciją vyraujant stochastinei paieškai, o informacijos gamyba šiltakraujų gyvūnų smegenų žievės neuronų tinklų priemonėmis – per individo mokymąsi ir patirtį ieškant esamų problemų sprendimo. Informacijos gamyba – naujų technologijų kūrybos pamatas.