In the monograph the full interpretation of human brain functioning as an object of electronics is first presented. Three hypotheses are formulated, which on the one hand, enable to explain perception, thinking and other important mental functions and, on the other hand, to propose a perspective combined approach of detailed analysis of the brain, based on multilevel simulation in conjunction with experimental methods. The principles of brain functioning are explained from the point of view of a specialist in electronics. A clear definition of what is the thought is first proposed. The monograph will be of interest to a wide range of readers, including specialists in neurophysiology, neuropsychology, neurocybernetics, electronics, etc., as well as students, as it is written in a clear language without new terms.

Igor I. Abramov

Abramov Igor Ivanovich – Doctor of Science in physics and mathematics (Russian Federation, 1994), professor (Republic of Belarus, 1999). He is the author of more than 300 scientific papers, six monographs, and five lecture courses. His current research interests: physics and simulation of micro- and nanoelectronic devices and circuits; human brain.

978-3-659-44638-2

Igor I. Abramov

Brain as an Object of Electronics

Monograph

LAP LAMBERT Academic Publishing

Igor I. Abramov

Brain as an Object of Electronics

Igor I. Abramov

Brain as an Object of Electronics

Monograph

LAP LAMBERT Academic Publishing

Impressum / Imprint
Bibliografische Information der Deutschen Nationalbibliothek: Die Deutsche Nationalbibliothek verzeichnet diese Publikation in der Deutschen Nationalbibliografie; detaillierte bibliografische Daten sind im Internet über http://dnb.d-nb.de abrufbar.

Bibliographic information published by the Deutsche Nationalbibliothek: The Deutsche Nationalbibliothek lists this publication in the Deutsche Nationalbibliografie; detailed bibliographic data are available in the Internet at http://dnb.d-nb.de.

Coverbild / Cover image: www.ingimage.com

Verlag / Publisher:
LAP LAMBERT Academic Publishing
ist ein Imprint der / is a trademark of
AV Akademikerverlag GmbH & Co. KG
Heinrich-Böcking-Str. 6-8, 66121 Saarbrücken, Deutschland / Germany
Email: info@lap-publishing.com

Herstellung: siehe letzte Seite /
Printed at: see last page
ISBN: 978-3-659-44638-2

"Only physiology is able to do all that, as it possesses the key to the truly scientific analysis of psychological phenomena." I.M. Sechenov [1].

"The electrical changes which cause alternating currents of variable frequency and amplitude registered by us occur in the cells of the brain itself. There is no doubt that it is their only source. The brain must be pictured as a vast aggregation of electrical cells, numerous as the stars of the Galaxy." Grey Walter [2].

Contents

Preface

In the monograph an interpretation of human brain as an object of electronics, in particular, of organic hybrid nanoelectronics is presented. The author called it the "full electronic interpretation". From my point of view it allows to understand more profoundly the principles of human brain functioning. To be concise, the brain is a very "sly" electronics, an original transceiver in one object, a masterpiece based on elegant interaction of electrical and chemical processes, created by Nature.

Before formulating the suggested interpretation, the author had been studying intensively a lot of literature on human brain, first of all in neurophysiology, neuropsychology, psychology, and neurocybernetics for several years. It was a preparatory period of work. The main references are given at the end of the book.

The draft of the book was written in the period from 26 February to June 17, 2012 and it was the most interesting and at the same time very hard in my life. I hardly would have written the book without an experience of "marathon work" on a series of my 8 papers published in the "Journal of Nano- and Microsystem Technique" (in Russian) during the period from 2006 to 2010 (see the References).

Further presentations are followed at three prestigious International conferences.

The first plenary presentation (30 minutes) was given in Taganrog on June 27, 2012 at the conference organized by my Russian friend Boris Georgievich Konoplev (*I. I. Abramov. The Brain is an Object of Organic Hybrid Nanoelectronics// International Conference "Nanotechnology – 2012" ,Taganrog, Russia, June 25-29, 2012, p. 17-18 (in Russian). The publication is available on the website www.fep.tti.sfedu.ru)*.

The second plenary presentation (30 minutes) was given in Sevastopol on September 10, 2012, where I have many friends and acquaintances (*I. I. Abramov. The Human Brain as an Object of Nanoelectronics // 22nd International Crimean Conference "Microwave and Telecommunication Technology". Conference Publications. September, 10 -14, 2012, Sevastopol, Crimea, Ukraine, v. 1, p. 17-19 (in Russian).*).

The third oral presentation (30 minutes) was given in "Podmoskovnie Lipki" on October 2, 2012, where I also have many friends and acquaintances (*I.I. Abramov. The brain is a nanoelectronic object // International Conference "Micro- and*

Nanoelectronics – 2012", ICMNE – 2012. Book of Abstracts, October 1st-5th, 2012, Moscow – Zvenigorod, Russia, O1-10.).

The papers caused a "flurry" of questions. Preparing the presentations, the author pursued two purposes:

First, to report the main ideas of the work;

Second, to reveal its possible weaknesses which required clarification.

These purposes were reached. The opinions were very diverse. From enthusiastic to quite unfavorable, to put it mildly. As usual, the truth must be somewhere in the middle. Thus, several prominent scientists said that "the author was absolutely right". There was even an opinion that "the work deserves 2 Nobel Prizes. One – in physics, and another – in chemistry". In response, the author made a joke: "One would do". In the backrooms other suggestions were made, such as "We should put him in his place". Unfortunately, such propositions are quite common in our "Slavic world", and they don't surprise established scientists. Many of us experienced this. The author is by far not the first one. It should be noted that particularly at the second conference the harshest statements usually came from the scientists who had neither publications nor presentations, not to mention plenary ones. As popularly stated: "It's easy to criticize and difficult to do". It was also suggested to name the brain as an object of "nanoionics". The author didn't go on the way of introduction of new terms. In the work was used already well-known terminology. Everything else was explained. It was done with the purpose to avoid adding complexity to this very complicated field. I wanted to make the book accessible to a relatively large readership, including students. By the way, having learnt about this book, no less a "flurry" of questions was among my students. Thus, the lecture on the subject simply stopped. For the above mentioned reasons, I employ already known terms in neurophysiology, neuropsychology, psychology and electronics. The book was prepared for printing on July 19, 2012. Last discussions only more assured the author that I am right, and therefore, the book is published almost without corrections. I only supplied it with a Preface.

I cannot, however, mention the following. After the book was finished the author went through several life crises. On August 14, 2012 my father, who was recovering from a surgery, died, my mother* fell seriously ill, etc. The author is an atheist, but,

* On December 2, 2012 my mother also died.

apparently, the “the universal conservation law in Nature” exists. Ilya Andreevich Obuhov, a friend of mine, even told me: “Igor, leave this work”.

And nevertheless, I decided to publish the monograph, hoping that my reader will be friendly and thoughtful. Many of my listeners and students also asked me about its publication. I hope that the book will give answers to many questions that arise from them. So, it is up to the reader to decide as far as the author is right.

Supplement to the English edition.

This book is a translation from Russian language of the monograph: Игорь Абрамов. Мозг как объект электроники. LAP LAMBERT Academic Publishing, Saarbrücken, Germany, 2012. 80 p. As the quotes in the original are taken from Russian translations, unfortunately double-translation may cause some inaccuracies. Inaccuracies may also be found in the translation at English the monograph itself. In both cases, as the authors advise, it is expedient to appeal directly to the originals. With any questions you can contact the author on e-mail: nanodev@bsuir.edu.by.

Introduction

The brain functioning is one of the greatest challenges that human faces and a most puzzling mystery of Nature.

On the one hand, many works, ranging from serious scientific researches and ending with religious and science fiction books, are dedicated to this problem. And it's simply impossible to analyze all of them. The author did not intend to; however, I tried to study the most significant literature related to the subject under discussion. First of all I want to note a huge number of common, streamlined wordings, approvals, various complications, surmises, new terms, concepts, etc., which is the evidence of the exceptional complexity of the problem. This was also marked by some other researchers. That is why many following (after describing in general the brain functioning correctly) works might be, in principle, interpreted as their particular cases, which at best clarify and specify them.

In this respect the study of the state of conditioned reflex problem after I.P. Pavlov conducted by famous Soviet scientist E. A. Asratyan is quite illustrative. Specifically, his understanding (interpretation) of the words of the great physiologist led him to the conclusion that "later conceptions of "neuronal ensembles" (Hebb), "image of the external world" (Beritashvili), "neural model" (Sokolov) and "local conditioned state" (Asratyan) restate or evolve Pavlov's idea" [3]. In view of the above, and in principle, this book can also be considered as a clarification to the only two epigraphs given above. For completeness we can add the following statement [4]: "…the brain is a data transmission device; this is the way the brain communicates with the world. The rest is insignificant". Nevertheless, I would like to clarify something, i.e. more detalization and thus go a little further are needed, as dissatisfaction with our knowledge of brain functioning is still remains.

On the other hand, it is advisable to recall the words of I.P. Pavlov, a great Russian physiologist, namely: "After glorious victories of science over the dead world it's time to work on the living world and in it the brightest jewel in the crown of Nature – brain functioning. At this last point the problem is so immense and challenging that it requires all resources of the thought: absolute freedom, renunciation of stereotypes, the widest possible variety of opinions and patterns for action, etc. to succeed. Every intellectual, whatever side of the subject he explores, will find his share to study, and all the shares will eventually contribute to the solution of the greatest problem of human thought" [3].

In the present work, the brain is considered from the viewpoint of a specialist in micro- and nanoelectronics*, i.e., to put it simply, electronics, using the minimum number of terms. The aim of the monograph is an attempt to answer the following questions:

1) Why the brain can be interpreted as an object of organic hybrid nanoelectronics?
2) How does the brain approximately function from the viewpoint of a specialist in electronics?
3) Is quantum mechanics enough for description of the brain functioning, including consciousness, thought and other mental functions?
4) How to investigate the brain further?
5) What's further?

In answering these questions, the author was guided, first of all, by a very beautiful modernized formulation evolved from the genuine idea (see epigraph) of Ivan Mihailovich Sechenov, a great Russian physiologist. This formulation is called in perfect book [7] "the "central dogma" of neurobiology", namely : "Everything that is to be said is based on the assumption that all normal, healthy brain functions as well as all pathological disorders, however complicated they might be, can eventually be explained from the features of the major structural components of the brain. We call this statement our "central dogma"". Similar "working hypotheses" are also set forth in the books D. Wooldridge [5] and J. Delgado [8]. Similar viewpoints are also held by many neurophysiologists, beginning with S. Ramón y Cajal, including many of cited here.

Analysis is based on the author's professional knowledge of physics and, of course, electronics, as well as on the basic information of neurophysiology (see, e.g., [9-12]), neuropsychology (see, e.g., [13,14]) and psychology (see, e.g., [15-17]). It should be emphasized that the important feature of this analysis is its consistency (at least the absence of inconsistency) with the principles and the basics of the above mentioned special disciplines about the brain, which are confirmed in experiments. The author's stand developed under the influence of several wonderful books [2,5,8,18,19]. Here it

* Why not? After all, the problem was considered by physicists (see, e.g.,[5]) and mathematicians (see, e.g., [6]).

is necessary to add legendary works by J. von Neumann [6, 20-22]. Everything what is written by me in further one needs to consider as just an attempt to evolve the ideas of these outstanding scientists. I cannot but mention it either.

1. **Why the brain can be interpreted as an object of organic hybrid nanoelectronics?**

Let us give a more detailed explanation of this interpretation of the brain* [23] as an object of natural electronics created by Nature.

To begin with, let us give only following facts:

1) Two types of electrical signals are of key importance for information transfer in the brain [12]: local (graded) potentials located in the specialized regions of neurons and the action potentials, whose signals are transmitted along the entire length of the nerve cell;

2) All influences on the human organism are "converted (or transformed) into the electrical signal" with subsequent recognition in the central nervous system [12];

3) "Autonomic and somatic functions, individual and social behaviors, emotional and mental reactions may be evoked, maintained, modified, or inhibited, both in animals and in human, by electrical stimulation of specific cerebral structures"[8].

All these facts, known in neurophysiology and neuropsychology, are sufficient, in principle, to interpret the brain as an object of natural electronics. We shall, however, move forward to detailed explanation (as stated above), with some comments made in the beginning.

First, fact 2 indicates that among mechanical, optical, thermal, chemical, electrical and etc. signals acting on human, Nature preferred electrical ones for subsequent information procession in the brain as the most universal (all other signals can easily be converted into electrical signals) and sufficiently fast-acting at the same time, i.e., they are selected for being optimal.

Second, among numerous analogies (see, e.g., [7]), the artificial objects that are most similar to the brain are computer [6], TV set [3, 24], and integrated circuit (IC) [23], i.e., the products of electronics. In the author's opinion, from marked exactly IC. As will follow from the below consideration, this statement is also of importance, adding to the expediency of the analysis of the brain as an object of electronics.

---

* The interpretation was first proposed at the 11th International Crimean Conference "Microwave and Telecommunication Technology" (CriMiCo' 2001) (10-14 September, 2001, Sevastopol) in author answer to the question about the advances in nanoelectronics.

At present, distinction between micro- and nanoelectronics ICs are distinguished by the characteristic lengths of their active elements. Particularly, nanoelectronics ICs include whose active elements (transistors, diodes, etc.) with the indicated sizes have at least one dimension in the nanometer range (from 1 to 100 nm) [25,26]. What structures are of crucial importance for the brain? Note here that the whole variety of electrical activity of neurons in the brain "eventually depend on the activation or deactivation of ion channels, thereby regulating the flow of ion currents across the nerve cell membranes" [12]. At the same time, the conformational changes (transitions) in the proteins of the channels, as a rule, result in opening or closing of the channels [27]. The main sizes of these active elements, i.e., proteins and/or their subunits (domains) determining the features of ion channels at least in one dimension just lie in the nanometer range [12]. For these (and other, see below) reasons we shall consider organic molecules: DNA, RNA and others as the determining elements for the brain.

It is a common statement in neurophysiology that besides electrical processes, chemical processes also play an important role in information transfer in the brain [7,11,12,28]. But generally speaking, other processes can also influence. It was J. von Neumann that pointed to the importance of mechanical processes (conformational transitions in proteins) in particular.

Summarizing the above, *the brain can be interpreted as an object of organic hybrid* * *nanoelectronics.*

* Hybrid, because not only electrical processes play an important role, but also chemical ones at least**.**

2. How does the brain approximately function from the viewpoint of a specialist in electronics?

A specific "tangle" of numerous physicochemical processes, often interconnected, that one faces studying brain functioning, especially its psychic functions, is the main difficulty of pure neurophysiological consideration of brain functioning. To try to "disentangle" it, we shall, based on the above interpretation, *take the following hypothesis: we will consider that electrical processes have a predominant effect on brain functioning*. So, it is considered that information in the brain is basically processed at the level of electrical processes. What does provide another kind of fundamentally important processes? Chemical processes* supply electrical circuits of the brain with energy, and provide their modification. Let's see what this approach leads to.

Before answering on the posed question, we will characterize briefly the state of the problem, according to data about the brain from specialized disciplines. Currently, clearly distinguished two levels of the description of brain functioning: neurophysiological and neuropsychological.

Very brief summary of brain functioning and nervous system on the neurophysiological level is given in a remarkable course book [16]: "The human nervous system is built from billions of cells called *neurons*. A neuron receives signals from other neurons through the branches of dendrites and cell, integrates these signals into the cell and sends an electrical impulse (action potential) along the axon. When the action potential reaches the knoblike terminals at an axon's end, it triggers the release of chemical messengers, called *neurotransmitters* or *mediators.* These molecules transfer their excitatory and inhibitory signals when travel across the synapse and bind to receptor sites of the receiving neuron."

Let us point out two issues that are important for further consideration. First, according to the neurophysiology, information procession in the brain, as well as different psychic functions are related to the operation of neuron ensembles. As academician Natalia Petrovna Bekhtereva, an outstanding Soviet and Russian neurophysiologist, and her colleagues stated [19]: "The supposition that the complex brain functions are performed by the systems of nerve cells rather than individual neurons has a long history. So, as early as in 1949, Hebb defined a neuronal ensemble

---

* They play a peculiar role in chemical synapses (see below).

as a hypothetical group of neurons formed in the process of learning and performing a certain function. The experimental evidence for the existence of such systems of functionally integrated nerve cells and the general principles of their organization were later reported by Mountcastle, 1957; Hubel, Wiesel, 1968; Kogan, 1979 and others." We shall further hold to this point of view became canonical in neuroscience. It is necessary at once note the large number of names for such forms of ensembles of neurons in the literature. Here are just some [29]: neural networks and netlets, neuronal ensembles and microensembles, neuronal modules, neuronal columns, nets, sets, neurocenosis, neuronal populations, functional modules, small barrels and microsystems. Further in this book (except quotes), all these combinations will be termed the "neuronal ensembles".

Second, the above description (summary), strictly speaking, is given for the case of chemical synaptic transmission (first type synapse). It should be noted that electrical synaptic transmission is also possible in the brain (second type synapse) as well as mixed chemical and electrical synaptic transmission, i.e., mixed (third) type synapse. Lets us, however, remark that the first-type synapses are predominating in brain [12,30].

The brief but thorough neuropsychological description of brain functioning is given in another remarkable course book [14]: "…the brain is a complex integrated metasystem built from different macrosystems (projection, associative, integration-triggering, limbico-reticular), each macrosystem is made of various microsystems (microensembles). The integrative activity of the different-level systems is provided by their hierarchical dependence and horizontal-horizontal… and vertical-horizontal… interactions. The dynamicity of brain structures and their individual variability is achieved by means of the dynamicity and variability of the microsystems composing them. Qualities of dynamicity and variability are inherent for different systems for different degree."

And at the same time, evaluation of our understanding of complex mental functions, including thinking, of the brain well and accurately described in the book [7]: "Generalization of the working principles are more or less well-known systems can actually lead to an understanding of more complex processes close to the thinking, but it is far from clear".

Summarizing the above, let us note the following. The neurophysiology data indicate that electrical and chemical processes are of primary importance for brain functioning

[7,11,12,28]. Moreover, many authors emphasized that electrical processes are important for understanding mental functions of the brain [2,3,5,8,18,19]. Nevertheless, special disciplines, studying the brain, traditionally prioritize chemical signals over electrical ones. This canonical viewpoint is expressed in the next phrase [31]: "Fundamentally the brain is rather a chemical network than electrical one. Within neurons information is carried by electricity, but between neurons it's carried by chemical substances."

Why is it so? We needed to answer this question, as it is of principle importance for us. It is a common belief that it was the experiments performed by K. Lashley, a known psychologist, that "knocked out the electrical network theory" [3] because there are gaps (clefts) in the neuronal ensembles in the form of synaptic junctions (chemical synapse). This was a sort of ruthless conclusion, concisely, but figuratively expressed in [12]: "…the idea of animal electricity had such a potent hold on people's thinking that it was more than 100 years before contrary evidence finally overcame the assumption of electrical transmission between nerve and muscle, and by extension between nerve cells in general." Thus, chemical synapse became a "stumbling block" in brain study.

But we shall try to explain the principles of brain functioning with the use of hypothesis accepted.

First of all, we shall demonstrate that *all elements of neuronal ensembles in the brain can be considered (interpreted) as the elements of electrical circuits*.

A very accurate characteristic of the neuron as a whole was given by J. von Neumann in [21]: "…pulse is a degenerate state of the complicated electrochemical complex which constitutes the neuron, and which in its fully analyzed functioning must be viewed as a modeling machine." Though currently there are a lot of simplified models of neurons (see, e.g., [32,33]), the following "electronic" interpretation, now accepted in the literature and more simple than that cited above, is sufficient for us at this stage, namely: on the whole, the neuron is a summation pulse generator based on the "all-or-nothing" approach. Nerve fibers (extensions), i.e., axon, dendrites, spines of the neuron can also be interpreted as electrical elements. So, a quite adequate passive transfer cable theory, developed now, describes how the axon and dendrites transmit the electrical signal. The most accurate results are obtained when the nerve fiber is divided into compartments [27]. At the same time, in order to describe the action potential generation in response to excitation, one should necessarily consider the effects of ion channels, particularly their selective permeability, and voltage-induced conformational transitions of proteins. This process in biophysics is traditionally described using the phenomenological Hodgkin – Huxley equations [27,34]. Unfortunately, "these equations were not derived from physical principles, but are empirical representations" [27]. It is appropriate to note that these equations are not easy to derive because just ion channels themselves are very complex nanoelectromechanical systems, and the number of various channels present even in one neuron can be enormous [11]. Though marked theories still explains the generation and propagation of the action potential (i.e., electrical signal) across the neuron [12].

As mentioned above, the "stumbling block" is chemical synapse, providing the contacts between neurons of the set and thus being of principal importance for the neuronal ensemble. So, what processes occur in a chemical synapse according to the data of neurophysiology? "A nerve impulse arrives at the axon terminal and causes special neurotransmitter molecules to be released. These neurotransmitters act on the postsynaptic membrane either to lower its membrane potential or to keep its membrane potential from being lowered. If the membrane potential is lowered, the frequency of pulsation increases; we call such a synapse *excitatory*. If instead the membrane potential is stabilized at a value above threshold, impulses do not occur or occur less often; in this case, the synapse is called *inhibitory*" [11]. What happens from the electronics viewpoint? The excitatory and inhibitory chemical synapses act as frequency converters of the impulses. In the case of inhibitory synapse, when impulses are not generated at all, we have just a switch. Thus, chemical synapse* is also an element of the electrical circuit! Let us recall here that an ordinary electrical battery, whose operation is also based on chemical processes, is seen as an object of electronics and this fact is accepted.

As follows from the above, *the neuronal ensemble of the brain can be interpreted as a nonlinear electrical circuit!* The integrated circuit being its closest artificial analogue.

---

* We should mention that electronic interpretation of other two types of synapses does not present any difficulty. Thus, the electrical synapse is a nonlinear capacity with a leakage or an "electrical rectifier" [30]. A mixed synapse can be interpreted as a combination of two other synapse types. On the whole, other representations of these nonlinear elements of neuronal circuits are also possible (see below).

Let us consider what are the main differences between neuronal circuits (type I) and modern ICs of micro- and nanoelectronics (type II).

First, neuronal circuits are built from organic materials, while ICs are built from inorganic materials. Second, the operation of the former is determined by ionic conduction, while that of the latter is determined by electron (and hole) conduction. These two factors result in a slower operation of the circuits of type I compared to those of type II. It does not seem to be an advantage, but as will be shown later, such slow behavior is of principal importance and is connected, first of all with the necessary interactions (conversion) of electrical and chemical processes in the brain. To demonstrate this and to analyze the third important difference, we shall return to modern neurophysiology for the explanation of how neuronal ensembles are formed (see, e.g., [7,12,16]).

According to [7], "the development of all parts of the brain has 8 main stages.

1. The neural plate cells become determined as to be neurons of some general type. The mesodermal cells underlying the neural plate are supposed to produce signal matters affecting the cells growing from ependyma in some way, which is still unknown.
2. The cells of the determined area start dividing.
3. These cells migrate to their interim or final destination.
4. Reaching their final position, the immature neurons form clusters, which are developed into the "nuclei" of a mature nervous system.
5. Fetal neurons of the clusters stop dividing and extend axons and dendrites.
6. This leads to early formation of the connections and provides the possibility neurotransmitters synthesis and release.
7. Finally, the "right" connections are set, and the cells with "inappropriate" or deficient connections die. This process is known as a "programmed cell death".
8. When the number of neurons has set, the pathways slightly change to fit the functions of the system."

What is most important for us? We can state that neuronal ensembles possess two important features: it first grows and then it is modified. This means that *the neuronal ensemble is an electrical circuit, growing in the beginning and then modified*! And here lies the most significant difference that distinguishes the neuronal circuit from the IC, leading to the main advantage of the circuits of type I over those of type II. The most fascinating feature of brain functioning is that the total number of neurons decreases* with age, while the amount of information stored in the brain, as a rule, increases**. Seems paradoxical! But what really happens?

Based on neurophysiology data, let us describe how the brain perceives and processes information within the framework of the suggested interpretation. For simplicity, we shall consider the stage of neuronal circuit modification.

As stated earlier after the information is perceived through the sensory receptors, the stimulus of the corresponding modality is *converted* into an electrical signal. This process involves transformations, decomposition (splitting) of primary information in different systems for its further reconstruction at the level of procession of electrical signals by the neuronal circuit. Let us consider the process of modification of the neuronal circuit itself.

After the electrical signal is excited and transmitted in the neuronal circuit, complex cascades of biochemical reactions are triggered in it (DNA → RNA → proteins and other molecular structures), forming the basis for the modifications in the proper places of the electrical circuit topology by transporting necessary substances via nerve fibers (axons, dendrites). In terms of anatomy, permanent morphological changes of the neuronal ensemble occur. If the information is necessary to fix for a longer period the reverberation of electrical signals in the neuronal circuit (the signal is transmitted again and again) is required to sustain biochemical reactions. Because of efficiency and rationality of Nature *new information is added to the already accumulated one, i.e., the information-coding circuit is constantly modified (the modification can be the little one).* Since the input information, as a rule, is characterized by different modalities, at least for this reason it is encoded in different parts of the brain (neuronal circuits).

---

* According to up-to-date information a relatively small number of neurons still can appear [35].

** Of course, a healthy brain is meant.

Nature may seem to be prodigal in this case, but – no – it is still genius. First, because of information decomposition, it is rationally that similar information, at least of same modality, be stored in the same (neighboring) field (domain) to reduce modifications of the neuronal circuit. One should also bear in mind that brain functioning has limitations (neurons decrease in number, the volume of the brain does not increase, the information does not vanish completely, but is, in fact, accumulated ("stratified")). Second, but possibly more important, due to this ensures reliability of brain functioning, as the information is duplicated (in some sense) in different parts of the brain, which is confirmed by neurophysiology and neuropsychology data [3,13,14,36]. Third, and most interesting, the efficiency of information processing does not deteriorate, but improves due to parallel processing (see below). As well it should be taken into account that information is stored in a compact (encoded) form, and hence it is incomplete. Despite seeming paradoxical, such memory organization, on the whole, appears to be economical under the noted limitations.

Thus, now we are coming to another important difference between neuronal circuits and ICs. *Neuronal circuits of the brain are characterized by a very complicated (practically individual) topology.* So, strictly speaking, there are no topologically identical neurons, including cell bodies, axons, dendrites, spines, etc., as well as the junctions – synapses, though all these elements of neuronal circuits can be referred to certain types. In principle, the information primarily stored in every individual brain is encoded in the topology of the neuronal circuits.

In particular the data obtained in consideration of a rather simple case prove the importance of topology. The author of the book [27] reports the simulation results obtained in studying the effects of axon varicosity on the behavior in action potential. It appeared that "depending on the diameter of the varicosity, the action potential will either be delayed, or reflected, or blocked" [27], i.e., its behavior can undergo qualitative changes. Hence, even when the brain is considered in the first approximation (see below) as a set of neuronal circuits (or simply as a neuronal circuit), every human has an individual set. This reveals extraordinary ingenuity of Nature. Unfortunately, for modern ICs regular topology is typical.

What determines individual differences in neuronal circuits? "Most researchers believe that the structural basis of memory lies in neuronal reorganization based on enduring modifications of synapses" [37], i.e., in fact it is related to the contact systems between neurons (synapses) of the electrical circuit of type I. Though there are other viewpoints (see, e.g., [38]), this opinion prevails in special disciplines studying the brain [16]. Let us mention here the viewpoint of G. Edelman, a famous American scientist, who suggested main candidates for the memory, namely [39]: "…new dendritic bonds, metastable changes in the cell membrane and the cell surface on the dendrite spines, and molecular changes of the synapses."

At the same time, the analysis of the data of modern neurophysiology shows that the number of changes affecting the functioning of neuronal circuit can be really large, i.e. much more. We shall mention here only some of them: 1) changes in the amount of mediator released in synapses; 2) change in the ion concentration in neurons, which affects the activity of cells; 3) change in the conduction of ion channels due to changing protein properties; 4) change in the number of conducting ion channels; 5) synthesis of RNA and proteins occurs that cause structural changes in synapses, spines, dendrites, and axons, as well as in the cell nucleus, etc. New bonds[*] between neurons may form.

So, we see that many factors can influence the individual differences in neuronal circuits and they are not related only to the circuit topology. This means that not only synapses are important, as many neuroscientists think, but the situation may be much more complicated. Each group of the listed-above changes is likely to determine the type of memory, and that is why the division of memory into instantaneous, short-term, and long-term [14] is quite relative[**]. Note here that some authors distinguish other types of memory in addition to those mentioned above [16,17,38,40]. It would be more appropriate to speak about different stages (phases) of memorizing (recording the information) which are related to possible various changes in the neuronal circuit. Important information is fixed in the neuronal circuit, e.g., as a result of the electrical signal reverberation (see above). When the information is not important, it is not fixed at all, i.e., the necessary changes in the neuronal circuit do not occur. It seems that both processes are possible in different parts of the brain, and different types of memory are not necessarily spatially separated, i.e., they may be also temporally separated.

---

[*] I should note here that a reverse process, i.e. "fading" of some old bonds can occur through death of neurons, and also forgetting, aging. The changes alike can take place in other old modifications.

[**] It is not without reason that in the book [17] they are called "hypothetical components of memory".

Thus, *nonlinear electrical circuits of type I are characterized not only by a very complicated topology, but also by variation of properties of its elements of the same type (cell bodies, axons, dendrites, spines, synapses, etc.),* while in modern ICs, conversely the minimization of such deviations is seen as desirable. Thus, neuronal circuits become more complicated with age (after a certain stage, see above) as a result of the increasing number of connections and other modifications, rather than as a result of growing number of neurons of these electrical circuits. The important role in the processes of modification and transformation of electrical circuits of type I (fixation of memory traces) is played by the changes in bonds, geometry, conduction, dielectric permeability, etc. (in microelectronics these are called the design, technological and material parameters) of the appropriate parts of the neuronal circuits. These changes are caused by various biochemical processes. Everything (or almost everything) is significant for these processes, because all major constituent parts of the neuronal circuit (cell body, axon, dendrites, spines, synapses, ion channels etc.) are, in fact, nonlinear elements of an electrical circuit, whose properties may depend on different factors. Recall here that even when considering passive axonal transmission of electrical signals, axons* should be simulated using the compartment method. Hence, *chemical reactions are responsible not only for energy supply of electrical circuits of type I, but also for their modification!* This is the most important reason why Nature preferred the "hybrid way" to the purely "electronic way", i.e., the way of elegant interaction (transformation) between electrical and chemical processes. Two more reasons can be mentioned here: human brain receives signals of different modalities (visual, auditory, gustatory, etc.), which must be converted into electrical signals; all other processes (including chemical) in the organism, which are slower as a rule**, than electrical ones, and the environment must be coordinated with electrical processes.

Do all the circuits undergo modifications? Of course, not. First of all, neuronal circuits responsible for life support functions and storing information in a long-term memory over a life-long period should not undergo considerable modifications. Modification of some of them can cause irreparable damage or even death. At the same time, for neuronal ensembles involved in processing of sensory information and in mental activity, which are located mainly in the brain cortex, the possibility of such modifications can and must exist, at least in view of the enormous diversity of

* According to modern data, axons are capable of stimulating "memory" effects in neurons [35].
** Except for optical signals among earlier noted.

the world around us and due to the limitations we have mentioned earlier in this chapter. This opinion agrees well with N. P. Bekhtereva's conception "about the existence of rigid and flexible links with different functions in neurophysiological systems sustaining mental functions" [19]. By "rigid and flexible links", the author understands the "populations of neurons". It should be noted, however, that "flexible links" are not necessarily realized via the modification of neuronal circuits, but also via various potentialities of nonlinear electrical circuits of type I themselves (see below).

Thus*, from the viewpoint of electronics, a mature human brain is, first of all*, a set of nonlinear electrical (neuronal) circuits of two types: the circuits that should not undergo modifications, and those that can undergo modifications.* Their close microelectronic analogues are (see, e.g., [42]) memory ICs, namely read-only memory and programmable read-only memory. Now let us turn to *memory*. It is to the point to recall here what Ivan Michailovich Sechenov, a great Russian physiologist, wrote about it: "Memory is the power underlying the entire process of mental development – without it mental development would be impossible" [1]. Let us note here that many other brain researchers pointed out the importance of memory for brain functioning (see, e.g., [36,38,43]), but none of them has ever considered it within the framework of the full electronic interpretation. As indicated in modern experimental investigations, there are three brain structures that play the key role for memory [17]: brain cortex, cerebellum, and hippocampus; "though it should be mentioned that the memory functions are distributed throughout the brain".

Now we can proceed to the consideration of how approximately brain is functioning. Because the brain is a polyfunctional device, let us at first describe the principles of its operation in several different modes. This seems reasonable because many processes occur simultaneously or in parallel, for example, procession of the input information, remembrance, thinking, control of different systems of the organism. Some of these processes are conscious (they involve specific brain structures, seemingly hippocampus [16]), others are unconscious (i.e. without these structures). Various brain structures, or to be more precise neuronal ensembles composing them, can operate in many different modes. Moreover, not only neuronal populations, but

---

* Certainly, we should not ignore other components of the brain [41]: blood-vascular system, neuroglia cells, which exceed neurons in number, etc. They provide to other important functions (delivery of the required substances, nutrition and so on). Here the brain is treated as an information processing and data storage device, as well as a device performing mental activities.

neurons themselves are polyfunctional [19]. On the one hand, this makes the brain very complicated for analysis; on the other hand, this makes brain functioning remarkably flexible.

We can conditionally distinguish three types of brain functioning modes in terms of a set of nonlinear electrical circuits, namely: 1) under external influence; 2) without external influence (internal); 3) mixed. In this case, every separate mode of brain functioning, including perception, remembrance, thinking and other mental functions refers to one of the stated types. Moreover, any specific mode of brain functioning is a result of passage of an electrical signal (or signals) across the corresponding set of electrical circuits of the type I. The main possible operations are comparison, encoding, decoding, action command, and modification of neuronal circuits.

Sensory information processing refers to the first type of modes. As has already been noted, the information received through sensory receptors is converted into electrical signals, which then undergo various *transformations*[*] (decomposition, etc.), i.e., the information is *encoded* through hierarchical processing. Then the electrical signal (signals) propagates along the neuronal circuits of memory in different brain regions (mainly in the brain cortex). Because these circuits are nonlinear and in some sense diffusely located in the brain, divergence and convergence are both possible in the signal propagation. Eventually, identification occurs through *comparison* operation of the input encoded electrical signal (signals) with the stored information encoded by neuronal circuits. The coincidence with certain degree of accuracy between the two causes a kind of resonance, and as a result, identification of the object. But if not? What if the necessary coincidence is not established? In this case, *the action command* is taken, particularly here[**] it is the command for the *modification of neuronal circuits* in the appropriate regions of the brain, i.e., new additional encoding in neuronal circuits occurs. Let us note that when the coincidence is not full and slight distinctions are present, the object can be identified, but the command is still given to modify the neuronal circuits. Such hierarchical diffusive processing of electrical (input) signal (signals) in the brain enables massive parallelism in the procession of input sensory information, e.g. in image recognition. Since electrical signals propagate rather fast, the parallelism procedure in information processing is highly efficient, which was mentioned by many researchers.

---

[*] This term is rather general. Consequently, it may be applied to describe almost all the brain transformations of electrical signals. Thus, more specific terms noted earlier will be used further.

[**] Action command may be taken after the object is identified, for example the command to move.

Remembrance refers to the second type of the brain functioning mode. According to the proposed interpretation, remembrance implies propagation of the electrical signal (signals) induced by the brain itself (that is why it refers to the internal mode) along the appropriate (defined in space and time) neuronal circuits of memory, where this encoded information is stored, i.e., *decoding* of the internal signal (signals) occurs. It is appropriate to recall here that external electrical stimulation of the brain (certain brain regions) can evoke remembrance, as well as other mental reactions (see earlier), which were obtained by many researches, even using rather primitive electrode technique (see below).

Thinking activity involves similar processes, though the connections are not as rigid as in the case of remembrance of certain events. For this reason, many events of thinking activity may be referred to the second type of the brain functioning mode (internal). Here Nature reveals its ingenuity again: human's thinking activity is extremely efficient and economical. Thus, *thought is decoding (internal reproduction) of the electrical signal (or signals) initiated by the human brain itself that propagates along brain's neuronal circuits of appropriate spatial-temporal configuration*. Hence, thought is the process somewhat inverse to external information processing (direct process) that is likely to be mainly initiated by the brain cortex, i.e., currents pass through neuronal circuits, causing the images, events, concepts, etc. to appear as a result of decoding the information stored in the appropriate neuronal circuits. This means that we mainly think in "patterns" that are encoded in the electrical circuits of type I. This makes brain functioning really efficient and economical. The electrical (rather fast*) signal can propagate somewhat by "leaps" between different circuits, i.e., not in that regular manner (sometimes rather chaotically) as in remembrance. Even in this case, thinking activity can be amazingly diverse due to an enormous number of such circuits.

Why thinking activity is such a much-argued research issue? The suggested electronic interpretation of brain functioning is needed to clarify some important aspects of this problem. There are also some objective factors that add to the complexity of the problem. First, thinking activity involves internal reconstruction of encoded information, i.e., strictly speaking, more complete, previously received information that is stored in a compact and transformed form in neuronal ensembles.

---

* In this respect the information concerning commensurable orders of impulse activity duration of neurons and timing data of thinking activity provided by N. P. Bekhtereva and her colleagues is very important [19].

Second, we should bear in mind that the brain constantly accumulates information, which is added and in some sense "stratified" to the previously written data (see above). These factors create an illusion of something unusual, mysterious, and incomprehensible.

The interesting problem is whether or not neuronal circuits can be modified in the process of thinking activity. If not, we only think in patterns or stereotypes. This agrees with the data of many brain researchers that the brain often "thinks up" the missing information, altering the solutions and vision in order to fit the existing ones* (see, e.g., [16,17,31,44]). I still hope that in the process of creative work, neuronal circuits modifications (not necessarily the formation of new connections, see above), like those occurring under external influence and through learning**, are possible at least sometimes. It should be noted here that nonlinear electrical circuits of type I have a significant potential even without modification, e.g. when various signals are passed through neuronal circuits, number of which can be very large.

Psychology distinguishes four stages in creative process [17]: 1) preparation, 2) incubation, 3) insight (clarification), and 4) verification. It is possible that just during incubation, the modification of neuronal circuits or "scanning" through them occurs, which at least in some cases is a faster process. When a necessary set of neuronal circuits, corresponding to the problem solution, is formed, insight comes about as a result of the propagation of the electrical signal in this set of neuronal circuits.

Thus, as a rule thinking is the human's internal perception of the information encoded in the brain itself.

An important mixed mode of brain functioning is the control of the various systems of life's important functions by means of neuronal circuits of fixed form performed simultaneously with the external information processing. Because many other operation modes can work in parallel, the typical mode of brain functioning, strictly speaking, is mixed***. For example, thinking activity often takes place with the external information processing, i.e., in a mixed mode. Obviously, modification of

---

* Seemingly, it is more typical of the elderly people, as the ability to modify of neuronal ensembles weakens with age.

** It is interesting to note that in the creation process many components are perceived as self-learning without external influence.

*** In this respect internal mode of brain functioning is a convenient idealization (see also below).

neuronal circuits in this case is possible. I will note here that various specific modes of brain functioning can interact and influence one another.

Let us point out that normally developed, healthy brain, where the appropriate consolidation processes based on electrical and chemical processes take place is necessary but not sufficient condition for the consciousness to exist. As stated by many researchers, the interaction with the environment is necessary (see, e. g., [7,8,14,16]), i.e., the normal development cycle under this interaction must be complete. The key points of this interaction have already been described within the framework of full electronic interpretation of brain function.

It is pertinent to consider here how complicated the set of neuronal circuits of the brain is. The brain possesses an impressive number of main structures [11,12,28,45]: 10^{10}–10^{12} nerve cells, 10^{14}–10^{15} synapses, and even more molecules*, ion channels, i.e., key elements. Moreover, according to the modern data, there are "more than hundreds, and may be a thousand" [11] of different types of nerve cells; ion channels can also be rich in variety [12]. Morphological data [47] show that synapses of even the same type differ significantly. The neuron can be connected with other neurons by a large number of bonds: from one synaptic bond to ten thousands synaptic bonds and even more [31]. Moreover, there are many individual peculiarities in neuronal circuits, which were noted above. So, the data of electrophysiology [48] prove that even axons and dendrites cannot be considered as the simple passive elements of electrical circuits because the action potential is regenerated, spikes are formed, etc.

Thus, strictly speaking, almost there are not identical elements of neuronal circuits; ion channels of one type formed by the corresponding molecular structures seem to be the only exception (see above).

The complexity of the set of these peculiar electrical circuits of type I is really impressive**. Because of it becomes clear why the brain potential in information memorization is immense. The estimates of the memory capacity as large as 10^{15}–10^{16} bits [3], made earlier seem to be too optimistic, though recent estimates of the memory capacity as 10^{9}–10^{12} bits [16] are also impressive.

* About 10^{22} per 1 cm^3 [46].

** That is why a complicated question about the accessibility of information [16] is quite clear.

As a result, there is a large variety in the behavior of nonlinear electrical circuits of type I. First, they demonstrate dynamic operation modes, as have noted earlier. Some researchers emphasize the variety in the neural codes of the brain and in the transmission of messages in the impulsive form [19,32,49]. Second, many kinds of mental functions are associated with the operation of a large number (set) of neuronal ensembles (circuits). According to N. P. Bekhtereva and colleagues, the "number of such links* is likely to be not less than one or rather tens of thousands of zones" [19]. For this reason, "collective" or "cooperative effects" can be of importance [19]. Particularly, the "holographic brain theory" [49] can be associated with these effects. It is interesting to note that similar to these collective effects can be of importance for complex ultra large-scale integration ICs (ULSI) (see, e.g., [50]), i.e. for electrical circuits of type II. As a result, for example, in image recognition the neuronal circuits function often reveals resonance-like behavior (see earlier). The simplest example is the function of the striate cortex cells in processing optical signals. They are most responsive to certain stimuli [12].

In this regard, the results of computer simulation of the simplest neural network**, described in the book [33] are of interest. They indicated that within one network, a great variety in behavior is possible even for steady vibrational states, for which the modification of synaptical bonds is not necessarily required. Even one non-modified network can store a great number of images. Based on qualitative analysis using the asymptotic study, the authors of [33] gave a simplified description of the variety of possible operation modes for circular neural networks. Many of these modes have biological analogues. It was also demonstrated the possibility of short-term memory based on circular and local neural networks. These results are important to our investigation because they illustrate one of the possible options of the brain's electrical circuits function in information processing, e.g. in image recognition.

Because electrical circuits of type I are nonlinear and some of them are regularly modified, probabilistic behavior mechanisms can also be realized, depending on the signal, or to put it more precisely, the mechanisms creating the illusion of such behavior. It is to the point to recall here the words of D. Hubel, the Nobel Prize laureate, namely [11]: "…I nevertheless suspect that those who speak of random networks in the nervous system are not constrained by any previous exposure to

* "Rigid and flexible links of brain systems" [19] are meant.

** The author deliberately applies the term "neural networks" characteristic of the works on artificial intelligence. This term is also used in the monograph cited.

neuroanatomy". I think that it is more appropriate to speak here about the "pseudorandom behavior of brain cells" [51]. It is likely that in this case, the structure and composition of processing and reproducing neuronal ensembles alter in a rather unpredictable way, i.e., the structure and composition of the electrical circuit composed of the appropriate set of elements is changed. As a result, figurately speaking, information is processed by a "probabilistic neural ensemble" [29]. But it is not always the case. Fixed circuits are also important (see earlier).

Thus*, depending on the input and passed signals, electrical circuits of type I can demonstrate a great variety in behavior.*

Why this behavior is so varied? The answer is simple – the enormous amounts of input information and still existing limitations of the brain capabilities. As is known, the brain processes enormous information flows, moreover, it often deals with incomplete information and knowledge. It also has to solve problems that do not have definite solutions. From early age human learns to work under such difficult conditions and solves such tasks more or less successfully (most of normal people). This becomes possible, first of all, owing to substantial amount of encoded information stored in the brain and quite fast procession of the input and stored information using electrical signals. Its economical storage (and at the same time, efficient processing) is achieved by numerous (multi-level) hierarchical encoding of information in different brain structures. It is enormous amount of input information that a peculiar "motor" (initiator) of evolution.

Because brain has to deal with such information flows, the author considers that sleep is important in the physiological sense [16]. On the one hand, the brain needs rest (to restore its capabilities in some sense), on the other hand, it is likely that when human sleeps, his brain still processes (systematizes) information (compression, classification, fixation, etc. [16,38]). What concerns dreams, this (inner*) mode of brain functioning is rather to be associated with relaxation processes. In any case, there is evidence of more chaotic electrical signal transmission through the neuronal circuits of the brain, i.e. there is less** (or even not) control in signal transmission than in the process of thinking (see above). Hence, dreams are a "chaotic mode" of

*Seemingly, it is as close as possible to "purely" inner mode of brain functioning.
** Data obtained in neurophysiology of dreams [10] confirm it.

brain functioning[*]. It is also interesting whether the neuronal circuits undergo modifications in one's sleep. Supposing that neuronal circuits undergo some restructurizations (there is enough time for this to take place), modifications should be occurred.

---

[*] It is of relevance here to note that some thinking acts may be very close to "pseudo-chaotic" behavior. It is confirmed by the possibility of creation in dreams [38].

3. Is quantum mechanics enough for description of the brain functioning, including consciousness, thought and other mental functions?

First of all, I will mark that here quantum mechanics will be understood in wide sense. To make it clear I will cite the Nobel Prize laureate in physics S. Weinberg, namely [52]: "All the fancy mathematical theories that the physicists have pursued in recent years: quantum field theories, gauge theories, superstring theories, are formulated within the framework of quantum mechanics". Thus, it means the modern level of quantum physics, i.e. in this book the author holds the point of view of the outstanding American physicist.

Before trying to answer on the putting question, let us make a few remarks.

First of all, let us consider the completeness of quantum mechanics. Having been lecturing on quantum mechanics since 1995, the author points out that in a legendary dispute on completeness of quantum mechanics between Albert Einstein and Niels Bohr, two great physicists, both parties are right to a certain extent*, or "the coin has two sides". Thus, proving that quantum mechanics is incomplete, Albert Einstein was right in a general philosophical sense. Mathematical models** in quantum mechanics are idealizations, and they cannot fully correspond a more or less complicated object of study. In the paper [23] the author called it the problem of "the first step" (the beginning of the idealization). Apparently, it is unavoidable in science based on mathematical models. This very problem may be and will be "fundamental basis for endless speculations" like: "We don't understand something in brain functioning. There is something mysterious about it".

Hence, the accurate description of brain functioning with the use of quantum mechanics at the present stage of its development is impossible.

Wherein are Niels Bohr and his numerous followers right? They actually right that possible values of physical quantities, including the results of measurements, which describe the behavior of particles and their ensembles, can be predicted with the use of quantum mechanics formalism with sufficiently high accuracy, if such

---

* I note that the viewpoint below in fact is formulated applying a wider interpretation of Niels Bohr's complementarity concept.

** The author here uses the definition of this term accepted in Russian literature; see Great Soviet Encyclopedia, Encyclopedia of Physics, Great Encyclopedia.

measurements are possible in principle*. Anyway, for now numerous searches of any experimental disproof of quantum mechanics in both past [53] and more advanced researches (see, e.g., [54, 55]) have failed. "This is not only because quantum mechanics is the basis of all of our present understanding of matter and force and has passed extraordinarily stringent experimental tests; more important is the fact that no one has been able to think of any way to change quantum mechanics in any way, that would preserve its successes without leading to logical absurdities" [52]. For the first time this fundamentally important logical consistency of quantum mechanics was persuasively demonstrated by J. von Neumann in his became legendary monograph [56].

Secondly, let us consider the possibilities of describing living organisms by means of physics. Despite long-lasting discussions on the topic (see, e.g., [7]), N. Bohr and E. Schrödinger were the first among the founders of quantum mechanics to raise this issue with regard to "the new physics". The issue naturally proceeded to the discussion of brain functioning. What is more, Vitaliy Lazarevich Ginzburg, an outstanding Soviet and Russian physicist and a Nobel Prize laureate, considered "the possibility to explain the origin of life and thinking on the basis of physics alone" to be one of "the three "great" problems of modern physics" [57].

On the whole, the opinions of the scientists about these issues and the problems alike were divided. Thus, at present there exist a wide range of views and theories (see, e.g., [15-17, 40, 58]) about thinking alone. However, despite of that, still two diametrically opposed viewpoints on the problem are distinguished. According to the first one, it's impossible to reduce biology to physics in principle. It should be noted that in present many specialists in psychology admit at least the following [16]: "No principle is more centrals today's psychology…, than this: *everything psychological is simultaneously biological***". According to the second viewpoint, biological phenomena can only be ultimately explained on the basis of physics (reductionism). Unfortunately, in the literature a "primitive view" upon reductionism is popular. An outstanding Soviet and Russian biophysicist M. V. Volkenstein presented convincing criticism of this opinion in the paper [59]: "Dogmatists perceive reductionism, physicalization and mathematization of biology as a harmful heresy. In fact, such understanding of reductionism is completely devoid of content. It is not reductionism,

---

* We should bear in mind that some values according to quantum mechanics cannot be measured simultaneously.

** Emphasized by the author of this remarkable book.

but integrative character of natural science that is meant. Science studies the holistic material world and its multilevel system*. Different levels of research are represented in all branches of natural sciences. The underlying level is always that of physics, and this very thesis stipulates the importance and the rich contents of chemical and biological specific levels of researches, as well as prospects for their further development". It should be noted that an interesting continuing of the theme of life from the physicist point of view on the modern level of development that was presented in [60] and also a serious historical review in the same direction of the article [61].

Many physicists share the second view on consciousness and thinking, sometimes with certain reservations. Among the most prominent works of recent time I note papers and books by professors M.B. Menskii [62-65] and R. Penrose [66, 67], and numerous subsequent discussions primarily of those and other works [58, 68]. Very interesting in this regard is R. Penrose's classification of "various viewpoints that one can take about the relationship between conscious thinking and computation" (see table 3.1 [58]). Thus four approaches (A–D) were distinguished. R. Penrose considers that modern physics lacks something [66,67] (approach C). The author's position is closer to the approach B: "Awareness is the only one of the characteristics of features of brain's physical action; and, whereas any other physical action can be simulated computationally, but this simulation cannot be itself awareness" [58].

Thus, the author's point of view is as follows. *On the one hand, mental functions of the brain cannot be accurately described by means of quantum mechanics in principle. On the other hand, in principle, brain functioning can be described with a high degree of accuracy (sufficient) with the use of quantum mechanics formalism at the present stage of its development*. The latter statement formulates *the hypothesis of the sufficiency of quantum mechanics* (as the basis for the study of the brain). At present this hypothesis cannot be proved in explicit form. It should be noted that in formulating this hypothesis the concept of complementarity by N. Bohr was applied also in its broad sense.

Here are some arguments in favor of the hypothesis.

Firstly, quantum mechanics is a reliable fundamental basis for studies of physical properties of various objects of the material world, namely: elementary particles,

* Multilevel structure conception will be very important for us and further.

atoms, molecules, various systems of these particles. It is very important to state that quantum mechanics provides a good agreement with experiment. It has already been emphasized that no experimental refutation of quantum mechanics has been obtained so far. At the same time, the brain is a material system consisting of the above mentioned particles.

Secondly, quantum mechanics underlies the description of basic processes, i.e. electrical and chemical (see above), which determine brain functioning. As for chemical processes, the author confines himself to the statement of Linus Pauling, who won the Nobel Prize twice (one in chemistry), namely [52]: “There is no part of chemistry that does not depend, in its fundamental theory, upon quantum principles”.

Thirdly, quantum mechanics underlies modern solid-state physics, electronics, including ICs of micro- and nanoelectronics. Anyway, experts have no doubt about it. What is more, this detailed level of description is not required as a rule. At least, to design a computer, a TV set, an IC and, of course, to understand the principles, important moments of their functioning a much more simple regularities are used. However, they are founded on quantum mechanics.

Finally, perhaps, the most important. According to the data obtained in modern neurophysiology and neuropsychology, the brain reflects the reality and processes the external information only approximately (also see above). For example, it is a well-known fact that we do not perceive optical signals in a certain range of wavelengths (see, e.g., [11]). In this connection, a simple question emerges: is it necessary to describe such a device, i.e. the brain, accurately? Evidently, the answer is no!

Thus, quantum mechanics is quite sufficient for describing brain functioning.

4. How to investigate the brain further?

Before answering this question it is advisable to comment related to the necessity very thoughtful and careful one should apply quantum mechanics, the most powerful theory human has ever created. Even such great physicists as A. Einstein and E. Schrödinger, scientists related to its creators, were mistaken. As this issue was examined repeatedly for a long time on pages of the journal "*Physics-Uspekhi*" (see, e.g., [69-71]), here I will give only short explanations useful for us in the future.

Thus, several postulates of quantum mechanics are often forgotten, as well as that it is intended for the behavior of closed systems description. The very object of its study, namely [72]: "…the object of quantum mechanics is the motion of particles" is also often forgotten. Not only particles themselves are meant, but also their ensembles [72].

The requirement that the system be closed may grow into a serious technical problem. The system under study should be completed to the closed one, and, as it was rightly noted in [73], this addition may be "the rest of the Universe", provided that the Universe is considered as a closed system, which is by the way problematic. Thus, any reduced description of a system under study with the use of quantum mechanics is strictly speaking approximate, at least for this reason (see above). Why did this problem arise? From the author's point of view, if you want, "the salt" of quantum mechanics expressed in a simple and absolutely correct statement: "Everything* interacts with everything!" That is why, applying quantum mechanics, we need to explicitly or implicitly introduce approximations (which are the next steps of idealization) in order to analyze more simple studied systems.

Forgetting about the subject of quantum mechanics, some authors may come to the conclusion that it "doesn't work" for the macroscopic objects. Indeed "head-on" it may "not work" correctly. This is mainly how various paradoxes, like Schrödinger's cat, appear. In this connection only two facts, known from textbooks, should be mentioned:

1) The equations of classical mechanics are derived from those of quantum mechanics in certain conditions (assumptions) that, as a rule, hold true for macroscopic bodies (see, e.g., [72]). This means that such conditions

* Particles and their ensembles are meant.

(assumptions) are acceptable in the transition from a rigorous model (quantum mechanics) to a simpler one (classical mechanics).

2) The solid state physics is based on the laws of quantum mechanics in certain assumptions (see, e.g., [74]), the validity of which is traditionally established after comparing the respective theory with the experiment, i.e. actually after validating of this or that simplification.

Thus, in both cases, quantum mechanics "works", nevertheless, the use of it is very difficult, and often just technically impossible (see further) , i.e., in many cases, it is far too detailed. However, it should be noted that this problem is of technical* and not of principle character. Hence, in the cases mentioned above and the cases alike, it is desirable to use simpler and more less adequate approximate models, which follow from quantum mechanics. Consequently, it is more than sufficient to apply quantum mechanics as physical and mathematical basis of at least two scientific disciplines mentioned above.

The use of quantum mechanics as the basis of the band theory of solids is an illustrative example of its correct application. Quite briefly, the application scheme consists in the following (see, e.g., [75]). A crystal, which is a system of light (electrons) and heavy (nuclei) particles, is described by a wave function depending on their coordinates. Then the Hamiltonian of the system writes down, taking into account the dominant interactions. The corresponding multi-particle stationary Schrödinger equation (even ignoring the influence of electron and nucleus spins) contains 3(Z+1) N coordinates of the particles, where N is the number of atoms in the crystal, Z is the atomic number of the element in the periodic table. When considering that the estimated number of atoms in 1 cm^3 is about $5 \cdot 10^{22}$, for Z=14 the number of variables in this case is about $2 \cdot 10^{24}$ [75], i.e. fantastically large. Clearly, even having completed at least the initial two steps of idealization (see above), it is impossible to solve the obtained Schrödinger equation, at least at the present stage of development of computer machinery, as well as in the nearest future. That is why sufficiently serious approximations (adiabatic Born – Oppenheimer approximation, one-electron approximation) are introduced. As a result, a simplified one-electron *Schrödinger-type* equation for the envelope wave function is obtained. It should be pointed out that for this function, the superposition principle may not hold true. Perform a consistent examination of the system in the paradox of Schrödinger's cat

* Certainly, it differs from the technical problem of the second step of idealization (see earlier).

(describe the cat as an ensemble of particles, etc.), derive, if you can, the equation which provides an agreement with the experiment and make sure that the cat is dead or alive, depending on the ampoule with poison integrity*.

It is also expedient to comment on the wave function reduction. Indeed, it is a very convenient phenomenological procedure, which may well be released in quantum mechanics (see, e.g., [76, 77]). It is very convenient when considering measurements, as it can significantly simplify the description of the system under study within the framework of a compound system (the system under study and the measuring instrument). You can also take a more rigorous approach, if you like. Then you should proceed to the description based on the statistical operator (density matrix) or a more complicated system, initially for wave function. It is important to stress that J. von Neumann was the first to examine this problem correctly (see his fundamental monograph [56], chapter V in particular).

Despite the accepted second hypothesis of the sufficiency, the rigorous application of quantum mechanics to the description of brain functioning, as well as to solids (see above), unfortunately is practically impossible for the same reason. Particularly, the number of interacting molecules in 1 cm^3 of the brain is approximately of the same order as the number of atoms in a crystal, i.e., about 10^{22} (see above). In mathematics similar on complication problems are called NP class problems. In view of the above, we shall accept the third hypothesis: *rigorous mathematical description of brain functioning with the use of quantum mechanics is an NP class problem.* Unfortunately, at present this hypothesis cannot be proved**.

Thus, *apart from the two steps of idealization* (the first one – unavoidable, the second one – technical, see above*), the following considerable idealizations in a theoretical study of brain functioning on the basis of quantum mechanics are actually forced.* Unfortunately it is not only because a rigorous examination of brain functioning on the level of molecules is impossible. It is also practically unfeasible on the much simpler level of interacting neurons, first of all due to their enormous number (see above).

Also note the two difficult problems. Firstly, in the external action mode (see above), it is necessary to study interactions within a complex composite system, namely: "object – sensory system – brain". This problem was firstly examined by the classics

---

* It should be noted that usually another explanation of the paradox is given in the literature.

** By the way, it is typical of the problem of the kind (see, e.g., [78]).

(W. Heisenberg, N. Bohr, J. von Neumann and others) and represents exceptionally difficult quantum mechanical problem [62].

Secondly, according to the accepted interpretation, the brain is a very complex set of nonlinear electrical neuronal circuits, as many of them can be modified during functioning. It should be noted that even elementary non-modifying nonlinear electrical circuits are quite difficult to analyze [79, 80].

How can one analyze such highly complex systems? Is it possible? A generally accepted approach is that complex systems should be studied by decomposition approach. The decomposition methods are effectively used in solving various problems (in electrodynamics [81], quantum mechanics, the studies of multiatomic molecules etc. [82]), including the analysis of nonlinear electrical circuits [82] and integrated circuits of different integration [83-86], which is of special importance for us.

Thus, at present, successfully developed ULSIs with the number of elements more than 10^9 on the chip are produced. Though this number is still far less than that of neurons in human brain as was mentioned, the IC is still the closest artificial analogue of it. What is more, ULSI simulation problem can also be classified as an NP class problem. It should be mentioned here that there is no doubt among experts in micro- and nanoelectronics that the development of ICs with a higher integration compared with noted will successfully further continue according to Moore's law [87].

Hence, the information above allows one to conclude that *human has a long-term positive experience in dealing with such problems, while not that complex, in micro- and nanoelectronics*. Particularly, this refers to the study* of ULSI.

In this connection, here it is desirable to describe briefly at least simulation (computer-aided design) principles for modern ICs (for detailed information see, e.g., [83-87]). For the decomposition of the IC description the different levels (degrees) of detail are used. On each of them the hierarchy of models can be used. Bearing in mind that the problem is classified as an NP class, such decomposition cannot be unique. Consequently, it is impossible to create a unique universal simulation (computer-aided design) methodology which can be implemented successfully on modern computers, at least for ICs with high integration level, and for ULSIs in

* It is of interest that ULSIs are man-made, unlike the brain. In view of that, the problem for the brain is easier, at least at this stage.

particular. As a result, there exists a variety of methodologies, and hence the possible structures of the IC computer-aided design systems are not unique. Nevertheless, the following basic IC simulation (design) levels are often marked out [84,86] (see Table 1). The numeration starts from lower hierarchy levels (the higher level of detailing). For the sake of comparison Table 1 also gives basic levels of brain study (in fact, special disciplines).

Table 1

Basic levels of object study

Brain	Modern ICs
	6. System
2. Neuropsychological	5. Topological layout
	4. Functional and Logic
	3. Circuit
	2. Device
1. Neurophysiological	1. Technology

Thus, because it is impossible to solve the problem rigorously, *modern IC simulation is hierarchical on the whole, i.e., between levels (multilevel), and in particular, i.e., within one level a hierarchy of models is commonly used. Besides, various modern experimental methods and equipment are intensively used.* There are many reasons for that. The most important ones are as follows: initial data errors and compensation for "losses" in models adequacy because of the above mentioned reasons, as well as simulation errors, etc. From the point of view of the author this combined approach is the most promising for further study of the brain, i.e. electrical circuits of type I, despite all the serious problems described above.

Let us go back to Table 1. As follows from it, a higher number of hierarchal levels are involved in ULSI analysis. Besides, the key level is that of circuit simulation, i.e., the level of electrical circuits. It is very important (see below). Despite the much more complexity of the brain, it is studied only at two levels*. Consequently, the subdivision in this case is rather rough, which was mentioned by some of the researchers of brain.

* Of course, only main special disciplines are meant.

This rough subdivision into two levels results in our present progress in the study of the brain which is beautifully and creatively described by the following quotation [31]: “Right now all that we can do is establishing correlations: Pattern X is associated with behavior model Y”. In this respect the estimation of R. Solso, one of the known specialists in cognitive psychology, on the common approach in this field is very characteristic, namely [17]: “Many cognitive psychologists involuntarily committed such the jumps from empirical data to hypothetical constructions; and some have consciously and willingly make on the basis of the available data different conclusions (and hence envision different models)”.

Nevertheless, the author’s opinion is not so pessimistic. In fact, remarkable results* have been obtained in neurophysiology, neuropsychology, and psychology. These results can be and must be used within the framework of a combined hierarchal approach to the study of the brain. Of course, should be more levels. And here, broadly speaking, as the problem is NP class, many variants of decomposition are possible. It should be noted that the principles of decomposition may be different as well on the basis of the views upon brain functioning.

Hence, within the framework of neurobiology, the author considers the division into levels of organization of the nervous system, given in the remarkable book by G. M. Shepherd, an outstanding American neurobiologist, to be quite suitable (Figure 1.6 [88]). It is interesting to note that the type of charge carriers aside from, there are also six levels here (Figure 1 compare with Table 1, right column). Other variants of course are acceptable (see below).

What does inspire some confidence in the possibility of successful multilevel brain simulation? Apart from the stated above, the main idea, in general, very aptly and vividly expressed in the following words of the outstanding researcher of the brain D. Hubel [11]: “…the enormous complexity of nervous system is almost always accompanied by a certain degree of orderliness”. Thus, it was established in neurophysiology, neuropsychology and neurocybernetics [7, 11-14, 19, 28, 32, 89, 90] (see also above) that the brain is characterized by a certain hierarchy of its systems at different levels with multiple vertical, horizontal and inverse connections. This indicates that Nature had no other way, because otherwise the brain would not

* I should mention that if it were not for these results the book would not be written.

be able to process the enormous flows of input information*. A very powerful, efficient and economical hierarchal system of information processing and storage was needed, i.e., the brain.

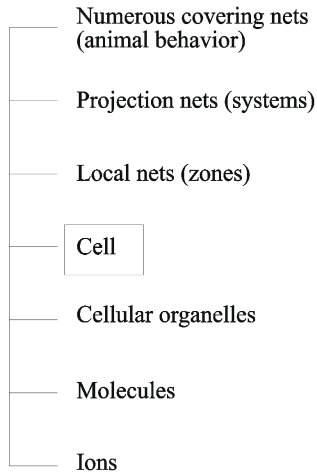

Figure 1. The organization levels of the nervous system [88].

The research of crucial importance was carried out by an outstanding American neurophysiologist V. Mountcastle, who demonstrated that the brain cortex applies the similar principle for processing signals of different modalities (visual, auditory, etc.).

According to V. Mountcastle [39]: “The general idea consists in the following. Large structures in the brain, known as nuclei (or regions) of the neocortex, limbic lobe, dorsal thalamus, etc., they are made from the repetitive *local neural ensembles* or modules, varied from one large structure to another in the number of cells, internal links, and the procession mode, but which are basically similar within one structure (Szentagothai, Arbib, 1974; Szentagothai, 1975). Each module is a local neural ensemble that processes the information and transfers it from its input to output, wherein transforming it in accordance with the general properties and the external links of the structure. The modules are combined into structures – e.g., nuclei or the cortex areas, – by a common or dominant connection, the necessity to impose the function on a certain topographic representation, or by some other factor. The set of

*So, the estimates show “the visual system alone can transfer to the brain $4.3\cdot10^6$ bits of information per second” [17].

modules that make up the structure can be divided itself into subgroups by different connections with similarly separate subgroups in other large structures. In this way, closely and multiply interconnected subgroups of modules in different and often distant structures form precisely connected, but distributed systems. Preserved neighbor relations between the interconnected subgroups of topographically arranged structures lead to the formation of "cluster" distributed systems. *Such distributed system is intended for maintaining the distributed function.* One module of the structure can be a part of several (but not many) systems of this type. All modules of the set can have the identical connections only in frontier case.

I intend to consider these ideas, in particular, to the consideration of the neocortex, and to analyze the general conception that the processing function performed by the modules of the neocortex is qualitatively similar for all regions".

It is also important for us to note that V. Mountcastle defined "the basic modular unit of the neocortex as a minicolumn" which contains about 110 – 260 neurons [39]. However, there exist much larger units called "macrocolumns" the number of which in the neocortex is about $6 \cdot 10^5$, "each packaging several hundred minicolumns" [39].

What could be the principle of the multilevel brain simulation system, for instance, psychic functions, according to the accepted electronic interpretation? Firstly, let us estimate, if only roughly, the complexity of the electrical circuit of type I. As is known, "during the mental processes the ensembles about 10^5–10^6 neurons are excited" [3]. A more pessimistic estimation is possible. It has already been mentioned that the number of zones involved in mental activity is about 10^3–10^5. Taking into account that, according to V. Mountcastle (see above), a zone may be formed by microcolumns and macrocolumns, the lower limit is also 10^5, while the upper limit is considerably higher, about 10^9. It is interesting to note that even the upper (pessimistic) limit corresponds to the integration level of modern ULSIs. Thus, *one may cautiously forecast that the problem of mental process simulation is possible in principle.*

With the foregoing as background, it is reasonable to begin with a certain combination between the levels given in Table 1 (right column) and Figure 1. Hence, local nets (zones) (in accordance with the accepted terminology, electrical circuits of type I, comprising a small number of neurons), may apparently be simulated at the circuit level[*]. To do this, it is necessary, first of all, to develop a library of element models (in terms of micro- and nanoelectronics); it is done at the device level, the second level in Table 1 (right column). Actually, one should create numerous electrical models[**] of the following elements (see above): ion channels, axons, dendrites, spines, synapses, cell bodies, etc. Besides, in principle it is possible to take into account the effects of chemical, thermal and other important processes. After the simulation at the circuit level is accomplished, macromodels of local circuit are formed, and we transfer to the next simulation level, for example with regard to Figure 1, it is the level of projection nets (systems), etc.

First of all I should note here that in multilevel IC simulation it is lower hierarchical levels that are most difficult to develop, i.e. 1 and 2 (Table 1, right column) [84, 86]. Hence, it suffices to note that the lowest technology level for the brain corresponds to the level of the neuronal circuit formation simulation. It is an extremely difficult (fantastic) problem, as it actually requires simulation of the full history of their formation, including the above-mentioned 8 stages of development.

The second hierarchical level, i.e. device level is also quite difficult to develop. The world experience in the field of microelectronics, and nanoelectonics, particularly, in device simulation confirms that. The author provided a detailed analysis of the problem in the series of articles [23, 91]. Thus, a well-known simulation system NEMO, developed to some nanoelectronic devices, has been created in the USA since 1993 (at present under the patronage of NASA) and intended for use on supercomputers. Under the guidance of the author the NANODEV system has been developed since 1995 [92,93]. It is a system for simulation of nanoelectronic devices based on the single-electron and resonant-tunneling effects, and quantum wires. Here, the problems mostly arise in connection with the necessity to develop complex combined models, and common cases involve interactions between nanostructures (active regions) and macroscopic regions, i.e., quantum measurements in the sense, traditionally accepted in quantum mechanics, take place. Experts know this to be a challenging problem. Besides, it is advisable to develop model hierarchies of different adequacy. As a result, the works are time-consuming.

[*] If it is failed (large needed computing resources), the circuit is divided into subcircuits with a smaller number of elements. This is common practice in IC simulation.
[**] The definition of the electrical model which is based on equivalent circuits see in [84,86].

According to the noted above, ion channels – complex nanoelectromechanical systems – are the key elements of neuronal circuits. It is expedient to apply multilevel simulation to analyze them in detail. This approach proved to be successful in simulating another relatively complex nanoelectromechanical system, particularly, a radio receiver based on carbon nanotubes [94]. Though this problem also required the use of powerful computers, the application of licensed software, developed earlier, was important in this case. It allowed the authors to solve this sufficiently difficult problem quickly.

So, what do we have? Won't the above mentioned cautious prediction come true?

The author believes that it may, in spite of the extreme difficulties, particularly at lower hierarchical levels, described above. However, the "price" for success is further simplifications (further steps of idealization), at least at early stages of development. It is important to note here that in IC simulation, levels 1 and 2 are not realized in detail as a rule, but "cunningly" avoided. To achieve this combined* (empirical to a large extent) device models (like BSIM2,…, BSIM5 [95]) are applied. In this case, by setting the main design, technological and other parameters one immediately transfers to level 3, i.e., the circuit level, leaving behind levels 1 and 2. Hence, in brain studies it is advisable to develop similar electrical models of basic neuronal circuit elements, depending on morphological, neurophysiological and other data. It is evident that the most up-to-date equipment should be used.

It is worth mentioning that nowadays a wide range of experimental methods and various equipment is used, namely [12, 16, 17]: brain scanning methods (computer tomography, positron emission tomography, magnetic-resonance imaging), electroencephalography, electrical stimulation of the brain with the use of microelectrode technique, chemical substances and medicines, studies based on brain damage and brain pathologies, etc. It is of relevance here that back in the 1960s, academician N. P. Bekhtereva and colleagues introduced a complex approach to the study of the brain, based on various experimental methods [19, 36]. Nevertheless, the author believes that qualitatively new opportunities will appear in connection with more intense use of achievements in nanoelectronics, nanophotonics, nanotechnology and nanomaterials. Wonderful examples confirming this are the applications of

* Such, strictly speaking, combined models include components of electrical, based on equivalent circuits, physical, and formal models with intensive use of experimental data. But electrical models remain basic, because these combined models are developed for circuit simulation [86]. For this reason, further they are referred to as electrical models.

optogenetics and nanowires [31]. One of the most important reasons for such development is that many experimental data obtained in special areas of brain studies need to be checked up or just revised due to obvious contradictions*.

Thus, *having developed electrical models of neuronal circuit elements also with the use of the most up-to-date equipment in accordance with the accepted electronic interpretation, one will be able to simulate a great deal of brain behavior at the circuit level, i.e. nonlinear electrical circuits of type I.* After the realization of this main stage, as noted it becomes possible to transfer to higher hierarchical levels in order to simulate more complex functions. It should be noted that not only approaches and methods used in the similar studies of ICs, i.e., the accumulated experience in this field may be applied to the proposed multilevel simulation approach, but also a lot of developed software. It is extremely important, as it may significantly facilitate the study of the brain.

Will numerous models developed earlier in biophysics, neurophysiology, neuropsychology, neurocybernetics (see, e.g., [6, 12, 17, 19-22, 27, 32-34, 36, 40, 89, 90, 96-109]) be of use here? In spite of some chaotic character of their development, they certainly will. The author's belief is related to the fact that in view of the above, including the second hypothesis, the most successful models in these fields, and they are a lot, can be considered as macromodels, which likely may be obtained from more rigorous models that are quantum mechanical ultimately, through simplifications. Consequently, these successful models may be incorporated into the multilevel simulation of the brain. Because of the extreme difficulty of the problem, the synergetic approach is quite promising [46, 110]. Nevertheless, the situation can be accurately described by the forty years ago words of outstanding American neurocyberneticist M. Arbib [89]: "…our models are still too rough and simplified in comparison with the complexity of the brain". Unfortunately, at present there is a great deal of phenomenology and poorly grounded guess-work here.

Summing up the analysis above, the author will briefly answer the following question: "What instills the confidence in the possibility that the problem of a more detailed study of brain functioning can be solved?"

I will note only three main arguments.

---

* Unfortunately, many of the experimental techniques used in brain study are rather rough even now.

Firstly, we possess a unique and very powerful quantum mechanics formalism which has never failed when applied correctly to most diverse and difficult problems. It has also provided a reliable basis for such research. Secondly, the data given above prove the structuredness of the brain, the hierarchical nature of its functioning, the presence of a common processing principle for input information of different modalities (visual, auditory, olfactory, gustatory and tactile). Thirdly, we have accumulated considerable experience in solving similar problems in micro- and nanoelectronics. It is of relevance to mention here J. von Neumann's words on the brain wrote more than 60 years ago: "We have absolutely no past experience with systems of this degree of complexity" [21]. But now we are able to abandon the "frog's view perspective" [21] in brain studies.

I consider here that it is useful to make two additional comments that follow from the mentioned experience. Firstly, as evidenced by the analysis above, a highly detailed simulation of brain functioning is hardly possible. However, though we deal with an extremely difficult problem of electronics, we will succeed in studying the most important aspects (mechanisms) of brain functioning, just as we do in ICs analysis with high integration level. It should be noted here that in the latter case we do not know everything either and we will never know. Secondly, the experience in micro- and nanoelectronics proves that the transition to technological norm smaller than 100 nm appeared to be less complicated than it seemed earlier. Moreover, specialists are aware that a "campaign" to achieve even the submicron technological norm in microelectronics was considered hardly possible, not to mention a nanometer scale. Thus, it is likely that brain study will be less difficult than it seem now. The most important for us is appropriate to follow the suggested approach, i.e., that of multilevel simulation of the brain within the framework of the proposed full electronic interpretation.

5. What's further?

We can define lots of interesting problems related to the brain. It is simply impossible to consider all of them in this book. So, we shall briefly dwell on several sets of such problems.

About direct research of the brain itself. The key problems of this research were distinguished by many scientists. I will mention here only "two main problems of physiology" defined by V. Mountcastle [39]. Following this outstanding neurophysiologist and based on the analysis of the literature and the above consideration, I will highlight two main directions (problems) for further study of the brain itself, namely:

1) it is necessary to elucidate the main details in the formation and functioning of local neuronal ensembles (conditionally the *microlevel* of the research);

2) it is necessary to understand how various mental processes are initiated and controlled and what brain structures in what succession are involved in this (conditionally *macrolevel* of research).

Speaking about the first problem a lot has been done, however, the modern data of neurophysiology indicate that many issues still remain vague [12]. The second problem is by no means less exciting, as one has to understand the complexity of the cooperative functioning of different brain subsystems and, at the same time, independence of their functioning, i.e. in this unique "great orchestra", including its "conductor". In view of the considered multilevel approach to simulation of the brain and within the framework of the suggested full electronic interpretation of its functioning, the first problem relates to the lower hierarchical levels, while the second one – to the higher ones.

About the contact systems "brain – artificial object" and "brain – artificial object – brain". A lot of works, including science fiction as well as serious scientific publications, in fact, deal with this issue. Suffice it to mention the fundamental theory of voluntary and involuntary reflex actions, developed by Ivan Michailovich Sechenov and Ivan Petrovich Pavlov, greatest Russian physiologists [1, 111]. For this reason, we shall dwell on the results that are the most important for our consideration.

First of all let us recall the research into electrical stimulation of the brain (ESB) using electrode (microelectrode) implantation technique [8, 18, 19]. As mentioned above, ESB can cause a wide range of reactions, including psychic.

Pioneer experiments performed by J. Delgado and co-workers aroused great interest, based on a microelectrode technique by using the "stimoceivers" – miniature radioelectronic devices "that transmitted and received radio signals directed to the brain and back from it" [8]. They performed experiments mainly on monkeys and even used computers. These experiments confirmed that "direct communication can be established between brain and computer, circumventing sensory organs, and also that automatic learning is possible by feeding signals directly into specific brain structures without conscious participation" [8]. Not less impressive was the video "repeatedly demonstrating that cerebral stimulation produced inhibition of aggressive behavior, and a bull* in full charge could be abruptly stopped" [8].

Nevertheless, some behavioral acts were not obtained [8,18,19]. The pioneer researchers attributed this to the crudity of the method. So J. Delgado wrote [8]: "Electrical stimulation of the brain is in reality a rather crude technique". Indeed, within the framework of the suggested interpretation, it is likely that two conditions must be fulfilled in order to evoke certain complicated behavioral acts. First, the stimulus must be applied to a strictly determined point (site) of the neuronal circuit, or possible to the combination of points determined in space and in time by a signal (signals) of a certain form (current, voltage, frequency, etc.). Second, better electrodes must be used, e.g. as nanowires, which enable connection to even strictly determined point of a separate neuron, i.e., to the required site on the element of the electrical circuit** of type I (see earlier). In any case, real progress can be made along these directions. At the same time, it is known [19] that, in currently used microelectrode technique, large arrays of neurons are simultaneously excited, as a rule. In this regard other result seems surprising. How rather complicated behavioral acts were obtained at all? Their experimental observation*** supports the opinion that the brain is not that a "refined device", as it is many considered, and on the other hand, probably, that multilevel simulation approaches provide rather convincing

* The bull here refers to the brave bull, "an animal species which for generations has been bred to increase its ferocious behavior" [8].

** Obviously, more or less rigorous electrical model of even a single neuron should be represented as quite a complicated distributed equivalent electrical circuit. So, we shall speak about a definite point of the electrical neuronal circuit.

*** It is likely that a well-known dominant phenomenon [10] is realized in these investigations.

results, even if they are based on not very detailed models, including the above-described scheme.

Despite relative crudity of the ESB method based on microelectrode technique, its use enabled significant results in medicine. Suffice it to mention cochlear implants for losing a hearing people, used to restore hearing with much success, "that have become an undeniable evidence and a vivid example of the integration of humans and computers" [31]. This success is related to the replacement of the lost cochlear hair cells by cochlear implants, i.e., to rather highly localized action in this case, which indirectly confirms that the two conditions defined above should be fulfilled.

In view of the foregoing, the author believes that time will come when human thoughts will be possible to read and apprehend by other humans using artificial objects (devices). Here, of course, many problems will be encountered. One of the most interesting problems will deal with the differences in encoding information in the brain of different people, which are determined by the peculiarities (individual features) of the neuronal circuits (see above). This is a compatibility problem similar to that in human handwriting*. I think that in this case not only artificial devices can be useful, but also the brain directly of the person receiving the information, owing to the brain's major feature – plasticity. This means that it will be needed a certain amount of time for comprehension, adaptation, i.e., learning how to perceive the information such way. The problem of information recording directly from brain to brain seems to be as complicated as that of information transmission and perception. This will require the development of devices transforming different signals (optical, acoustic, chemical, etc.) directly into the brain codes. Nevertheless, the author considers that and these problems will be solved. For this reasons, I see the creation of the World Wide Mind [31] as quite a realistic project rather than a kind of science fiction. And here significant progress can be achieved using nanoelectronics, nanophotonics, nanomaterials, and nanotechnologies. Use of nanowires and optogenetics [31] can be regarded as the start of this process.

Let us note in conclusion that the division between the two sets of problems defined above is quite conventional because the real success in brain research can only be achieved when the interaction between the brain and other objects is taken into account.

* It is possible that the coding differences vividly reveal themselves in handwriting exactly.

Now let us briefly dwell on the development of artificial brain-like objects. This problem is most popular in literature on cybernetics and artificial intelligence. Dynamic of views of this problem is well reflected by the following phrase of M. Arbib [112]: "…many differences between humans and machines that seemed significant until recently are just quantitative". Though generally it is true, we have, however, as demonstrated earlier in this book that there are important and qualitative differences between the IC and the brain. One of the most remarkable differences is the ability of flexible modification of electrical neuronal circuits of type I. Nature created a very "sly" electronics – an original transceiver* in one object – a masterpiece based on the interaction of electrical and chemical processes. Unfortunately, we have to admit that it is impossible today to strictly prove that similar artificial objects can also be created.

Nevertheless, we can bring additional arguments set by the optimists in the area under consideration (see, e.g., [5, 31, 43]). According to the above, mental activities, all appearance, are macroscopic collective phenomena in nonlinear electrical circuits of type I. If so, it is pertinent to recall the words of H. Haken, an outstanding German scientist, one of the founders of synergetics, namely [46]: "…from the abstract viewpoint of synergy, the cooperative effects can lead to the same macroscopic behavior of the systems with quite different microscopic components, and only the order parameters are important". Based on these two premises, we can make a far-reaching conclusion that the brain-like systems can also be realized artificially! It does not seem out the question that system elements can also be realized not necessary on similar from those selected by Nature. Perhaps, the identified differences between electrical circuits of type I and those of type II, which have been outlined in this work, may assist in making advance in this field.

The direction for the development of artificial objects mentioned here will be connected with the technologies based on the "up-to-down" and "down-to-up" processes or their combinations. Anyway it is indicated by positive experience in micro- and nanoelectronics and nanotechnologies (see, e.g., [91,113]).

However, a qualitatively different, much more effective approach is possible, which the author called "from available" [91]. This approach consists in modernization or modification of natural biological processes. It should be pointed out that implicitly

* As in receivers (radio receiver, TV set, etc), here information processing and reproduction are also important.

this approach has successfully been used in medicine for a long time. Examples can serve numerous medicines, improving the brain function, cochlear implants for deaf people, etc. In a certain sense it is possible to replicate Nature's creation (to be more precise, to "outsmart" Nature), i.e., to do exactly such system as human, certainly including the brain. In fact, it is cloning, but do we really need it? (see below).

Here it seems appropriate to dwell briefly on another grand problem: quantum computers. The view upon this problem can be shortly characterized by phrase "from euphoria to growing pessimism". A detailed consideration of this problem is given by academician K.A. Valiev, an outstanding Soviet-Russian scientist in micro- and nanoelectronics, and his colleagues [114,115]. So here I would like to stress one important issue that is usually overlooked. Analyzing ballistic transport in nanotransistors [91], the author pointed out that, according to quantum mechanics, any interaction of particles can be considered as a collision and will occur even in vacuum with permanently created and annihilated particles, i.e., in fact such transport is a usable idealization. Certainly, this doesn't evidence that quantum computers cannot be realized in principle, but it adds "a blot on the landscape". But work in this direction should continue, nevertheless. Here I fully agree with professor M.B. Menskii [65]. It is known from history that the rigorous proof of the impossibility to construct a perpetuum mobile of the second kind, on the one hand, led to creation of thermodynamics, – a powerful part of physics. On the other hand, the efforts undertaken in this direction resulted in very interesting achievements in physics, mathematics, electronics and other fields [114,115]. So it seems that this is another at least "marathon problem"; simply one should not hope for quick success.

Let us say some words about the mysteries of the brain – mythic, mysterious, and real that produce a beautiful effect (see, e.g., [13,16,35, 116-118]). Really, the author supports the opinion of D. Myers [16], in the majority of cases most of these "phenomena" appear to be just "soap bubbles" – incorrect data or explained by random coincidences. Nevertheless, there are some serious questions related to extrasensorics (see, e.g., [117]) that are not satisfactory answers jet. Science should treat these problems with more care, at least because in other case, we will see the increasing number of the opponents of science and especially so, because, as mentioned above, in brain studies there is an objective basis for speculations. Nevertheless, the author has no doubt that within the framework of the suggested full electronic interpretation of brain functioning, many phenomena can be explained by the peculiar character of operation of electrical (neuronal) circuits of type I.

Conclusions

As stated earlier, for rigorous consideration of brain functioning, one has to analyze very complex and unique "tangle" of numerous physicochemical processes, often interconnected. The suggested full electronic interpretation of brain functioning was offered in order to "disentangle" it. It is up to the reader to judge if this has been achieved. By analogy with the known computer [6,89] and holographic [49] metaphors* [89], the interpretation suggested in principle can be called the electronic metaphor. In this connection I just want to emphasize that I do not deceive myself and realize that the brain is much more complicated, in fact it is an arch-complicated system. No doubt, the considered problem is picturesquely said to be the "Everest** of Science". Thus it would seem that any details when "climbing" it can be important. Therefore pertinently to remember the words of Grey Walter, a great English physiologist, namely [2]: "When you speak about the brain better to proceed from situation that no insignificant phenomena exist". Many brain researchers adhered the similar point of view.

Though such influences on the brain as, for example, temperature, ionizing radiation, lighting, mechanical overload, atmospheric pressure, in principle can be taken into account within the framework of the suggested interpretation, much remains to be done to develop appropriate models, because many issues are not yet well understood. There are considerable obscurities in neurophysiology itself, particularly the role of neuroglial cells***, which are much larger in number (approximately by one order of magnitude) than neurons [41].

And nevertheless the author believes in usefulness of the electronic metaphor, except already noted, for the following reasons. First, it enables making progress in understanding the brain, helping to clarify the problem at least in general. Second, it offers a "natural bridge" to other important disciplines, in particular cybernetics (artificial intelligence and others) and artificial electronics. And in them there are a lot of the outstanding achievements having huge practical meaning which can be useful. And at last, third, the electronic metaphor may provide "a route for conquering the "Everest of Science"". Though this route is not that straightforward

* Critical comments on the computer and holographic metaphors are given in books [119] and [89], respectively.

** Similar comparisons with Everest, orchestra and conductor sometimes can be found in the literature (see, e.g., [118]).

*** They are likely to perform different additional functions [12].

and easy, it is quite realistic at this point in time. Mount Everest, as it is known, conquered step by step, i.e., from a lower level to a higher one.

In conclusion, let us mention ethical aspects of brain study. Many scientists wrote about it (see, e.g., [8,13,14,19]). This problem gains very serious, international character with the development of nanoelectronics, nanophotonics, nanomaterials, nanotechnologies, and nanoscience on the whole*. Even nuclear weapon can appear to be "nothing" compared with possible "incursion" into the most intimate sphere of a human being – his brain. It is clear that such brain research can be conducted only under the very rigid supervision of international community.

But let me finish my book on an optimistic note by the quotation from J. Delgado, an outstanding brain researcher, namely [8]: "There is one aspect of human research which is usually overlooked: the existence of a moral and social duty to advance scientific knowledge and to improve the welfare of human."

Acknowledgements

The author is grateful for the accurate translation of the monograph into English by K.O. Hanysh, I.Y. Shcherbakova and also N.V. Kolomejtseva, I.A. Romanova, I.Y. Shcherbakova for preparing the monograph for publication.

* Here it is pertinently mention the modern book on military nanotechnologies [120].

References

1. Sechenov I.M. Selected Works. M.: Gos. uchebno-pedagogicheskoe izdatelstvo Ministerstva prosvessheniya RSFSR, 1958. 416 p. (in Russian).
2. Грей Уолтер. Живой мозг. М.: Мир, 1966. 300 с. [Grey Walter W. The Living Brain. London: Pelican Books, 1963.]
3. Ivanov-Muromsky K.A. Neuroelectronics, Brain, and Organism. Kiev: Naukova Dumka, 1983. 175 p. (in Russian).
4. Мак-Каллок У. Надежность биологических систем. В сб.: Самоорганизующиеся системы. М.: Мир, 1964. С. 358–380. [McCulloch W.S. The reliability of biological systems. Self-Organizing Systems. New York: Pergamon, 1960.]
5. Вулдридж Д. Механизмы мозга. М.: Мир, 1965. 344 с. [Wooldridge D.E. The Machinery of the Brain. New York: McGraw-Hill Book Company, Inc., 1963.]
6. Нейман Дж. Вычислительная машина и мозг. Кибернетический сб. Вып. 1. М.: Изд-во иностранной литературы, 1960. С. 11–60. [Von Neumann J. The Computer and the Brain. New Haven, Connecticut: Yale University Press, 1958.]
7. Блум Ф., Лейзерсон А., Хофстедтер Л. Мозг, разум и поведение. М.: Мир, 1988. 248 с. [Bloom F.E., Lazerson A., Hofstadter L. Brain, Mind, and Behavior. New York: Educational Broadcasting Corp., 1985.]
8. Дельгадо Х. Мозг и сознание. М.: Мир, 1971. 264 с. [Delgado J.M.R. Physical Control of the Mind. Toward a Psychocivilized Society. New York: Harper & Row, Publishers, 1969.]
9. Куффлер С., Николс Дж. От нейрона к мозгу. М.: Мир, 1979. 440 с. [Kuffler S.W., Nicholls J.G. From Neuron to Brain. Sunderland, Massachusetts: Sinauer Associates, Inc. Publishers, 1976.]
10. Kogan A.B. The Physiology Principles of Higher Nervous Activity. M.: Vysh. shk., 1988. 368 p. (in Russian).
11. Хьюбел Д. Глаз, мозг, зрение. М.: Мир, 1990. 239 с. [Hubel D.H. Eye, Brain and Vision. New York: Scientific American Library, 1988.]
12. Николлс Дж.Г., Мартин А.Р., Валлас Б.Дж., Фукс П.А. От нейрона к мозгу. М.: Изд-во ЛКИ, 2008. 672 с. [Nicholls J.G., Martin A.R., Wallace B.G., Fuchs P.A. From Neuron to Brain. 4-th ed. Sunderland, Massachusetts: Sinauer Associates, Inc. Publishers, 2001.]

13. Luria A.R. An Introduction to Neuropsychology. Moscow: Moscow State University, 1973. 375 p. (in Russian).
14. Homskaya E.D. Neuropsychology. Moscow: Moscow University, 1987. 288 p. (in Russian).
15. Stolyarenko L.D. Basics of Psychology. Rostov-on-Don: Feniks, 2003. 672 p. (in Russian).
16. Майерс Д. Психология. Мн.: Попурри, 2006. 848 с. [Myers D.G. Psychology. 5-th ed. N. Y.: Worth Publishers, 1998.]
17. Солсо Р. Когнитивная психология. СПб.: Питер, 2006. 589 с. [Solso R.L. Cognitive Psychology. 6-th ed. Boston: Allyn & Bacon, 2001.]
18. Пенфильд В., Робертс Л. Речь и мозговые механизмы. Л.: Медицина, 1964. 264 с. [Penfield W., Roberts L. Speech and Brain-mechanisms. Princeton, New Jersey: Princeton University Press, 1959.]
19. Bekhtereva N.P, Gogolitzin Y.L., Kropotov Y.D., Medvedev S.V. Neurophysiological Mechanisms of Thinking : Reflection of thinking activity in neuronal spike activity. Leningrad: Nauka, 1985. 272 p. (in Russian).
20. Нейман Дж. Вероятностная логика и синтез надежных организмов из ненадежных компонент. Автоматы. Сб. статей. М.: Изд-во иностранной литературы, 1956. С. 68–139. [Von Neumann J. Probabilistic logics and the synthesis of reliable organisms from unreliable components. Automata studies. Princeton, New Jersey: Princeton University Press, 1956.]
21. Фон Нейман Дж. Общая и логическая теория автоматов. В кн.: Тьюринг А. Может ли машина мыслить? М.: Гос. изд-во физико-матем. литер., 1960. С. 59–101. [Von Neumann J. The general and logical theory of automata. Ed. by A. Taub, John von Neumann – Collected Works, 5. Pergamon Press, Oxford, 1961. P. 288–326.]
22. Фон Нейман Дж. Теория самовоспроизводящихся автоматов. М.: Мир, 1971. 384 с. [Von Neumann J. Theory of Self-Reproducing Automata. Ed. by A.W. Burks. Urbana and London: University of Illinois Press, 1966.]
23. Abramov I.I. Problems and principles of physics and simulation of device structures of micro- and nanoelectronics. Part I. Basic positions // Journal of Nano- and Microsystem Technique. 2006. No. 8. P. 34–37. (in Russian).
24. Anohin P.K. Selected Works. Philosophical Aspects of the Theory of a Functional System. Moscow: Nauka, 1978. 400 p. (in Russian).
25. Abramov I.I. The "element" term in micro- and nanoelectronics // Journal of Nano- and Microsystem Technique. 2008. No. 6. P. 2–4. (in Russian).

26. Nanotechnology, Metrology, Standardization and Certification in Terms and Definitions / Ed. by M.V. Kovalchuk, P.A. Todua. Moscow: Tehnosfera, 2009. 136 p. (in Russian).
27. Джаксон М.Б. Молекулярная и клеточная биофизика. М.: Мир, БИНОМ. Лаборатория знаний, 2009. 551 с. [Jackson M.B. Molecular and Cellular Biophysics. Cambridge University Press, 2006.]
28. Мозг. М.: Мир, 1984. 280 с. [The Brain. Scientific American. September, 1979.]
29. Chorayan O.G. Neuronal Ensemble (Idea, Experiment, Theory). Rostov-on-Don: Izdatelstvo Rostovskogo universiteta, 1990. 88 p. (in Russian).
30. Экклс Дж. Физиология синапсов. М.: Мир, 1966. 396 с. [Eccles J.C. The Physiology of Synapses. Berlin: Springer-Verlag, 1964.]
31. Хорост М. Всемирный разум. М.: Эксмо, 2011. 288 с. [Chorost M. World Wide Mind. Free Press, a division of Simon & Schuster, 2011.]
32. Ivanov-Muromsky K.A. Neurophysiology, Neurocybernetics, Neurobioinics. Kiev: Vissha shkola, 1985. 240 p. (in Russian).
33. Kashchenko S.A., Mayorov V.V. The Models of Wave Memory. Moscow: Knizhny dom “LIBROKOM”, 2009. 288 p. (in Russian).
34. Volkenstein M.V. Biophysics. Moscow: Nauka, 1981. 576 p. (in Russian).
35. Bernatsky A.S. The Mysterious and Paradoxical Brain. Minsk: Narodnaya asveta, 2011. 176 p. (in Russian).
36. Bekhtereva N.P. Healthy and Diseased Human Brain. Leningrad: Nauka, 1988. 262 p. (in Russian).
37. Vartanyan G.A. Problems in experimental memory control // Fiziologiya Cheloveka (Human Physiology). 1977. Vol.3, No 5. P. 789–795. (in Russian).
38. Ivanov-Muromsky K.A. Brain and Memory. Kiev: Naukova dumka, 1987. 136 p. (in Russian).
39. Эделмен Дж., Маунткасл В. Разумный мозг. М.: Мир, 1981. 135 с. [Edelman G.M., Mountcastle V.B. The Mindful Brain. The MIT Press, Cambridge, Massachusetts, 1978.]
40. Rapoport G.N., Hertz A.G. Biological and Artificial Mind. Moscow: Knizhniy dom “LIBROKOM”, 2011. P.I, 184 p.; P.II, 296 p. (in Russian).
41. Khomutov A.E., Kulba S.N. The Anatomy of Central Nervous System. Rostov-on-Don: Feniks, 2007. 315 p. (in Russian).
42. Stepanenko I.P. Fundamentals of Microelectronics. Moscow: Laboratoiya Bazovych Znanij, 2004. 488 p. (in Russian).

43. Хокинс Дж., Блейксли С. Об интеллекте. М.: ООО “И.Д. Вильямс”, 2007. 240 с. [Hawkins J., Blakeslee S. On Intelligence. New York: Times Books. Henry Ford and Company, 2005.]
44. Макдональд М. Научи свой мозг работать. М.: Эксмо, 2010. 304 с. [MacDonald M. Your Brain: The Missing Manual. O’Reilly Media, Inc., 2008.]
45. Blinkov S.M., Glezer I.I. The Human Brain in Figures and Tables. Leningrad: Meditsina, 1964. 472 p. (in Russian).
46. Хакен Г. Принципы работы головного мозга: Синергетический подход к активности мозга, поведению и когнитивной деятельности. М.: ПЕР СЭ, 2001. 351 с. [Haken H. Principles of Brain Functioning. Berlin: Springer-Verlag, 1996.]
47. Babmindra V.P., Bragina T.A. Structural Bases of Interneuronal Integration. Leningrad: Nauka, 1982. 164 p. (in Russian).
48. Guselnikov V.I. Electrophysiology of the Human Brain (lectures). Moscow: Vysshaya shkola, 1976. 423 p. (in Russian).
49. Прибрам К. Языки мозга. М.: Прогресс, 1975. 464 с. [Pribram K.H. Languages of the Brain. Englewood Cliffs, New Jersey: Prentice-Hall, Inc., 1971.]
50. Ферри Д., Эйкерс Л., Гринич Э. Электроника ультрабольших интегральных схем. М.: Мир, 1991. 327 с. [Ferry D.K., Akers L.A., Greeneich E.W. Ultra Large Scale Integrated Microelectronics. Englewood Cliffs, New Jersey: Prentice-Hall, Inc., 1988.]
51. Эйди У.Р. Организация мозга: мозг как шумящий компьютер. В сб.: Основные проблемы электрофизиологии головного мозга. М.: Наука, 1974. С. 350–366. [Adey W.R. Organization of brain tissue: is the brain a noisy processor? // Intern. J. Neuroscience 3, 271–284 (1972).]
52. Вайнберг С. Мечты об окончательной теории: Физика в поисках самых фундаментальных законов природы. М.: Издательство ЛКИ, 2008. 256 с. [Weinberg S. Dreams of a Final Theory. New York: Vintage books, A Division of Random House, Inc., 1992.]
53. Джеммер М. Эволюция понятий квантовой механики. М.: Наука, 1985. 384 с. [Jammer M. The Conceptual Development of Quantum Mechanics. New York: McGraw-Hill Book Company, 1967.]
54. Скалли М.О., Зубайри М.С. Квантовая оптика. М.: ФИЗМАТЛИТ, 2003. 512 с. [Scully M.O., Zubairy M.S. Quantum Optics. Cambridge University Press, 1997.]

55. Гринштейн Дж., Зайонц А. Квантовый вызов. Современные исследования оснований квантовой механики. Долгопрудный: Изд. Дом “Интеллект”, 2008. 400 с. [Greenstein G., Zajonc A.G. The Quantum Challenge. Modern Research on the Foundations of Quantum Mechanics. Boston: Jones and Bartlett Publishers, Inc., 2006.]
56. Фон Нейман И. Математические основы квантовой механики. М.: Наука, 1964. 368 с. [Von Neumann J. Mathematische Grundlagen der Quantenmechannik. Berlin: Verlag von Julius Springer, 1932.]
57. Гинзбург В.Л. “Физический минимум” – какие проблемы физики и астрофизики представляются особенно важными и интересными в начале XXI века? // УФН. 2007. Т. 177, № 4. С. 346. [Ginzburg V.L. “Physical minimum” — What problems of physics and astrophysics seem to be especially important and interesting at the beginning of the XXI century? // Phys. Usp. 50, 332 (2007).]
58. Пенроуз Р., Шимони А., Картрайт Н., Хокинг С. Большое, малое и человеческий разум. М.: Мир, 2004. 191 с. [Penrose R., Shimony A., Cartwright N., Hawking S. The Large, the Small, and the Human Mind. Ed. by M. Longair. Cambridge University Press, 1997.]
59. Волькенштейн М.В. Дополнительность, физика и биология // УФН. 1988. Т. 154, вып. 2. С. 279–297. [Volkenstein M.V. Complementarity, Physics and Biology // Sov. Phys. Usp. 31, 140–150 (1988).]
60. Иваницкий Г.Р. XXI век: что такое жизнь с точки зрения физики // УФН. 2010. Т. 180, № 4. С. 337–369. [Ivanitskii G.R. 21st century: what is life from the perspective of physics? // Phys. Usp. 53, 327–356 (2010).]
61. Реутов В.П., Шехтер А.Н. Как в XX веке физики, химики и биологи отвечали на вопрос: что есть жизнь? // УФН. 2010. Т. 180, № 4. С. 393–414. [Reutov V. P., Schechter A. N. How in the 20th century physicists, chemists and biologists answered the question: what is life? // Phys. Usp. 53, 377–396 (2010).]
62. Менский М.Б. Квантовая механика: новые эксперименты, новые приложения и новые формулировки старых вопросов // УФН. 2000. Т. 170, № 6. С. 631–647. [Menskii M. B. Quantum mechanics: new experiments, new applications, and new formulations of old questions // Phys. Usp. 43, 585–600 (2000).]

63. Менский М.Б. Концепция сознания в контексте квантовой механики // УФН. 2005. Т. 175, № 4. С. 413–435. [Menskii M.B. Concept of consciousness in the context of quantum mechanics // Phys. Usp. 48, 389–409 (2005).]
64. Менский М.Б. Квантовые измерения, феномен жизни и стрела времени: связи между "тремя великими проблемами" (по терминологии Гинзбурга) // УФН. 2007. Т. 177, № 4. С. 415–425. [Menskii M.B. Quantum measurements, the phenomenon of life, and time arrow: three great problems of physics (in Ginzburg's terminology) and their interrelation // Phys. Usp. 50, 397–407 (2007).]
65. Menskii M.B. Human and Quantum World. Fryazino: Vek2, 2005. 320 p. (in Russian).
66. Пенроуз Р. Новый ум короля: О компьютерах, мышлении и законах физики. М.: Издательство ЛКИ, 2008. 400 с. [Penrose R. The Emperor's New Mind. Oxford University Press, 1999.]
67. Пенроуз Р. Тени разума: в поисках науки о сознании. Москва–Ижевск: Институт компьютерных исследований, 2005. 688 с. [Penrose R. Shadows of the Mind. Oxford University Press, 1994.]
68. Отклики читателей на статью М.Б. Менского "Квантовая механика: новые эксперименты, новые приложения и новые формулировки старых вопросов" // УФН. 2001. Т. 171, № 4. С. 437–462. [Readers' comments on "Quantum mechanics: new experiments, new applications, new formulations" by M.B. Menskii // Phys. Usp. 44, 417–442 (2001).]
69. Fock V.A. On the Interpretation of Quantum Mechanics // Phys. Usp. 1957. Vol. 62, No 4. P. 461–474. (in Russian).
70. Ахиезер А.И., Половин Р.В. Почему невозможно ввести в квантовую механику скрытые параметры // УФН. 1972. Т. 107, вып. 3. С. 463–487. [Akhiezer A.I., Polovin R. V. Why it is impossible to introduce hidden parameters into quantum mechanics // Sov. Phys. Usp. 15, 500–512 (1973).]
71. Клышко Д.Н. Основные понятия квантовой физики с операциональной точки зрения // УФН. 1998. Т. 168, № 9. С. 975–1015. [Klyshko D. N. Basic quantum mechanical concepts from the operational viewpoint // Phys. Usp. 41, 885–922 (1998).]
72. Blokhintsev D.I. Fundamentals of Quantum Mechanics. Moscow: Nauka, 1976. 664 p. (in Russian).

73. Панов А.Д. О проблеме выбора альтернативы в квантовом измерении // УФН. 2001. Т. 171, № 4. С. 447–449. [Panov A.D. On the problem of selection of an alternative in quantum measurement // Phys. Usp. 44, 427–429 (2001).]
74. Ашкрофт Н., Мермин Н. Физика твердого тела. М.: Мир, 1979. Т. 1, 400 с.; Т. 2, 424 с. [Ashcroft N.W., Mermin N.D. Solid State Physics. New York: Holt, Rinehart and Winston, 1976.]
75. Kireev P.S. Physics of Semiconductors. Moscow: Vysshaya shkola, 1975. 584 p. (in Russian).
76. Blokhintsev D.I. Quantum Mechanics. Lectures about Selected Questions. Moscow: Atomizdat, 1981. 96 p. (in Russian).
77. Липкин А.И. Существует ли явление “редукции волновой функции” при измерении в квантовой механике? // УФН. 2001. Т. 171, № 4. С. 437–440. [Lipkin A .I. Does the phenomenon of “reduction of the wave function” exist in measurements in quantum mechanics? // Phys. Usp. 44, 417–421 (2001).]
78. Гэри М., Джонсон Д. Вычислительные машины и труднорешаемые задачи. М.: Мир, 1982. 416 с. [Garey M.R., Johnson D.S. Computers and Intractability. A Guide to the Theory of NP-Completeness. San Francisco: W.H. Freeman and Company, 1979.]
79. Andronov A.A., Vitt A.A., Khaikin S.E. Theory of Oscillations. Moscow: Nauka, 1981. 568 p. (in Russian).
80. Mathanov P.N. Basic Analysis of Electrical Circuits. Non-Linear Circuits. Moscow: Vysshaya shkola, 1977. 272 p. (in Russian).
81. Nikolsky V.V., Nikolskaya T.I. Decomposition Approach to the Problems of Electrodynamics. Moscow: Nauka, 1983. 304 p. (in Russian).
82. Крон Г. Исследование сложных систем по частям (диакоптика). М.: Наука, 1972. 544 с. [Kron G. Diakoptics. London: Macdonald, 1963.]
83. Kazennov G.G., Sokolov A.G. Principles and Methodology of LSI CAD Development. Moscow: Vysshaya shkola, 1990. 142 p. (in Russian).
84. Abramov I.I. Lectures on Integrated Circuit Elements Simulation. Moscow–Izhevsk: NITS “Regulyarnaya i Haoticheskaya Dinamika”, 2005. 152 p. (in Russian).
85. Kazennov G.G. Design Fundamentals of Integrated Circuits and Systems. Moscow: BINOM. Laboratoriya znanij, 2009. 295 p. (in Russian).
86. Abramov I.I. Lectures on Integrated Circuit Elements Simulation of Microelectronics. Saarbrücken: LAP LAMBERT Academic Publishing, 2012. 116 p. (in Russian).

87. International Technology Roadmap for Semiconductors: 1999 edition. Austin, TX: International SEMATECH, 1999; 2009 edition.
88. Шеперд Г. Нейробиология: В 2-х т. Т. 1. М.: Мир, 1987. 454 с. [Shepherd G.M. Neurobiology. New York: Oxford University Press Inc., 1983.]
89. Арбиб М. Метафорический мозг. М.: Мир, 1976. 296 с. [Arbib M. The Metaphorical Brain. New York: Wiley-Interscience, a Division of John Wiley and Sons, Inc., 1972.]
90. Сентаготаи Я., Арбиб М. Концептуальные модели нервной системы. М.: Мир, 1976. 200 с. [Szentágothai J., Arbib M.A. Conceptual Models of Neural Organization. A report based on a NRP Work Session, October 1–3, 1972. Boston: Yvonne M. Homsy NRP Writer-Editor, 1974.]
91. Abramov I.I. Problems and principles of physics and simulation of device structures of micro- and nanoelectronics // Journal of Nano- and Microsystem Technique. 2006. P. II. No 9. P. 26–36; 2007. P. III. No 1. P. 36–47, P. IV. No 2. P. 24–32, P. V. No 3. P. 57–70, P. VI. No 7. P. 10–24; 2009. P. VII. P. 14–29, No 8. P. 7–23; 2010. P. VIII. No 9. P. 27–37, No 10. P. 28–41, No 11. P. 29–42. (in Russian).
92. Абрамов И.И., Гончаренко И.А., Игнатенко С.А., Королев А.В., Новик Е.Г., Рогачев А.И. Система моделирования наноэлектронных приборов – NANODEV // Микроэлектроника. 2003. Т. 32, № 2. С. 124–133. [Abramov I.I., Goncharenko I.A., Ignatenko S.A., Korolev A.V., Novik E.G. and Rogachev A.I. NANODEV: a nanoelectronic device simulation software system // Russian Microelectronics. 2003. Vol. 32, No 2. P. 97–104.]
93. Abramov I.I., Baranoff A.L., Goncharenko I. A., Kolomejtseva N.V., Bely Y.L., Shcherbakova I.Y. A nanoelectronic device simulation software system NANODEV: New opportunities // Proc. of SPIE. 2010. Vol. 7521. P. 75211E-1–75211E-11.
94. Barkaline V., Abramov I., Belogurov E., Chashynski A., Labunov V., Pletezhov A., Shukevich Y. Simulation of carbon nanotubes and resonant excitation of their mechanical vibrations by electromagnetic field for nanoradio applications // Nonlinear Phenomena in Complex Systems. 2012. Vol. 15, No 1. P. 23–42.
95. Zakharov S.M., Masalsky N.V., Shafigulin M.M. Integrated Circuit Simulation Problems // Progress of Modern Radio Electronics. 2005. No 2. P. 43–50. (in Russian).

96. Экклс Дж. Физиология нервных клеток. М.: Изд-во Иностранной литературы, 1959. 300 с. [Eccles J.C. The Physiology of Nerve Cells. Baltimore: The Johns Hopkins Press, 1957.]
97. Джордж Ф. Мозг как вычислительная машина. М.: Изд-во Иностранной литературы, 1963. 528 с. [George F.H. The Brain as a Computer. Oxford: Pergamon Press, 1961.]
98. Росс Эшби У. Конструкция мозга. М.: Мир, 1964. 412 с. [Ross Ashby W. Design for a Brain. London: Chapman & Hall Ltd., 1960.]
99. Розенблатт Ф. Принципы нейродинамики. Перцептроны и теория механизмов мозга. М.: Мир, 1965. 480 с. [Rosenblatt F. Principles of Neurodynamics. Perceptons and the Theory of Brain Mechanisms. Washington, D.C. : Spartan Books, 1960.]
100. Штейнбух К. Автомат и человек (кибернетические факты и гипотезы). М.: Советское радио, 1967. 496 с. [Steinbuch K. Automat and Mensh. Kybernetishe Tatsachen und Hupothesen. Berlin: Springer-Verlag, 1965.]
101. Катц Б. Нерв, мышца и синапс. М.: Мир, 1968. 221 с. [Katz B. Nerve, Muscle and Synapse. New York: McGraw-Hill Book Company, 1966.]
102. Бернс Б. Неопределенность в нервной системе. М.: Мир, 1969. 252 с. [Delisle Burns B. The Uncertain Nervous System. London: Edward Arnold (Publisher) Ltd., 1968.]
103. Дейч С. Модели нервной системы. М.: Мир, 1970. 326 с. [Deutsch S. Models of the Nervous System. New York: John Wiley & Sons, Inc., 1967.]
104. Antomonov Y.G. The Modelling of Biological Systems. Kiev: Naukova dumka, 1977. 260 p. (in Russian).
105. Khodorov B.I. General Physiology of Excitable Membranes. Moscow: Nauka, 1975. 408 p. (in Russian).
106. Dunin-Barkowski V.L. Information Processes in Neuronal Structures. Moscow: Nauka, 1978. 167 p. (in Russian).
107. Sokolov E.N., Shmelev L.A. Neurobionics. Organization of Neuron-like Elements and Systems. Moscow: Nauka, 1983. 280 p. (in Russian).
108. Ivanitsky A.M., Strelets V.B., Korsakov I.A. Brain Informational Processes and Mental Activity. Moscow: Nauka, 1984. 201 p. (in Russian).
109. Sokolov E.N., Vaitkyavichus G.G. Neurointellect: From Neuron to Neurocomputer. Moscow: Nauka, 1989. 238 p. (in Russian).
110. Хакен Г., Хакен-Крелль М. Тайны восприятия. М.: Институт компьютерных исследований, 2002. 272 с. [Haken G., Haken-Krell M.

Erfolgsgeheimnisse der Wahrnehmung. Stuttgart: Deutsche Verlags-Anstalt GmbH, 1992.]

111. Pavlov I.P. Lectures on the Work of the Cerebral Hemispheres. Moscow: Izdatelstvo AMS USSR, 1952. 288 p. (in Russian).
112. Арбиб М.А. Мозг, машина и математика. М.: Наука, 1968. 224 с. [Arbib M.A. Brains, Machines and Mathematics. New York: McGraw-Hill Book Company, 1966.]
113. Kobayasi N. Introduction to Nanotechnology. Moscow: BINOM. Laboratoriya znanij, 2005. 134 p. (in Russian).
114. Валиев К.А. Квантовые компьютеры и квантовые вычисления // УФН. 2005. Т. 175, № 1. С.3−39. [Valiev K.A. Quantum computers and quantum computations // Phys. Usp. 48, 1–36 (2005).]
115. Valiev K. A., Vyurkov V.V., Orlikovsky A.A. Silicon Nanoelectronics: Problems and Prospects // Progress of Modern Radio Electronics. 2010. No 6. P. 7–22. (in Russian).
116. Kastrubin E.M. The Key to the Mysteries of the Brain. Moscow: Triada,1995. 240 p. (in Russian).
117. Phenomenon “D” and Others / Compiled by Kolodny L.E. Moscow: Politizdat, 1991. 335 p. (in Russian).
118. Bernatsky A.S. 100 Great Mysteries of Consciousness. Moscow: Veche, 2011. 384 p. (in Russian).
119. Дрейфус Х. Чего не могут вычислительные машины. Критика искусственного разума. М.: Прогресс, 1978. 336 с. [Dreyfus H.L. What Computers Can’t Do. A Critique of Artificial Reason. Harper & Row, Publishers, 1973.]
120. Альтман Ю. Военные нанотехнологии. Возможности применения и превентивного контроля вооружений. М.: Техносфера, 2008. 424 с. [Altman J. Military Nanotechnology. Potential application and preventive arms control. New York: Routledge, Taylor & Francis group, 2006.]