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NEURAL-LIKE GROWING NETWORKS IN THE DEVELOPMENT OF GENERAL INTELLIGENCE. NEURAL-LIKE ELEMENT (P. I)

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Анотація. *У статті розглядається новий підхід до створення штучного нейрона та нейронних мереж як засобу розробки штучного інтелекту, подібного до природного. Стаття складається із двох частин. У першій частині розглядається система формування штучного інтелекту порівняно з системою формування природного інтелекту. Виходячи з розгляду й аналізу структури та функцій біологічного нейрона, зроблено висновок, що пам'ять зберігається в нейронах головного мозку на молекулярному рівні. Інформація, що сприймається людиною з моменту її народження та протягом усього життя, зберігається в ендоплазматичній мережі нейрона. У мозку людини знаходиться близько 100 мільярдів нейронів, причому кожен нейрон містить мільйони рибосом, що здійснюють синтез медіатора, який включає близько 10000 молекул. Якщо припустити, що одна молекула відповідає одній одиниці інформації, то пам'ять людини безмежна. У нервовій клітині відбувається синтез біологічно активних речовин, необхідних для аналізу та запам'ятовування інформації. Фабрикою з виробництва білків є ендоплазматичний ретикулум, у якому накопичуються мільйони рибосом. Одна рибосома синтезує білок зі швидкістю 15–20 амінокислот на секунду. Враховуючи те, що функціональна структура рибосом аналогічна машині Тьюренга, можна дійти висновку, що нейрон є аналоговим багатомашинним комплексом – швидкодіючим молекулярним багатомашинним суперкомп'ютером із надзвичайно простим аналоговим пристроєм програмування. Розглянуто штучний нейрон, запропонований Дж. Маккалоком та У. Піттсом як сильно спрощену математичну модель біологічного нейрона. Запропоновано максимально наближений аналог біологічного нейрона – нейроподібний елемент. Наведено опис нейроподібного елемента. Показано процес вирощування та запам'ятовування інформації в нейроподібному елементі порівняно з аналогічним процесом у нервовій клітині головного мозку.*

Ключові слова: *природний інтелект, штучний інтелект, нервова система, біологічний нейрон, штучний нейрон, нейроподібний елемент.*

Abstract. *The article discusses a new approach to the creation of artificial neurons and neural networks as the means of developing artificial intelligence similar to natural. The article consists of two parts. In the first one, the system of artificial intelligence formation is considered in comparison with the system of natural intelligence formation. Based on the consideration and analysis of the structure and functions of a biological neuron, it was concluded that memory is stored in brain neurons at the molecular level. Information perceived by a person from the moment of his birth and throughout his life is stored in the endoplasmic reticulum of the neuron. There are about 100 billion neurons in the human brain, and each neuron contains millions of ribosomes that synthesize a mediator consisting of about 10,000 molecules. If we assume that one molecule corresponds to one unit of information, then human memory is unlimited. In the nerve cell, there is a synthesis of biologically active substances necessary for the analysis and memorizing information. The "factory" for the production of proteins is the endoplasmic reticulum which accumulates millions of ribosomes. One ribosome synthesizes protein at a rate of 15-20 amino acids per second. Considering that the functional structure of ribosomes is similar to the Turing machine, we can conclude that the neuron is an analog multimachine complex – an ultra-fast molecular multimachine supercomputer with an unusually simple analog programming device. An artificial neuron proposed by J. McCulloch and W. Pitts is considered a highly simplified mathematical model of a biological neuron. A maximally approximate analogue of a biological neuron, a neural-like element, is proposed. A description of the neural-like element is given. The process of perception and memorizing information in a neuron-like element is shown in comparison with a similar process in a nerve cell of the brain.*

Keywords: *natural intelligence, artificial intelligence, nervous system, biological neuron, artificial neuron, neural-like element.*

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1. Introduction

The history of artificial intelligence (AI) alternates between periods of increased interest in its developments and periods of cooling. In the mid-1950s, researchers hoped that building AI at the level of human intelligence would take several years. By the 1970s, this optimism faded. The next wave began in the 1980s. Once again, the grandest promises remained unfulfilled.

Modern artificial intelligence systems are very effective in solving highly specialized tasks. For example, the AlphaGo artificial intelligence program beat Korean professional Lee Sedol who is considered one of the strongest masters of this intellectual game in the world. But the mentioned program is completely helpless for solving other problems. Modern AI researchers are striving to create "artificial general intelligence" (AGI) with broad capabilities, as opposed to "narrow artificial intelligence" (NAI), which can solve only special tasks. However, these efforts have so far been unsuccessful.

Perhaps this is due to the fact that neural networks used in AI development mainly use an artificial neuron, which is a mathematical model of a biological neuron proposed by W. McCulloch and W. Pitts. It was one of the first attempts to describe the principles by which a "thinking" machine like the brain could work. Their model, published in 1943 in an article entitled "The logical calculus of ideas relating to nervous activity", was a very innovative invention. However, the McCulloch-Pitts artificial neuron is a very simplified model of a real biological neuron. The model does not take into account many features of the functioning of real neurons. Despite the fact that neuromathematics has come a long way over the years, many of McCulloch's statements remain relevant today. In particular, with a wide variety of neuron models, the principle of their operation, laid down by McCulloch and Pitts, remains unchanged. To develop artificial intelligence similar to human intelligence, it is necessary to develop an artificial neuron that has broader functionality than the McCulloch-Pitts neuron.

The aim of this article is to describe an artificial neuron-like cell in terms of its functionality that is as close as possible to a biological neuron and is the main element for building neural-like growing networks.

2. Formation of natural intelligence

The intelligence of man and living organisms is formed by their nervous system (NS). The higher the organization of the nervous system of a living organism, the higher the intelligence. The main functional unit of the NS is the neuron. The interaction between neurons determines the functions performed by the NS.

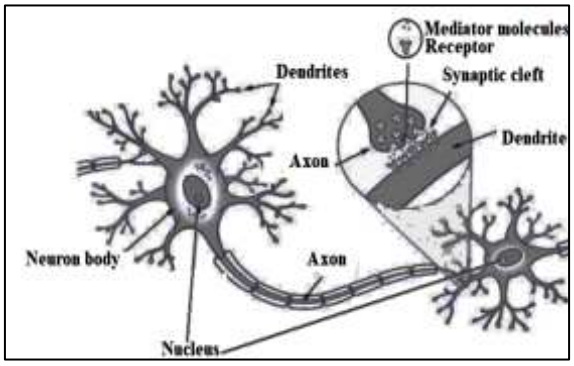


Figure 1 – Neuron

2.1. Neuron

Neurons consist of a cell body, dendrites, and a single axon (Fig. 1). The number of neurons in the human brain is enormous. According to recent studies conducted by Brazilian physiologists, there are about 86 billion neurons in the human brain and hundreds of thousands of connections between neurons.

The bodies of neurons make up the gray matter of the brain. Dendrites are branched processes of neurons that receive impulses from other neurons [1]. Axon is a long nerve fibre by which a nerve cell transmits impulses to other nerve cells through synapses. The protoplasm of the axon contains neurofibrils, mitochondria, and microtubules. Microtubules form the

cytoskeleton of the cell and are used for particle transport (axon transport) [2]. It involves the movement of membrane vesicles and mitochondria from the cell body to certain areas of the axon (Fig. 2).

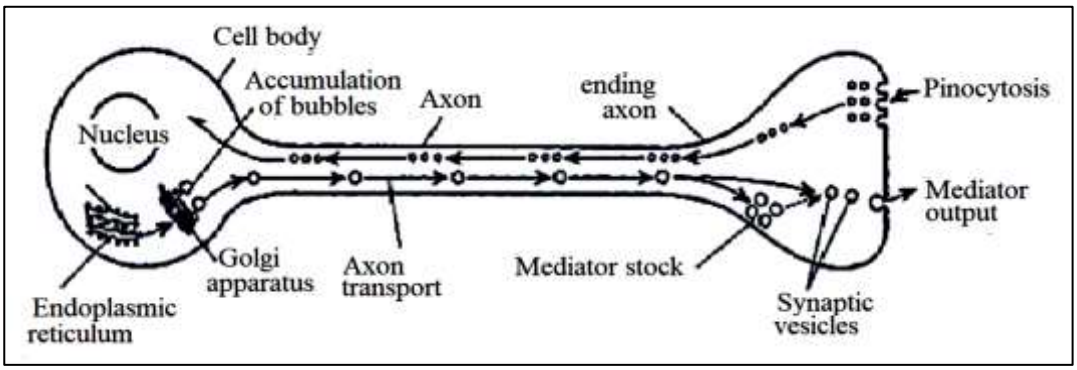


Figure 2 – Axon transport

In addition to direct axon transport, there is also reverse (pinocytosis), the essence of which is the capture of substance molecules from the synaptic cleft by axon endings and their preservation in the body of the neuron. The formation of pinocytic vesicles was traced by phase-contrast microscopy and filming. Pinocytic vesicles can move inside the cell and merge with each other and with intracellular membrane structures. Transportation through microtubules is carried out by motor proteins [3].

2.1.1. Neurons are living cells

The activity of nerve cells in the brain can be observed with one's own eyes. Scientists introduced the thinnest light guides connected to a video camera into the human brain and saw that neurons move like tiny amoeba. The more intense the work of the brain, for example, when solving mathematical problems or memorizing unfamiliar words, the more active the movement of nerve cells [4].

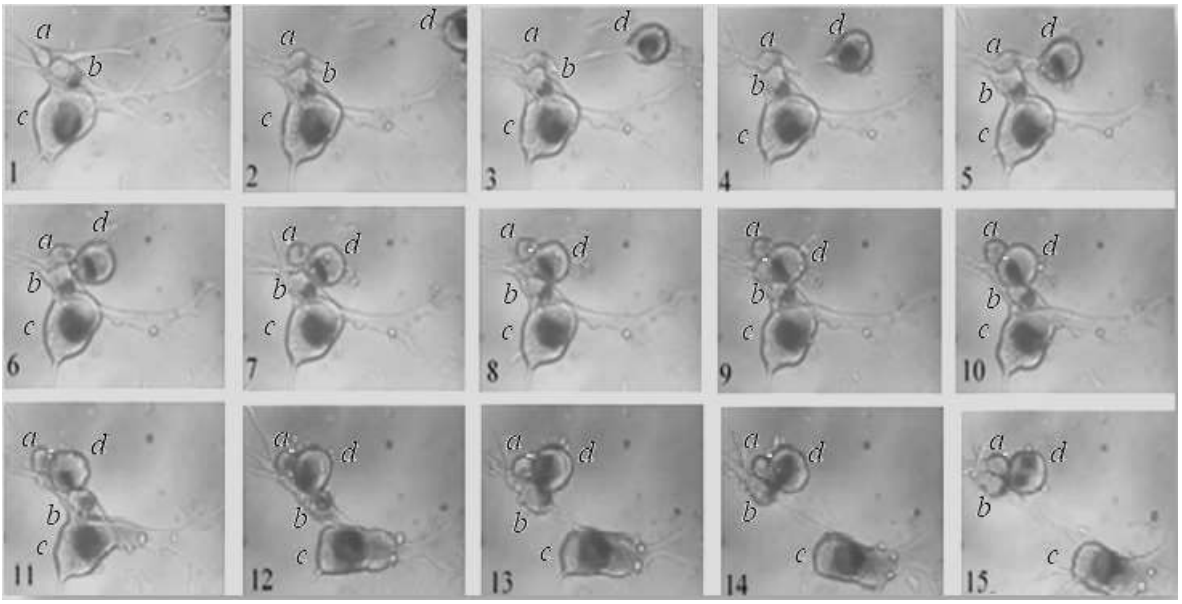


Figure 3 – Connection and disconnection of neurons

Scientists joke that in order to solve complex problems, you need to actively move your brain. Fig. 3 shows a storyboard of a video filmed at the Institute of Biophysics of the Academy of Sciences in Pushchino. Special filming made it possible to see some fragments of the life of neurons. Frames 1–10 show how another neuron *d* joins the group of neurons *abc*, and a new group of *adbc* neurons is formed.

On frames 11–15, neuron *c* leaves this group.

In Fig. 4, there is a storyboard of a video recording the sprouting of an axon, the formation of a connection between neuron 1 and neurons 2 and 3, and the transmission of an impulse. Nerve impulses propagate when ions move across the membrane of a nerve cell and are transmitted from one nerve cell to another with the help of neurotransmitters.

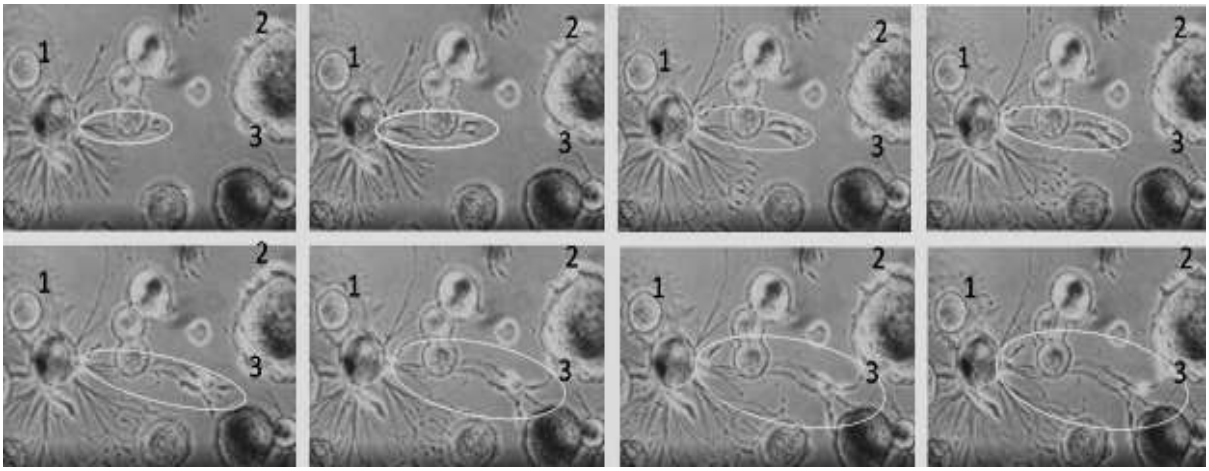


Figure 4 – Axon sprouting

2.1.2. Classification of neurons by function

According to their function, neurons are divided into sensitive (sensory), intercalary (interneurons), and effector executive (motor neurons) (Fig. 5). Sensory neurons perceive stimuli, convert them into nerve impulses and transmit them to the brain.

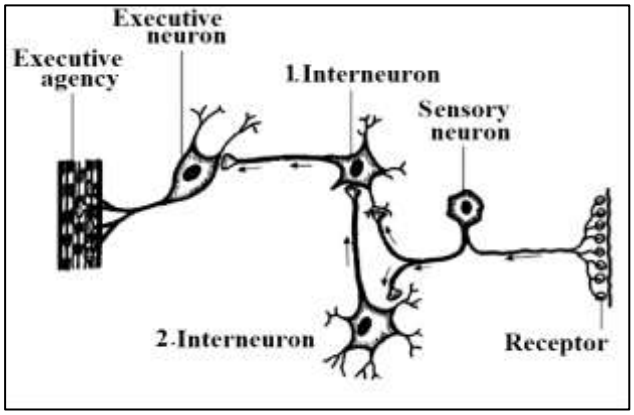


Figure 5 – Classification of neurons

Effector neurons (from lat. effectus – action) develop and send commands to the working bodies.

Intercalary neurons provide a connection between sensory and motor neurons, and participate in information processing, and command generation. Fig. 1 shows an unconditioned reflex. A sensitive neuron perceives receptor irritation, converts them into a nerve impulse, and transmits them to interneuron 1 and interneuron 2 in the CNS. Interneuron 1 processes information and transmits control nerve impulses to the executive neuron, which generates control signals for the executive body. Interneuron 2 allows or forbids the execution of commands by interneuron 1.

2.1.3. Neuron cell structure

For different cells of the body, including neurons, some common structural components are characteristic of the constant components of the cell – organelles, which are located in its inner part – the cytoplasm.

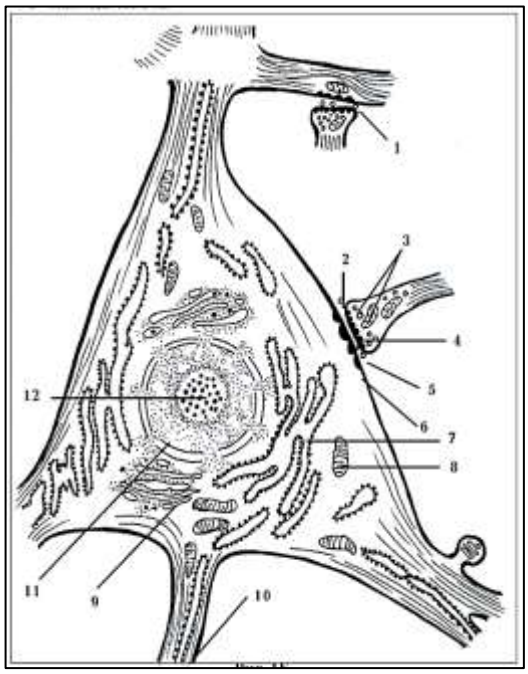


Figure 6 – Neuron cell structure

2.1.4. Functions of organelles

Fig. 6 shows the structure of a neuron cell and its constituent organelles.

1. Axodendric synapse is a synapse in which the axon contacts the dendritic process of the neuron.

2. Axosomatic synapse is a synapse in which the axon of one neuron contacts the cell body (soma) of another.

3. Presynaptic vesicle is a vacuole containing a neurotransmitter located in the presynaptic membrane.

4. Presynaptic membrane is a part of the surface membrane of the nerve fiber through which the mediator is released.

5. Synaptic cleft is the space between the presynaptic membrane and the postsynaptic membrane, which contains binding pre- and postsynaptic structures.

6. Postsynaptic membrane is a thickened surface cell membrane in the synapse region, which is sensitive to a mediator.

7. Endoplasmic reticulum (ER) (endoplasmic reticulum (ER)). The endoplasmic reticulum is the intracellular factory for the production of proteins. It consists of many membranes on which ribosomes accumulate.

8. Mitochondria are two-membrane organelles that contain deoxyribonucleic (DNA) and ribonucleic (RNA) acids.

9. The Golgi apparatus (AG) is a complex network of cavities that are the site of protein modification. AG is designed to remove proteins synthesized in the endoplasmic reticulum. Modified proteins are transported by vesicles to cell compartments, lysosomes, cytoplasmic membrane, or secretory vesicles. Secretory vesicles release their contents into the extracellular space (exocytosis).

10. Neurofibrils are filamentous structures of the cytoplasm of a neuron, forming a dense network in the cell body and parallel bundles in the processes. Participate in the conduction of nerve impulses.

11. Cell nucleus controls cellular processes and is the controlling center of the cell. Contains DNA molecules – genetic information. The nucleus stores, transmits, and implements hereditary information, and also provides protein synthesis.

12. Nucleolus. In the nucleus of nerve cells there is one, and sometimes 2-3 nucleoli. An increase in the number of nucleoli is accompanied by an increase in the activity of neurons. The main function of the nucleolus is the synthesis of ribosomal RNA and ribosomes [5–7].

Gene expression is the realization of the information embedded in them, that is, the synthesis of RNA and proteins. Gene expression includes two successive steps: transcription and translation. In cells, transcription occurs in the nucleus, where messenger RNA (mRNA) is synthesized from the DNA template. Translation occurs in the cytoplasm of the cell in ribosomes,

where the polypeptide is synthesized from the mRNA template. The transcription process proceeds continuously along the coding sequence along the chromosome, passing from several hundred to more than a million base pairs [8].

The cell membrane surrounds the cell and separates it from the environment or other cells. The membrane provides selective permeability of molecules of substances and promotes the process of arousal.

The ribosome is the most important organelle of a living cell, carrying out protein synthesis. Consists of: small subunit – 1; messenger RNA (mRNA) – 2; transfer RNA (tRNA) – 3; amino acids – 4; large subunit – 5; membranes of the endoplasmic reticulum – 6; polypeptide chain – 7 (Fig. 7). Ribosomes synthesize protein from amino acids based on the genetic information provided by messenger RNA.

Fig. 8 shows the process of protein synthesis on the ribosome. In the cell nucleus, mRNA is synthesized, which is a “copy” of the gene's DNA. The messenger RNA and the two subunits of the ribosome are assembled into a complex. Different tRNAs carry different anticodons corresponding to mRNA codons. The amino acid corresponding to its “own” codon is attached to the other end of the tRNA. On the ribosome, tRNAs line up against mRNAs. The codon and anticodon must match, otherwise, the tRNA is detached. At the molecular level, the codon-anticodon match is checked. If the distance between the bases is incorrect, the tRNA is detached. A peptide bond is formed between amino acids. The growing polypeptide chain moves to the tRNA in an adjacent position. The ribosome takes one step to the mRNA to bind the next tRNA molecule. The polypeptide chain begins to fold into a protein. Transfer RNA detaches and takes up a new amino acid.

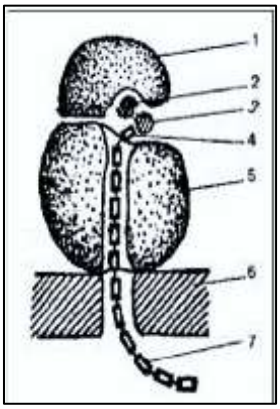


Figure 7 – Ribosome

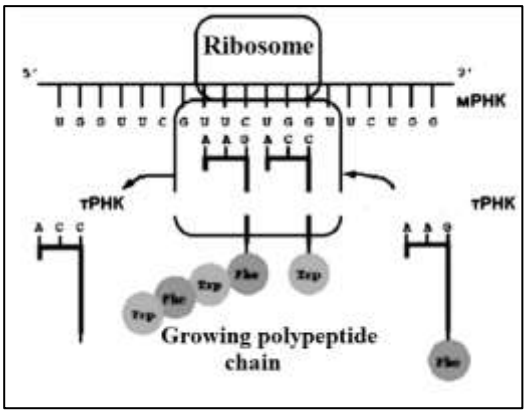


Figure 8 – Protein synthesis in the ribosome

The growing polypeptide chain moves on the tRNA in an adjacent position. The ribosome takes one step to the mRNA to bind the next tRNA molecule. The polypeptide chain begins to fold into a protein. The transfer RNA is detached and takes over the new amino acid.

Ribosomes are present in all types of cells, including neurons. But in ordinary cells, ribosomes are actually busy deciphering genetic information and synthesizing proteins, which are building materials for various organs. And in the nerve cell, they synthesize proteins and process information.

The structure and functioning of ribosomes almost completely coincide with the structure and functions of a Turing machine. The Turing machine consists of three parts: a tape, a read-write head, and a logic device (Fig. 9). The tape acts as external memory and is considered unlimited. The machine operates in an arbitrary finite alphabet $A=\{\Delta, a_1 \dots a_n\}$ – this alphabet is called external. The processing of information and the issuance of commands for writing a sign, as well as shifting the tape in the Turing machine, is carried out by a logical unit (LU). The LU can be in one of the states that form a finite set and are denoted by $Q=\{q_1 \dots q_m, z\}$. Moreover,

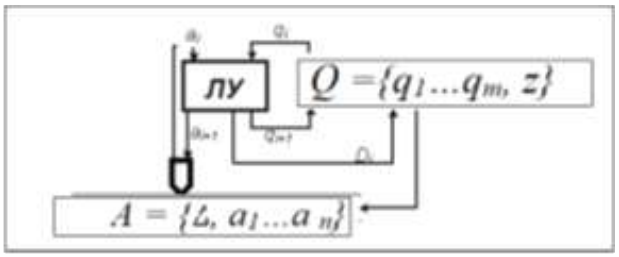


Figure 9 – Turing machine device

the state z corresponds to the completion of work, and q_1 is the initial one. The set of symbols $Q = \{q_1, q_2, ..., q_k\}$ and $D = \{R, L, E\}$ forms the internal alphabet of the machine (similar to mRNA in the sense of analogue to ribosomal protein synthesis). $A = \{\Delta, a_1 ... a_n\}$ is a machine external alphabet (similar to tRNA ribosomes).

The Turing machine is extremely simple. Simplicity lies in the fact that it has an extremely simple set of elementary operations (reading and writing), and also that access to memory cells (tape sections) in it occurs not by address, as in computers, but as a result of sequential movement along the tape. For this reason, even such simple operations as adding or comparing two symbols are performed by the Turing machine in several steps, and the usual operations of addition and multiplication require a very large number of elementary operations. Turing invented this machine in order to show the fundamental (theoretical) possibility of constructing arbitrarily complex algorithms from extremely simple operations, and the operations themselves are performed automatically. Obviously, nature invented the ribosome in order to build complex algorithms for creating biological objects with simple means.

In the cytoplasm of the cell, there are free ribosomes and bound ribosomes attached to the membranes of the endoplasmic reticulum. There can be millions of membrane-bound ribosomes in a cell. The coarse ER determines the "destination" of proteins and also functions as a place where proteins fold into three-dimensional functional units, such as a key with a lock. Proteins synthesized on free ribosomes are released into the cytosol, and proteins synthesized by bound ribosomes are transferred to the Golgi complex, after which the proteins are released from the cell or distributed among other organelles [9].

The ER serves as the starting point for the synthesis of all secreted proteins; it is also the place where the formation of the extracellular matrix (ECM) begins. In the developing cerebral cortex, there is a high concentration of ECM molecules that perform a variety of functions from network formation to activation of signaling pathways. ECM molecules are also actively involved in the regulation of neuronal migration during cortical development. Thus, the matrix regulates the processes of expansion of the cerebral cortex [10].

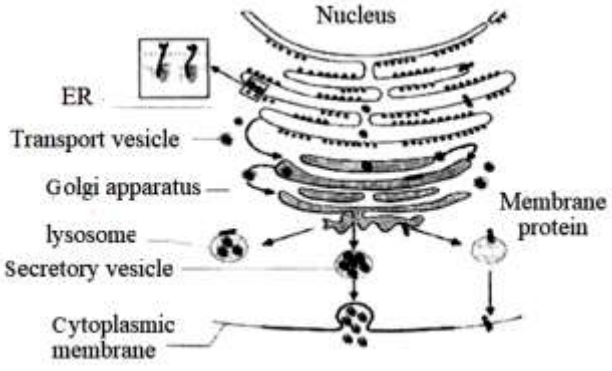


Figure 10 – Rough ER

There is a smooth and rough ER. Ribosomes (bound ribosomes) are attached to the membranes of the rough ER. Smooth ER has no associated ribosomes (Fig. 10).

The rough ER is a site of active biosynthesis of proteins that will function as part of membranes, lysosomes, or be secreted from the cell. The remaining proteins are synthesized in the cytoplasm on ribosomes not associated with ER membranes. Proteins synthesized on the rough ER either remain inside the rough ER or are transported via vesicles to the Golgi apparatus.

Modified proteins are transported by vesicles to cell compartments, lysosomes, cytoplasmic membranes, or secretory vesicles. Secretory vesicles release their contents into the extracellular space (exocytosis) [11].

2.1.5. Synapse

The synapse consists of a presynaptic membrane (1), a postsynaptic membrane (2), and a synaptic cleft (3) (Fig. 11). Signals pass through the synapse in the form of chemicals and electrical signals. Each neuron can have thousands of synapses.

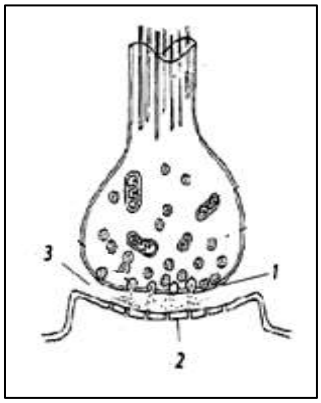


Figure 11 – Synapse

The presynaptic membrane is the end of the process of the nerve cell. Inside the process, there is an accumulation of vesicles containing the neurotransmitter. The postsynaptic membrane is the thickened part of the cell membrane. It contains receptors that perceive the action of mediators. A feature of receptors is the ability to enter into biochemical interaction only with a certain type of mediator. It has now been found that a single mediator can bind to several different receptors and induce different responses.

The synaptic cleft is a fluid-filled space between the pre- and postsynaptic membranes through which the mediator diffuses from the presynaptic membrane to the postsynaptic one. Functionally, synapses are divided into excitatory, in which an excitatory postsynaptic potential is generated, and inhibitory, which causes the appearance of an inhibitory postsynaptic potential [12].

According to the method of transmission of excitation, synapses are divided into chemical and electrical.

In an electrical synapse, excitation is transmitted by analogy with the propagation of excitation in a nerve fiber. An electrical current that occurs between the presynaptic and postsynaptic membranes irritates the postsynaptic membrane and causes the generation of an action potential in it.

The transmission of excitation in a chemical synapse is a complex physiological process. This process proceeds in several stages: mediator synthesis, mediator secretion, mediator interaction with the postsynaptic membrane, and mediator inactivation. In the cytoplasm of neurons, chemical mediators (biologically active substances) are synthesized. In nerve cell communication, the basic units of information are transmitted by synoptic mediators, with a given neuron using the same mediator in all of it.

2.2. “Communication” of neurons

Exocytosis is a process that involves the movement of substances from the cell into the external environment. During exocytosis, membrane-bound synaptic vesicles containing cellular molecules are transferred to the plasma membrane. Vesicles fuse with the cell membrane and expel their contents outside the cell. When one synaptic vesicle is emptied, a portion (quantum) of the mediator is ejected into the synaptic cleft, which includes about 10,000 molecules. The interaction of the mediator with its receptors causes excitation, which is a response of the neuron to irritation and is characterized by an increase in the functions of the neuron, or inhibition, characterized by a decrease in the functions of the neuron. Primary inhibition in the CNS occurs due to inhibitory neurons. There are two types of primary inhibition: postsynaptic and presynaptic. Postsynaptic inhibition occurs when the axon of an inhibitory neuron synapses with the body of the neuron and inhibits cell activity. Presynaptic inhibition occurs when the axon of an inhibitory neuron synapses with the axon of an excitatory neuron, preventing impulse conduction. The interaction of the processes of excitation and inhibition underlies the coordination activity of the CNS [13].

Exocytosis is the opposite of endocytosis, in which substances move inside the cell.

Endocytosis, depending on the mechanism, is usually divided into two broad categories: phagocytosis (capture of very large particles) and pinocytosis (capture of liquids, as well as mol-

ecules dissolved in them). Endocytosis plays a key role in the development of the body, the immune response, fat metabolism, the maintenance of cell size, and the transmission of signals into the cell [13].

Endocytosis is of particular interest, since the transmission of information between neurons, which occurs in synapses, is directly associated with the intensive use of this mechanism. The process of information transfer between neurons of "communication of neurons" is described in the article entitled "Endocytosis in the nervous system" published by Corresponding Member of the Russian Academy of Medical Sciences A.L. Zefirov and Candidate of Biological Sciences A.M. Petrov [14]. Below there is a fragment of this work, which makes it possible to understand the processes occurring in neurons during their "communication" with each other.

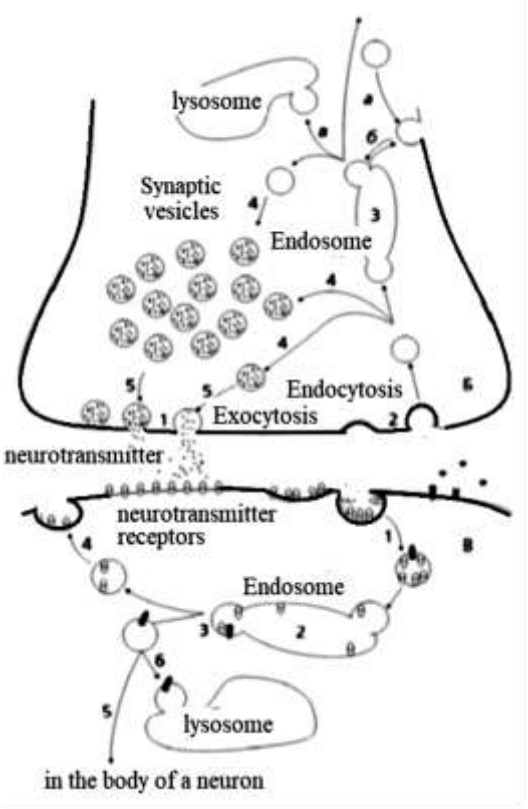


Figure 12 – Vesicular cycles in the synapse

"The transmission of information (a bit of information – a nerve impulse – an action potential) between a neuron and a secretory or muscle cell occurs in the synapse (Fig. 12). The part of a nerve cell that transmits a signal (presynaptic) and the part of another cell that receives a signal (postsynaptic) are separated by a narrow synaptic cleft. Presynaptic nerve endings contain a large number of vesicles filled with a chemical messenger (neurotransmitter). In response to a nerve impulse, vesicles fuse with the presynaptic membrane (exocytosis), releasing a neurotransmitter into the synaptic cleft. Having reached the receptors on the postsynaptic membrane, the neurotransmitter activates them, resulting in an electrical signal. Its value determines the excitation in the postsynaptic cell. The more neurotransmitter released by the vesicles, the stronger the postsynaptic response and the more reliable the transmission of excitation" [14].

Given that when one synaptic vesicle is emptied, a portion (quantum) of the mediator, which includes about 10,000 molecules, is ejected into the synaptic cleft, it can be assumed that simultaneously with the appearance of an electrical signal, there is transmitted some information represented by a set of molecules that are formed in the ER. "The endoplasmic reticulum is an intracellular factory for the production of proteins. It consists of many densely packed membranes on which ribosomes accumulate, which directly carry out protein synthesis. In addition, it was found that protein biosynthesis is activated upon excitation of neurons at different levels of CNS organization, and the blockade of protein synthesis makes it difficult or eliminates the formation of long-term memory. Memorizing information is carried out in the nerve cell and is associated with the synthesis of proteins. In ribosomes, protein synthesis is carried out from amino acids based on the genetic information provided by messenger RNA. The cytoplasm of the cell contains free ribosomes and bound ribosomes.

A cell can have millions of membrane-bound ribosomes attached to the membranes of the endoplasmic reticulum" [9].

In each neuron, millions of ribosomes are fixed on the ER membrane. There are about 100 billion neurons in the human brain. Perhaps it is in the endoplasmic reticulum that huge amounts of information perceived by a person are stored. If so, then human memory is limitless. When people are born, their brain stores everything to the smallest detail throughout their life.

“It is known that synaptic contacts operate in the mode of conducting high-frequency and long series of nerve impulses. This leads to a rapid decrease in the number of vesicles in the nerve ending. However, under natural conditions, along with exocytosis, new vesicles (endocytosis) are constantly formed in the nerve ending. They are filled with a neurotransmitter, transported to certain regions of the cell, and stand in line for repeated exocytosis. The combination of these processes is called recycling, and the constant circulation of vesicles is called the vesicular cycle” [14] (see Fig. 12 б).

New vesicles are filled in by the mediator and new packets of information are transmitted. The cycle is repeated. Thus, huge amounts of information are transmitted.

“Several variants of endocytosis coexist in nerve endings, most of which require the protein clathrin. There are two types of clathrin-dependent endocytosis: fast and slow. Rapid endocytosis (vesicular cycle 30–60 s) accompanies high-frequency activity. After the cessation of activity, the slow variant begins to work (circulation of vesicles is 5–15 min). The severity of one or another type of endocytosis depends on the activity and type of synapse” [14].

Perhaps rapid endocytosis (tens of thousands of information-carrying molecules are transferred to a nerve cell in 30–60 seconds) explains the extraordinary speed of information perception of some people.

“Clathrin endocytosis with very slow kinetics (several hours or more) is found in the postsynaptic membranes of nerve cells (Fig. 12 б). It is used to remove certain receptors (glutamate, β-adrenergic receptors), which reduces the sensitivity of the postsynaptic membrane to this neurotransmitter and leads to a decrease in the amplitude of postsynaptic signals and depression. The complete vesicular cycle includes vesicle exocytosis and endosomal sorting (Fig. 12 б). Endocytic vesicles with captured postsynaptic receptors are directed to endosomes. If necessary, receptors return to the surface of the neuron: vesicles with receptor proteins bud from the endosome using a clathrin-dependent mechanism, which subsequently merges (exocytosis) with the postsynaptic membrane. At the same time, its sensitivity to the neurotransmitter and, consequently, the “strength” of the synapse increase (long-term increase in the amplitude of postsynaptic signals, potentiation). According to recent data, such a change in the number of postsynaptic receptors is important for many integral processes of the nervous system (learning, memory, motor control, etc.). Postsynaptic endocytosis can regulate the synthesis of proteins, including receptors. For example, activated nerve growth factor receptors are absorbed, sorted in endosomes, and then transported in endocytic vesicles to the neuron body (Fig. 12 б). There, receptors, due to their enzymatic activity, act on factors that control the reading of information from certain genes and the subsequent synthesis of proteins (including receptors for neurotransmitters). Vesicles deliver the newly formed receptors back to the postsynaptic membrane and are embedded in it, while it becomes more receptive to the neurotransmitter. Another function of endocytosis in the nervous system is associated with the structural reorganization of the synaptic apparatus. During endocytosis, significant membrane fragments can be removed from the cell surface, as a result, the sizes of pre- and postsynaptic membranes decrease. This naturally weakens the transmission of information between nerve cells. A similar process can lead to the disappearance of the synapse” [14].

Thus, the analysis, synthesis, and transformation of information are carried out in the nerve cell.

2.3. Memory

Our knowledge, actions, experiences, and impressions do not disappear without a trace but are stored in our memory. Human memory is encoded in billions of nerve cells and trillions of connections between them. It demonstrates the amazing properties of the human mind. There are many examples of phenomenal memory. Alexander the Great could remember by sight and by name 30,000 of his soldiers. Francis Bacon, an English philosopher, could recite many of his

works by heart. Lord Byron knew all his poems by heart, and American botanist Asa Gray could name over 25,000 different plant species from memory [15].

Jill Price, a California resident, remembers every event in her life in chronological order since she was 12 years old. She remembers literally every little thing, including the program on TV at that moment or the events that took place in the world. Just name the date and she will tell you what day of the week it was and list everything that happened on that day [16].

Solomon Shereshevsky had a phenomenal memory. In experiments conducted with the famous psychologist Alexander Luria, it turned out that Shereshevsky's memory had no limits either in terms of volume or duration of storage. He remembered everything. He memorized long sequences of words, including those not connected by any common meaning, any formula, and any sets of numbers. Luria studied the memory of Solomon for decades, but the psychologist could not determine the clear boundaries of the amount of information to be remembered. Shereshevsky could remember the figures, words, and fragments of texts given to him when he was 15 or 20. Moreover, he remembered himself in his early infancy. Shereshevsky's memory tenaciously kept everything that got into it. The first memories that Solomon spoke about were in infancy when he still could not speak. These memories had a taste and smell and were colored in different colors. Later memories did not lose these qualities. Tastes, smells, and colors in his mind evoked associations with words or numbers. This perception of life was both a gift and a curse. On the one hand, it allowed unlimited use of memory, on the other hand, any sound or smell instantly triggered the images and information associated with it. Shereshevsky suffered all his life due to the fact that a huge amount of information that entered his brain remained there forever, and he had to make desperate attempts in order to forget [17].

Academician of the Russian Academy of Sciences and Doctor of Philosophy Vyacheslav Vsevolodovich Ivanov (1929–2017) also had a phenomenal memory and an extraordinary reading speed. T.V. Chernigovskaya, a scientist in the field of neuroscience and psycholinguistics, Doctor of Biological Sciences, and Doctor of Philology, recalls the abilities of V.V. Ivanov. “He has an extraordinary brain. He has an absolute memory and a special way of reading. He read at the speed of slowly turning pages and memorized. It's a humiliation to sit next to him. You see, he flips through the pages like this and remembers it all in its entirety. He read 28 books a day, and they lay down in some strange space in his brain”.

Until the 50s of the last century, few people were engaged in speed reading, only a few major politicians and great people. Napoleon Bonaparte read at a speed of 20,000 words per minute. Honore de Balzac, a French writer and one of the founders of realism in European literature, had a phenomenal memory. He once described his reading technique as follows: “The absorption of thought in the process of reading has reached a phenomenal ability in me. The gaze caught seven or eight lines at once, and the mind comprehended the meaning at a speed corresponding to the speed of the eyes. Often a single word made it possible to grasp the meaning of a whole phrase.” It is believed that Balzac did read all the words. Reading this or that work, he always singled out the main thing and omitted the superfluous.

To date, experts cannot accurately determine the cause of “abnormal memory”, but have already suggested that it is an increase in the size of the temporal lobes and the caudate nucleus in the brain. However, this is still only a hypothesis [18].

On the other hand, there is an opinion that all people have such a memory. The brain works correctly only when a certain level of activity of neurons is maintained. Increased activity can lead to an epileptic seizure, and underactivity can, so to say, put the brain to sleep. The level of activity is regulated and maintained at a certain level by the thalamus, through the mechanism of inhibition and excitation of neurons in the cerebral cortex.

In the nuclei of the thalamus, not only the switching of information takes place but also its processing. One of the main features of this processing is the selective transmission of information to the cerebral cortex. The thalamus acts as a filter, passing either very significant (strong,

new) signals to the telencephalon, or signals associated with the current activity of the cerebral cortex. Thus, the thalamus is one of the key structures providing and maintaining attention processes and protection against information overload [19].

2.4. Basic functions of a biological neuron

Receiving function. Synapses are points of contact; they receive information from receptors and neurons in the form of sequences of nerve impulses (spikes).

Integrative function. As a result of information processing, a signal is formed at the output of the neuron which carries information generated from all input signals. The neuron works as a signal converter. It processes many incoming stimuli and generates a response. As a rule, it does not generate a single pulse, but a series of pulses.

Conductor function. The axon carries information from the neuron to the synapses in the form of action potentials. Direct axon transport involves the movement of synthesized biologically active substances from the cell body to the end of the axon.

Transfer function. The nerve impulse, having reached the end of the axon, which is already a part of the structure of the synapse, causes the release of a mediator – a direct transmitter of excitation to another neuron or executive organ.

Spontaneous activity. Many neurons exhibit spontaneous activity (activity not associated with an external signal) [20].

3. Formation of artificial intelligence

The intelligence of robotic systems and artificial intelligence systems is formed by artificial neural networks (ANNs). The main element of each ANN is an artificial neuron – a computational element that is a mathematical model of a biological neuron.

3.1. Artificial neuron. Mathematical model of a biological neuron

The mathematical model of the biological neuron was proposed by J. McCulloch and W. Pitts in 1943.

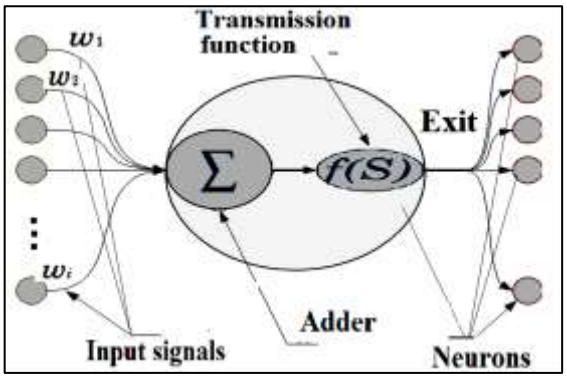


Figure 13 – Artificial neuron

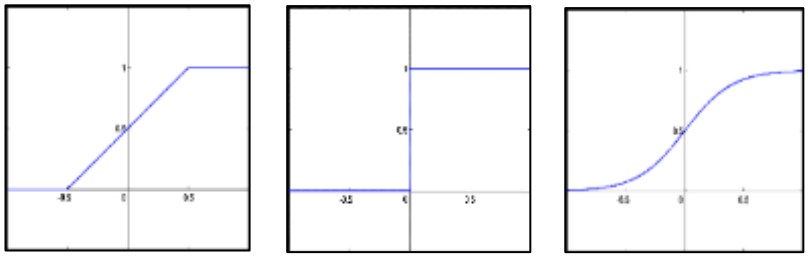
The artificial neuron of McCulloch and Pitts has many inputs (analogues of the dendrites of a biological neuron) and a single output (analogue of an axon) (Fig. 13).

$$y = f(S),$$

where $S = \sum_{i=1}^{n} w_i x_i + w_0$.

Each input has a certain weight w_i, which is multiplied by the value x_i obtained through this input. In the body of the neuron, the S weighted inputs are summed with the offset w_0, and the resulting sum is transformed using the non-linear function $f(S)$.

The nonlinear transfer (activation or characteristic) function $f(S)$ can have different forms: *a*) a linear function with saturation, *b*) a threshold function, *c)* a sigmoid function (see Fig. 14).



a *b* *c*

Figure 14 – Activation functions

More than half a century has passed and many other artificial neuron models have been developed. For example, there is an artificial neuron patent EP 0629969, where a multiplier is contained as a central element, which multiplies incoming signals and synaptic weight, and generates an output signal [21]. An artificial neuron is also known as patent US 7672918, which is a processor device with several signal inputs, a threshold value input, and one output [22].

Other implementations of the artificial neuron are also known. Basically, they are highly specialized processor devices incapable of implementing adaptive behavior and full emulation of the functions of a biological neuron, and almost all of them are based on the mathematical model of McCallock and Pitts. Despite the significant advances in the use of artificial neurons, it is very simplified to be analogous to the biological neuron.

3.2. Neural-like element as a model of a biological neuron

Each biological neuron processes many incoming stimuli (signals, signs) not in a binary representation but in the form of significant analog values, and unlike an artificial neuron, it generates not a single impulse but a series of impulses that travel along the axon with a certain frequency. This frequency representation of the output signal is a way of encoding information.

An important property of a biological neuron is the transformation of the input signal into biologically active substances. It can form extracellular matrix molecules that are part of long-term memory. ECM structures accumulate in the extracellular space and form perineural networks that play an important role in storing information in long-term memory. Perineural networks act on synaptic plasticity and memory and learning processes. Neuroscientists have found that when neurons are excited, protein biosynthesis is activated, and the blockade of protein synthesis makes it difficult or eliminates the formation of long-term memory. This fact indicates that the formation of memory is closely related to the synthesis of neurotransmitters. Some mediators convey specific data and facts, while others convey additional semantic shades.

The site of active protein biosynthesis is the rough endoplasmic reticulum. Some proteins synthesized on the rough ER remain inside the rough ER and undergo post-translational modifications. In this regard, it can be assumed that memory is formed and stored in the nucleus and rough ER of the neuron.

So, for the formation of unconditioned reflexes and instincts, the genetic apparatus of the neuron is used. They are formed in the nucleus of the neuron at birth. When learning, information enters the processes of the neuron, it is excited and biologically active substances are synthesized in the rough ER. For some time, they are in the stage, as neuroscientists say, of maturation. Perhaps the time of protein maturation is the time of short-term memory. Obviously, the need to repeat the memorized information is connected with this. If the information is confirmed, then biologically active substances are fixed on the membrane of the rough ER and long-term memorization of information is formed. It has been established that the time of information stored in short-term memory is characterized by fractions of seconds to tens of minutes. The storage time of information in long-term memory is comparable to the life span of an organism. The transition

from short-term memory to long-term memory is provided by the structural-chemical fixation of the experience gained and is associated with the activation of biochemical processes.

A biological neuron not only perceives, and transforms information and, as a result, forms a signal that carries information generated from all input signals. It, as can be seen from the analysis of the description of a biological neuron given above, using the mechanism of protein biosynthesis, remembers the information received by the dendrites, forms neural connections, and generates control signals for the internal and external organs of the body that are adequate to the perceived signals.

It should be noted here that a neuron that has memorized information when receiving new information must compare it with the previously memorized information and either recognize it or recognize only matching features and then divide the information into parts and output the matching part to another neuron. Old and new information will be contained in two neurons. If the new information does not match the previously memorized one, then a burst of impulses corresponding to the new information is generated and, with the help of axon sprouting and connection with a free neuron, is transmitted to its dendrites. The new neuron performs structural-chemical fixation of new information. The neuron perceives electrical signals (a sequence of nerve impulses) through dendrites, converts them into biologically active substances, stores them in a rough ER, and then converts them into impulses for transmission to other neurons. Scientists discover neurons containing information about lines, circles, and other elements of recognizable and memorized information, as well as neurons containing actual information (letters, words, objects, faces, etc.). It is possible that the sprouting of the axon described above (Fig. 4) and the unification and separation of biological neurons (Fig. 3) are the processes of analysis and synthesis of information. From the description of the functioning of natural intelligence, it can be seen that the functions of a biological neuron, which is the main element of the nervous system, which in turn is the basis for the formation of natural intelligence are much wider than the functions of an artificial neuron. For the most complete emulation of the functions of a biological neuron, a neural-like element was created as a structural and functional element of artificial neural-like growing networks.

3.2.1. Neural element

The neuron is the most elementary and at the same time complex system. Understanding the basics of cell functioning from the standpoint of the cybernetic system approach made it possible to develop a neural-like element (NE) – a model of an artificial neuron that is closest in analogy to a biological neuron.

A neural-like element (Patent UA 128798 G06G 7/60 2006.01) consists of a device (analogue of the cell body) with a plurality of excitatory, inhibitory $\vec{a}$, $\vec{a}'$, and modulating $\vec{b}$ inputs and one output Q. The output (analogue of an axon) consists of a plurality of conductors and a plurality of endings. Information (codes, bursts) is received at the inputs of the device. The device processes information and, in accordance with mutually exclusive relations $R1$, $R2$, $R3$, $R4$, and $R5$, determines operations $Q_{rj}^1, Q_{rj}^2, Q_{rj}^3, Q_{rj}^4$, or Q_{rj}^5 forming a neural-like growing network, generates codes (bursts of pulses) and simultaneously or with time separation transmits them to the inputs of other neuron-like elements. The inputs of the neural-like element (analogous to dendrites) are specialized in the perception of certain codes. Codes are transmitted from one neural-like element to another, through contacts (analogous to synapses). A neural-like element is a device that reacts or does not respond to one or another part of the codes coming to it, thereby increasing or decreasing the level of excitation of the neural-like element and the intensity of its response, while the minimum allowable threshold level of excitation of the neural-like element can be adjusted.

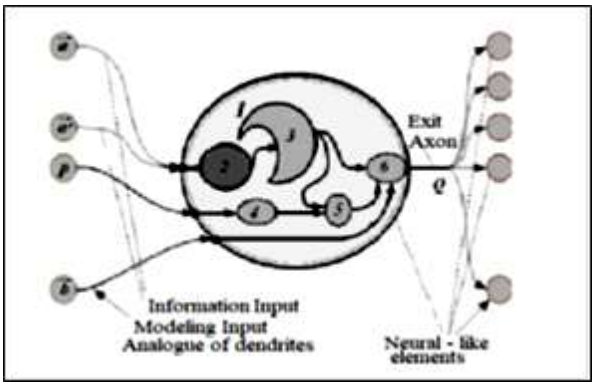


Figure 15 – Neural-like element

The block diagram of the neural-like element is shown in Fig. 15. NE contains the following blocks: 1) is a neural-like element; 2) is a block for determining the relations $R1, R2, R3, R4, R5$ on the set of pairs of vectors $\vec{a}, \vec{a}'$; 3) is a block for determining operations $Q^1_{rj}, Q^2_{rj}, Q^3_{rj}, Q^4_{rj}$, or Q^5_{rj} and generating control codes; 4) is a block for storing the minimum allowable threshold for excitation of a neural-like element; 5) is a block comparing the threshold of excitation with the minimum allowable threshold of excitation of the neural-like element; 6 is a block allowing the passage of the output code; $\vec{a}, \vec{a}'$ – information inputs; $\vec{b}$ – modulating input; Q – information output. The output (analogous to an axon) consists of a plurality of conductors and a plurality of endings. Information (codes, bursts) is received at the inputs of the device. The device processes information in accordance with mutually exclusive relations $R1, R2, R3, R4$, and $R5$. On the set of pairs of vectors $\vec{a}, \vec{a}' \in A$, five main mutually exclusive relations $R1, R2, R3, R4$, and $R5$ are defined.

$$\vec{a}\ R1_r\vec{a}' \equiv \forall \vec{a}_i^j, \vec{a}_i^{j+1} \in A : (\vec{a}_i^j \times \vec{a}_i^{j+1} = \vec{a}_i^j) \cap (\vec{a}_i^j \times \vec{a}_i^{j+1} = \vec{a}_i^{j+1}) \cap (\vec{a}_i^j \times \vec{a}_i^{j+1} \neq 0),$$

where $\vec{a}_i^j \times \vec{a}_i^{j+1}$ is a conjunction of vectors $\vec{a}_i^{j+1}$ and $\vec{a}_i^{j+1}$ $\cap$ is logical AND;

$$\vec{a}\ R2_r\vec{a}' \neq \forall \vec{a}_i^j, \vec{a}_i^{j+1} \in A : (\vec{a}_i^j \times \vec{a}_i^{j+1} \neq \vec{a}_i^j) \cap (\vec{a}_i^j \times \vec{a}_i^{j+1} \neq \vec{a}_i^{j+1}) \cap (\vec{a}_i^j \times \vec{a}_i^{j+1} = 0);$$

$$\vec{a}\ R3_r\vec{a}' \equiv \forall \vec{a}_i^j, \vec{a}_i^{j+1} \in A : (\vec{a}_i^j \times \vec{a}_i^{j+1} \neq \vec{a}_i^j) \cap (\vec{a}_i^j \times \vec{a}_i^{j+1} \neq \vec{a}_i^{j+1}) \cup (\vec{a}_i^j \times \vec{a}_i^{j+1} \neq 0);$$

$$\vec{a}\ R_r4\vec{a}' \equiv \forall \vec{a}_i^j, \vec{a}_i^{j+1} \in A : (\vec{a}_i^j \times \vec{a}_i^{j+1} \neq \vec{a}_i^j) \cap (\vec{a}_i^j \times \vec{a}_i^{j+1} = \vec{a}_i^{j+1}) \cup (\vec{a}_i^j \times \vec{a}_i^{j+1} \neq 0);$$

$$\vec{a}\ R_r5\vec{a}^{\copyright} \equiv \forall \vec{a}_i^j, \vec{a}_i^{j+1} \in A : (\vec{a}_i^j \times \vec{a}_i^{j+1} = \vec{a}_i^j) \cap (\vec{a}_i^j \times \vec{a}_i^{j+1} \neq \vec{a}_i^{j+1}) \cap (\vec{a}_i^j \times \vec{a}_i^{j+1} \neq 0).$$

Based on these relations, the following operations of analysis and synthesis of information are respectively performed:

$$Q^1_{r1}(\vec{a}, \vec{a}') = (\vec{a}^1_{ri}, \vec{a}^k_{ri}, \vec{a}^{k+1}_{ri}), \vec{a}^1_{ri} := \vec{a}^1_{ri}, \vec{a}^k_{ri} := 0, \vec{a}^{k+1}_{ri} := 0, m_k^{\vec{a}_i^1} := b_k, m_k^{\vec{a}_i^2} := b_k, P^0_{\vec{a}_i^1} = f(m_k^{\vec{a}_i^1}), P^0_{\vec{a}_i^2} = f(m_k^{\vec{a}_i^2});$$

$$Q^2_{r1}(\vec{a}, \vec{a}') = (\vec{a}^1_{ri}, \vec{a}^k_{ri}, \vec{a}^{k+1}_{ri}), \vec{a}^1_{ri} := \vec{a}^1_{ri}, \vec{a}^k_{ri} := \vec{a}^k_{ri}, \vec{a}^{k+1}_{ri} := 0, m_k^{\vec{a}_i^1} := b_k, m_k^{\vec{a}_i^2} := b_k, P^0_{\vec{a}_i^1} = f(m_k^{\vec{a}_i^1}), P^0_{\vec{a}_i^2} = f(m_k^{\vec{a}_i^2});$$

$$Q^3_{r1}(\vec{a}, \vec{a}') = (\vec{a}^1_{ri}, \vec{a}^k_{ri}, \vec{a}^{k+1}_{ri}), \vec{a}^1_{ri} := (\overline{\vec{a}^1_{ri} \times \vec{a}^k_{ri}} \times \vec{a}^1_{ri}) \cup c_{rj}, \vec{a}^k_{ri} := (\overline{\vec{a}^1_{ri} \times \vec{a}^k_{ri}} \times \times \vec{a}^k_{ri}) \cup c_{rj}, \vec{a}^{k+1}_{ri} := \vec{a}^1_{ri} \times \vec{a}^k_{ri}, m_k^{\vec{a}_i^1} := b_k, m_k^{\vec{a}_i^k} := b_k,$$
$$m_c^{\vec{a}_i^{1,k}} := f(P^0_{\vec{a}_i^{k+1}}), P^0_{\vec{a}_i^{k+1}} = f(m_k^{\vec{a}_i^{+1k}}), P^0_{\vec{a}_i^1} = f(m_k^{\vec{a}_i^1}, m_c^{\vec{a}_i^1}), P^0_{\vec{a}_i^k} = f(m_k^{\vec{a}_i^k}, m_c^{\vec{a}_i^k});$$

$$Q^4_{r1}(\vec{a}, \vec{a}') = (\vec{a}^1_{ri}, \vec{a}^k_{ri}, \vec{a}^{k+1}_{ri}), \vec{a}^1_{ri} := (\overline{\vec{a}^1_{ri} \times \vec{a}^k_{ri}} \times \vec{a}^1_{ri}) \cup c_{rj}, \vec{a}^k_{ri} := \vec{a}^k_{ri}, \vec{a}^{k+1}_{ri} := 0, m_k^{\vec{a}_i^1} := b_k, m_k^{\vec{a}_i^k} := b_k, m_c^{\vec{a}_i^k} := f(P^0_{\vec{a}_i^k}),$$
$$P^0_{\vec{a}_i^k} = f(m_k^{\vec{a}_i^k}), P^0_{\vec{a}_i^1} = f(m_k^{\vec{a}_i^1}, m_c^{\vec{a}_i^1});$$

$$Q^5_{r1}(\vec{a}, \vec{a}') = (\vec{a}^1_{ri}, \vec{a}^k_{ri}, \vec{a}^{k+1}_{ri}), \vec{a}^1_{ri} := \vec{a}^1_{ri}, \vec{a}^k_{ri} := (\overline{\vec{a}^1_{ri} \times \vec{a}^k_{ri}} \times \vec{a}^k_{ri}) \cup c_{rj}, \vec{a}^{k+1}_{ri} := 0, m_k^{\vec{a}_i^1} := b_k, m_k^{\vec{a}_i^k} := b_k, m_c^{\vec{a}_i^k} := f(P^0_{\vec{a}_i^1}), P^0_{\vec{a}_i^1} = f(m_k^{\vec{a}_i^1}),$$
$$P^0_{\vec{a}_i^k} = f(m_k^{\vec{a}_i^k}, m_c^{\vec{a}_i^k}).$$

Here $\cup$ is the disjunction of vectors applied to the components of the vectors.

If $\vec{a}^1_{ri} \neq \vec{a}^k_{ri}$,

then $\vec{a}^1_{ri} := \vec{a}^1_{ri}$, $\vec{a}^k_{ri} := \vec{a}^k_{ri}$, $\vec{a}^{k+1}_{ri} := 0$, $m^{a^1_i}_k := b^{r^1_i}_k$, $m^{a^1_i}_k := b^{r^1_i}_k$,
$P^0_{a^1_i} = f(m^{a^1_i}_k)$, $P^0_{a^1_i} = f(m^{a^1_i}_k)$, if $\vec{a}^1_{ri} \neq \vec{a}^k_{ri}$, then
$\vec{a}^k_{ri} := 0$, $\vec{a}^{k+1}_{ri} := 0$, $m^{a^1_i}_k := b_k$, $P^0_{a^1_i} = f(m^{a^1_i}_k)$.

$$k = \begin{cases} 1, \textit{ if operation } Q^1_{rj}, \\ 2, \textit{if ope k = ration } Q^2_{rj}, Q^4_{rj}, Q^5_{rj}, \\ 3, \textit{ if operation } Q^3_{rj}. \end{cases}$$

Here P_i is an excitation threshold of the neural-like element a_{ir}. $P_i = f(m_i)$, provided that the set of connections D_r coming to the neural-like element air corresponds to the set of values (weight coefficients) $M_r = \{m_i\}, i = \overline{1, w}$, and m_i can take both positive and negative values.

NE works as follows. When information arrives, block 2 determines in which of the relations $R1$, $R2$, $R3$, $R4$, $R5$ a pair of vectors $\vec{a}$, $\vec{a}'$ is. In accordance with a certain ratio in block 3, one of the operations $Q^1_{rj}, Q^2_{rj}, Q^3_{rj}, Q^4_{rj}$ or Q^5_{rj} is performed; as a result, the connections and the excitation threshold of the neural-like element are determined. If a permissive modulating signal is received at the input of block 6 and the excitation threshold exceeds the minimum allowable excitation threshold, then the neural-like element goes into an excited state, block 5 generates an enable code, and block (6) skips the output code [23].

3.2.2 The main functions of the neural-like element

Receiving function. Receipt at the inputs of a neural-like element of external information, presented in the form of values of its features (codes, bursts of impulses).

Integrative function. External information is processed according to mutually exclusive relations $R1$, $R2$, $R3$, $R4$, or $R5$. The operation $Q^1_{rj}, Q^2_{rj}, Q^3_{rj}, Q^4_{rj}$, or Q^5_{rj} is determined; as a result, analysis, highlighting differences, classification, synthesis, generalization, and memorization of perceived information is carried out. Codes for controlling external devices are developed and, in order to form connections between neural-like elements, the level of excitation of the neural-like element is also determined in accordance with the values of the features that characterize the input information.

Conductor function. An excitation impulse, codes, and bursts of impulses are carried along the axon.

Transfer function. The excitation impulse is transmitted to the inputs of other neurons.

3.2.3. Analysis, synthesis, and storage of information in neural-like elements

Depending on the function performed, neural-like elements are divided into three main groups: sensitive, efferent, and intercalary.

Sensitive NEs perceive information, convert it into nerve impulses, and transmit to the CNS. Efferent neurons generate and send commands to the working organs, ensuring the transfer of information from the central nervous system to the periphery. Intercalary neurons communicate between sensory and motor neurons, and participate in information processing and command generation, ensuring the transmission of information within the CNS.

3.2.4. Recognition of visual information by neural-like elements

A neural-like element, being a model of a biological neuron, works in accordance with its functioning. Let's consider the work of the neural-like element using the example of memorizing and recognizing letters of the Russian alphabet in comparison with the work of a biological neuron.

When the image of the letter "*а*" enters the retina, the information is processed and transmitted as a series of pulses. In response to a nerve impulse, a neurotransmitter is released. On reaching the receptors on the postsynaptic membrane, the neurotransmitter activates them, resulting in an electrical signal. In accordance with the description provided above, information in the form of biomolecules enters the cytoplasm of one of the sensory neurons and is stored.

In intelligent systems or robots, the image of the letter "*а*" is sent to the neural-like elements of the visual system. In neural-like element 1, information describing the image of the letter "*а*" in the form of a Boolean vector $\vec{a}$ arrives to the receptors. The information is processed in accordance with mutually exclusive relations $R1$, $R2$, $R3$, $R4$, and $R5$. Based on these relations, one of the following operations $Q_{rj}^1, Q_{rj}^2, Q_{rj}^3, Q_{rj}^4$, or Q_{rj}^5 of information analysis and synthesis in NE is determined and stored (Fig. 16).

Figure 16 – Memorization of the letter "*а*"

When the image of the letter "*б*" is received on the retina, the information is processed and transmitted as a series of impulses to neurons 1 and 2. They have receptors that perceive part of the information belonging to the letter "*б*". As a result of endocytosis, these receptors are removed and transferred to the nearest spontaneously excited neuron 3 (Fig. 17).

The sensitivity of postsynaptic membranes of neurons 1 and 2 to this neurotransmitter decreases. Neuron 3 remembers the transmitted information and goes into an excited state. As a result, the information describing the letters "*а"* and "*б*", as a result of the analysis, is divided and stored in neurons 1-3.

In intelligent systems or robots, the image of the letter "*b*" is sent to the neural-like elements. In neural-like elements 1 and 2, information describing the image of the letter "*б*" in the form of a Boolean vector comes to the receptors. A pair of vectors $(\vec{a}, \vec{a})$ is processed according to mutually exclusive relations $R1$, $R2$, $R3$, $R4$, and $R5$. Based on the relations $R1$, $R2$, $R3$, $R4$, and $R5$, the following operations $Q_{rj}^1, Q_{rj}^2, Q_{rj}^3, Q_{rj}^4$, and Q_{rj}^5 of information analysis and synthesis in NE are determined. A pair of vectors $(\vec{a}, \vec{a})$ in NE 1 and 2 is in relation to R3, respectively, the operation Q_{rj}^3, is performed. As a result, the information describing the letters "*а*" and b" is divided and stored in NE 1-3 (Fig. 17).

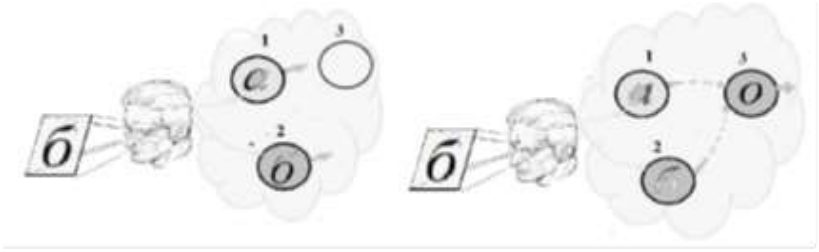


Figure 17 – Memorization of the letter "б"

When the image of the letter "*а*" is received again on the retina, the information is processed and transmitted in the form of a series of impulses to neurons 1-3. There are no receptors

in neuron 2 that perceive information belonging to the letter "*а*". Neuron 2 is not activated. Neurons 1 and 3 are excited to the maximum, connect with the nearest spontaneously excited neuron 4, and transmit information. As a result, the letter "*а*" is formed and remembered in neuron 4 (Fig. 18).

Figure 18 – Memorization of the letter "*а"*

In intelligent systems or robots, the image of the letter "*а*" is sent to the neural-like elements 1-3. In neural-like elements 1-3, information describing the image of the letter "*а*" in the form of a Boolean vector is directed to receptors.

Pairs of vectors are processed according to mutually exclusive relations $R1, R2, R3, R4$, and $R5$. Based on the relations $R1, R2, R3, R4$, and $R5$, the corresponding operations $Q_{rj}^1, Q_{rj}^2, Q_{rj}^3, Q_{rj}^4$ and Q_{rj}^5 of information analysis and synthesis in NE are determined. A pair of vectors in NE 1 is in relation to $R5$, the operation Q_{rj}^5 is performed. A pair of vectors in NE 2 is in relation to $R2$, the operation Q_{rj}^2 is performed. A pair of vectors in NE 3 is in relation to $R5$, the operation Q_{rj}^5 is performed. NE 1 and 3 are transferred to an excited state, connect with NE 4 and transmit information. As a result, the letter "*а*" is remembered in NE 4 (Fig. 18).

When the image of the letter "*б*" is received again on the retina, the information is processed and transmitted in the form of a series of impulses to neurons 1-4. There are no receptors in neuron 1 that perceive information belonging to the letter "*б*". Neuron 1 is not activated. In neuron 4, part of the receptors that receive information coincides with the letter "*б*". Neuron 4 fires according to the number of matching signs of the letter "*б*". In neurons 2 and 3, there is a complete coincidence of parts of the signs of the letter "*б*". Neurons 2 and 3 are maximally excited. They connect with the nearest spontaneously excited neuron 5 and transmit information. As a result, the letter "*б*" is formed and remembered in neuron 5 (Fig. 19).

In intelligent systems or robots, the image of the letter "*б*" is sent to neural-like elements 1-4. In neural-like elements 1-4, information describing the image of the letter "*б*" in the form of a Boolean vector $\vec{б}$ is sent to receptors. Pairs of vectors are processed according to mutually exclusive relations $R1, R2, R3, R4$, and $R5$. Based on the relations $R1, R2, R3, R4$, and $R5$, the corresponding operations $Q_{rj}^1, Q_{rj}^2, Q_{rj}^3, Q_{rj}^4$, and Q_{rj}^5 of analysis and synthesis of information in the NE are determined. A pair of vectors in NE 1 is in relation to $R2$, the operation Q_{rj}^2 is performed. A pair of vectors in NE4 is in relation to $R3$, the operation Q_{rj}^3 is performed. A pair of vectors in NE 2 and 3 is in relation to $R5$, and the operation Q_{rj}^5 is performed. NE 2, 3 are transferred to an excited state, connect with NE 5 and transmit information. As a result, the letter "*б*" is remembered in NE 5 (Fig. 19).

When the image of the letter *"d"* is received on the retina, the information is processed and transmitted in the form of a series of impulses to neurons 1-6. Neurons 1 and 2 do not have receptors that perceive information belonging to the letter *"д"*. Neurons 1 and 2 are not excited.

In neurons 4 and 5, part of the receptors perceives information that matches the letter *"д"*. Neurons 4 and 5 are excited in accordance with the number of matching signs of the letter *"д"*. In neurons 3 and 6, there are completely matching receptors that perceive part of the information belonging to the letter "*о*". As a result of endocytosis, receptors are removed from neuron 6 and transferred to neuron 3. Neuron 3 enters an excited state. Thus, the information describing the letters "*д,о*" is divided and stored in neurons 3 and 6 as a result of the analysis (Fig. 20).

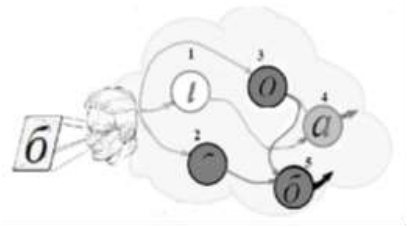


Figure 19 – Memorization of the letter "б"

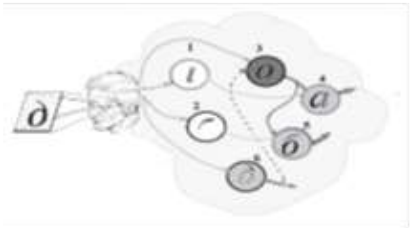


Figure 20 – Memorization of the letter "*д*"

In intelligent systems or robots, the image of the letter "*д*" is sent to neural-like elements 1-6. The information describing the image of the letter "*д*" is sent to NE receptors 1-6 in the form of a Boolean vector. Pairs of vectors are processed in accordance with mutually exclusive relations $R1$, $R2$, $R3$, $R4$, and $R5$. Based on the relations $R1$, $R2$, $R3$, $R4$, and $R5$, the corresponding operations $Q_{rj}^1, Q_{rj}^2, Q_{rj}^3, Q_{rj}^4$, and Q_{rj}^5 of analysis, synthesis of information in the NE are determined. A pair of vectors in NE 1 and 2 is in relation to $R2$, the operation Q_{rj}^2 is performed. A pair of vectors in NE 4, 5, and 3 is in relation to $R3$, the operation Q_{rj}^3 is performed. A pair of vectors in NE 3 and 6 is in relation to $R5$, the operation Q_{rj}^5 is performed. NE 3 is transferred to an excited state. As a result, the information describing the letters "*о"* and "*д"* is divided and remembered in NE 3-6 (Fig. 20).

When the image of the letter "*о*" arrives at the retina, the information is processed and transmitted in the form of a series of impulses to neurons 1-6. There are no receptors in neurons 1, 2, and 6 that perceive information belonging to the letter "*о*". Neurons 1, 2, and 6 are not excited. In neurons 4 and 5, part of the receptors perceives information that matches the letter "*о*". Neurons 4 and 5 are excited in accordance with the number of matching signs of the letter "*о*". In neuron 3, there is a complete coincidence of the signs of the letter "*о*". Neuron 3 is maximally excited. As a result, neuron 3 recognizes the letter "*о*" (Fig. 21).

In intelligent systems or robots, the image of the letter "о" is sent to neural-like elements 1-6. The information describing the image of the letter "*о*" is sent to NE receptors 1-6 in the form of a Boolean vector. Pairs of vectors are processed in accordance with mutually exclusive relations $R1$, $R2$, $R3$, $R4$, and $R5$. Based on these relations, the corresponding operations $Q_{rj}^1, Q_{rj}^2, Q_{rj}^3, Q_{rj}^4$, and Q_{rj}^5 of analysis and synthesis of information in NE are determined. A pair of vectors in NE 1, 2, and 6 is located in relation to $R2$, the operation Q_{rj}^2 is performed. A pair of vectors in NE 4 and 5 is located in relation to $R3$, the operation Q_{rj}^3 is performed. A pair of vectors in NE 3 is in relation to $R5$, the operation Q_{rj}^5 is performed. NE 3 is transferred to an excited state. As a result, information describing the letters "о" is recognized by NE 3 (Fig. 21).

When the image of the letter "*д*" is received again on the retina, the information is processed and transmitted in the form of a series of impulses to neurons 1-6. There are no receptors in neurons 1 and 2 that perceive information belonging to the letter *"д"*. Neurons 1 and 2 are not excited. In neurons 4 and 5, part of the receptors perceives information that matches the letter *"д"*. Neurons 4 and 5 are excited in accordance with the number of matching signs of the letter

"д". In neurons 3 and 6, there is a complete coincidence of parts of the signs of the letter *"д"*. Neurons 3 and 6 are excited to the maximum connect with the nearest spontaneously excited neuron 7 and transmit information. As a result, the letter "*д*" is formed and remembered in neuron 7 (Fig. 22).

In intelligent systems or robots, the image of the letter "*д*" is sent to the neural-like elements 1-6. The information describing the image of the letter *"д"* is sent to NE receptors 1-6 in the form of a Boolean vector $\vec{\partial}$. Pairs of vectors are processed in accordance with mutually exclusive relations $R1$, $R2$, $R3$, $R4$, and $R5$. Based on these relations, the corresponding operations $Q_{rj}^1, Q_{rj}^2, Q_{rj}^3, Q_{rj}^4$, and Q_{rj}^5 of analysis and synthesis of information in NE are determined. A pair of vectors in NE 1 and 2 is located in relation to $R2$, the operation Q_{rj}^2 is performed. A pair of vectors in NE 4 and 5 is located in relation to $R3$, the operation Q_{rj}^3 is performed. A pair of vectors in NE 3 and 6 is located in relation to $R5$, the operation Q_{rj}^5 is performed. NE 3 and 6 are transferred to an excited state, connected with NE 7 and transmit information. As a result, the letter "*д"* is remembered in NE 7 (Fig. 22).

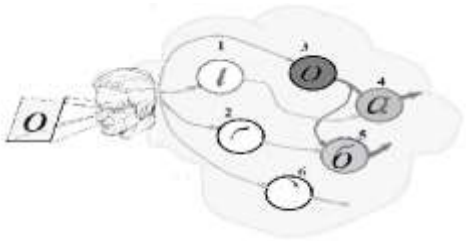


Figure 21 – Memorization of the letter "*о*"

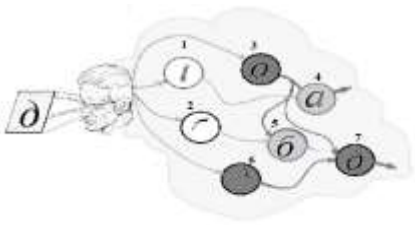
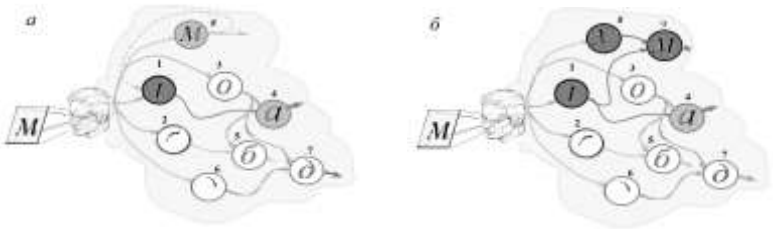


Figure 22 – Memorization of the letter "*д*"

When the image of the letter "*м*" arrives at the retina, the information is processed and transmitted in the form of a series of impulses to neurons 1-8 (Fig. 23 *а*). In neurons 2, 3, 5, 6, and 7, there are no receptors that perceive information belonging to the letter "*м*". Neurons 2, 3, 5, 6, and 7 are not excited. In neurons 4 and 8, part of the receptors perceives information that matches the letter "*м*". Neurons 4 and 8 are excited in accordance with the number of matching signs of the letter "*м*". As a result of endocytosis, receptors are removed from neuron 8 and transferred to neuron 1. Neuron 1 goes into an excited state. Thus, the information describing the letters "*м*", as a result of the analysis, is divided and stored in neurons 1 and 8 (Fig. 23 *а*). When the image of the letter "*м*" is received again on the retina, neurons 1 and 8 are maximally excited. They connect to the nearest spontaneously excited neuron 9 and transmit information. As a result, the letter "*м*" is formed and remembered in neuron 9 (Fig. 23 *б*).

In intelligent systems or robots, the image of the letter "*м*" is sent to neural-like elements 1-8. The information describing the image of the letter "*м*" is sent to NE receptors 1-8 in the form of a Boolean vector $\vec{м}$. Pairs of vectors are processed in accordance with mutually exclusive relations $R1$, $R2$, $R3$, $R4$, and $R5$. Based on these relations, the corresponding operations $Q_{rj}^1, Q_{rj}^2, Q_{rj}^3, Q_{rj}^4$, and Q_{rj}^5 of analysis and synthesis of information in



NE are determined. Pairs of vectors in NE 2, 3, 5, 6, and 7 are located in relation to $R2$, the operation Q_{rj}^2 is performed. A pair of vectors in NE 4 is located in relation to $R3$, the operation Q_{rj}^3 is performed. A pair of vectors in NE 1 and 8 is located in relation to $R5$, the operation Q_{rj}^5 is performed. NE 1 is transferred to an excited state. As a result, the information describing the letter "*м*" is divided and stored in NE 1-8 (Fig. 23 *а*). The image of the letter "*м*" is received again on neural-like elements 1-8. The pair of vectors in NE 1 and 8 is in relation to $R5$, the operation Q_{rj}^5 is performed. NE 1 and 8 are transferred to an excited state, connected with NE 9 and transmit information. As a result, the letter "*м*" is remembered in NE 9 (Fig. 23 *б*).

From the examples provided above, it can be seen that during the first perception, information is divided into separate parts during the analysis. With repeated perception, information from the parts is restored. Hence the need for repetition in learning and memorizing new information. "Repetition is the mother of learning" is a proverb that confirms this rule.

Perhaps the mechanism of operation of human brain neurons described here is not entirely accurate, but the work of neural-like elements in the "brain" of a humanoid robot or intelligent system is real and tested on the model of the intelligent information system "Dialogue" and the recognition system of various objects "Recognition".

4. Conclusions

Consideration and analysis of the structure and functions of a biological neuron showed it as the main component of natural intelligence. It is concluded that huge amounts of information perceived by people after their birth and throughout their life are remembered at the molecular level in the endoplasmic reticulum of neurons. There are about 100 billion neurons in the human brain, and each neuron contains millions of membrane-bound ribosomes that synthesize a mediator consisting of about 10,000 molecules. If we assume that one molecule corresponds to one unit of information, then human memory is unlimited.

In the nerve cell, there is a synthesis of biologically active substances necessary for the analysis and memorizing of information. The factory for the production of proteins is the endoplasmic reticulum, which accumulates millions of membrane-bound ribosomes. Ribosomes are used for protein biosynthesis on the basis of genetic information and information supplied to the dendrites of the neuron. One ribosome synthesizes protein at a rate of 15-20 amino acids per second. At the same time, it makes mistakes quite rarely: in 3000 amino acids may be only one mistake. Thus, the work of the ribosome is a highly precise process. Bruce Alberts, a famous American biochemist, compared the ribosome with a "molecular machine", emphasizing the coherence and elegance of the work of this molecular complex. Considering this fact and the fact that the functional structure of ribosomes is similar to the Turing machine, we can conclude that the neuron is an analog multimachine complex – an ultra-fast molecular multimachine supercomputer with an unusually simple analog programming device.

Despite the significant success in using the artificial neuron by J. McCulloch and W. Pitts as the main element of many neural networks, it is functionally very simplified to be an analogue of a biological neuron. In this regard, a neural-like element (an artificial neuron of a new type) is proposed as an analog of a biological neuron and the main element of a new type of neural network – a neural-like growing network (nGN).

The example of teaching letters shows the analysis, synthesis, and memorizing information in neuron-like elements.

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