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V. Yashchenko
Institute Problems of Mathematical Machines and Systems of the NAS of Ukraine, Ukraine
Akademika Glushkova avenue, 40, Kyiv, 03680
vitaly.yashchenko@gmail.com
http://orcid.org/ 0000-0001-9396-6581

SECRETS OF MEMORY. BIOLOGICAL AND COMPUTER PARALLELS

Abstract. This article explores one of the most mysterious and multifaceted aspects of human nature - memory. Memory defines the system's ability to learn, adapt, and make informed decisions based on accumulated experience. It plays an important role in solving conceptual and theoretical problems in the field of artificial intelligence and modeling. Learning and adaptation is one of the key aspects where memory models allow AI systems to not only reproduce but also improve their performance based on experience. It is also important to consider memory modeling as preserving the context of past events, which is important for the correct understanding and interpretation of current situations. The article examines the issue of memory location, starting with classical theories explaining the mechanisms of memory location in the brain, including neurophysiology and the theory of conditioned reflexes. However, special attention is paid to alternative approaches, such as the theory of intracellular memory, which offers new ways of understanding memory. Finally, the work draws attention to the connection between learning and memory, especially in the context of the formation of conditioned reflexes. In the process of considering the neuron as a key element of the nervous system and studying protein synthesis and polyribosomes, a surprising similarity between the process of protein synthesis in neurons and the functioning of the Turing machine was revealed. In the context of this analogy, a neuron can be perceived as a molecular computer, providing a new level of understanding of memory formation and information processing in the brain. The author hopes that this research will help to better understand the nature of human memory and enrich our knowledge about how the brain works.

Keywords: memory, neuron, biosynthesis Turing machine, neuron molecular computer.

1. Introduction

In the modern world, artificial intelligence is capable of creating incredible things, but the key to further development and improvement lies in a deeper understanding of the formation and functioning of the memory of biological systems. Memory determines a system's ability to learn, adapt, and make informed decisions based on experience. It plays an important role in solving conceptual and theoretical problems in the field of artificial intelligence and modeling, which manifests itself in several key aspects: Learning and Adaptation. Memory simulation allows artificial intelligence systems to learn from experience and adapt to changing conditions. Knowledge of previous events and interactions can be used to improve forecasting and make smarter decisions; Ability to understand context. Memory models allow systems to take into account the context of past events, which is essential for understanding and interpreting current situations. This is important in various fields such as natural language processing, where understanding context plays an important role; Emulation of cognitive processes. Memory modeling is necessary to emulate human cognitive processes such as memorization, recall, and generalization. This contributes to the creation of more human-like and efficient artificial intelligent systems; Solving the problem of forgetting. Memory is also a way to solve the problem of forgetting by allowing systems to store information for later use. This is particularly important in the context of long-term learning and knowledge accumulation; Information management. Memory modeling helps systems manage information and determine its importance and relevance. This can be useful in making decisions and selecting optimal strategies; Decision support. Memory provides the basis for making decisions based on past experiences. This helps artificial intelligence systems learn lessons from previous situations and apply them in new contexts.

Memory, this most important attribute of human existence, remains the subject of fascinating research. Over time, we take amazing trips down memory lane, collecting millions of pieces of the past, stories, emotions

and knowledge in our minds. Our ability to retain experiences and information throughout life's ups and downs makes memory one of the most mysterious and important aspects of our lives. Since ancient times, people have tried to understand how memory is stored in the human brain and how it affects our behavior and thinking. Today, thanks to the progress of scientific research and modern technology, we are gradually getting closer to unlocking the secrets of memory - the mechanisms behind it and the opportunities it provides for improving our lives and understanding of ourselves.

This article examines various theories of memory formation and storage. From this perspective, the functions of the biological neuron and the extraordinary similarity of its functioning to the Turing machine are also considered.

I hope this article will help learn more about what makes us unique creatures with a rich inner world and an endless supply of memories.

2. Memory

Memory is a complex and multifaceted process, and the mechanisms of its storage in the brain are still the subject of active research. Despite this, there are several theories and evidence that attempt to explain the mechanisms and location of memory in the brain at different levels.

At the molecular level, memory may be associated with changes in synaptic connectivity - the strength and efficiency of connections between neurons. Research has shown that molecular changes, such as changes in the number or sensitivity of receptors at synapses, may play an important role in the storage and retrieval of information in memory [1].

At the level of cellular memory, neurons may have special properties that allow them to encode, store, and retrieve information. For example, studies in primates have shown that some neurons in the brain respond to specific stimuli, such as images of a face or an object [2]. These "conceptual neurons" can signal the presence of certain information.

At the systemic level, memory can be associated with the activity of large networks of neurons and different brain regions. Areas such as the hippocampus, prefrontal cortex, and temporal lobes play key roles in the formation, storage, and retrieval of information from memory (EicSenbaum & CoSen, 2001) [3].

Despite significant advances in the study of memory, the exact location and mechanisms of its storage still remain a challenging research question. Further research and discoveries may help to more precisely define the mechanisms and basis of memory in the brain. But how and where exactly is memory stored in the brain? There are several theories that try to explain the mechanisms and location of memory at different levels - from molecular to systemic.

2.1. Classical theory of neurophysiology

According to the classical theory of neurophysiology, memory is realized through the formation and strengthening of synaptic connections between neurons in the brain. This theory, developed by Camillo Golgi, Santiago Ramon y Cajal and Donald Hebb, states that repeated co-firing of neurons leads to stronger connections between them, which is the basis of learning and memory formation.

Experiments using brain stimulation, electroencephalography, and functional magnetic resonance imaging support the relationship between repeated coexcitation and strengthening of synaptic connections [4]. For example, research has shown that long-term learning and long-term memory formation are accompanied by structural and functional changes in synaptic connections [5].

According to classical theory, different types of memory can be stored in different areas of the brain. For example, the prefrontal cortex is responsible for short-term working memory, the hippocampus and other temporal lobe structures are associated with long-term declarative memory, and procedural skill memory is associated with the cerebellum and basal ganglia [6,7].

2.2. Conditioned reflex theory

At the international medical congress in Madrid in 1903, I. P. Pavlov presented the conditioned reflex theory, which is considered

one of the foundations for understanding learning and memory formation [8]. According to this theory, conditioned reflexes play a key role in these processes.

A conditioned reflex is the body's reaction to a stimulus that initially does not cause such a reaction, but becomes pronounced after pairing with another stimulus. Pavlov studied conditioned reflexes in dogs, showing that they can be of various types - positive or negative, simple or complex, differentiated or generalized. He studied how conditioned reflexes could be strengthened or weakened depending on the sequence and frequency of presentation of stimuli.

Based on his research, Pavlov believed that memory represents dynamic stereotypes in the cortical centers of the brain - stable combinations of excitation and inhibition of neurons in response to stimuli [9]. He assumed that these stereotypes are the basis of memory, and thinking is the process of comparison and generalization of conditioned reflexes based on the analysis and synthesis of information.

Despite the fact that Pavlov's concept of conditioned reflexes and memory was developed at the beginning of the 20th century, it remains important in the study of the nature of memory and its formation in animals and humans.

2.3. Intracellular memory theory

Despite the significance of the classical theory of neurophysiology, problems and contradictions arise, stimulating the search for alternative explanations of memory mechanisms. One such alternative theory is the theory of intracellular memory, developed by Charles Randy Gallistel [10], which offers a different view of where and how memory information is stored within individual neurons, not just at synaptic connections.

Gallistel points out that synaptic connections, while important, can be unstable and subject to change over time [11]. He also makes the argument that the amount of information required for memory storage exceeds the capacity of synaptic plasticity. In this regard, he proposes that memory may be stored inside neurons in the form of special molecules or structures located in the cytoplasm [10]. These molecules or structures can encode information about past events and experiences using various encoding methods, such as chemical or electrical signals. He also suggests that these molecules or structures can exchange information between neurons or other cells through special channels or carriers. This envisions neurons as small computers capable of storing, processing, and transmitting information.

From this position, it is advisable to consider the structure and functions performed by the neuron.

3. Neuron

Neurons are living nerve cells that are the basic building blocks of the nervous system, capable of transmitting and processing information using electrical and chemical signals. They consist of three main components: the soma (cell body), dendrites and axons. The soma contains the nucleus and other necessary organelles.

Dendrites are branched processes that receive signals from other neurons or receptors. An axon is a long extension that transmits signals to other neurons, muscles, or glands. At the points of contact between the axon of one neuron and the dendrite or soma of another, there are synapses where chemical signal transmission occurs using neurotransmitters. Neurons form complex networks that control various aspects of thinking, memory, emotions, behavior and other body functions.

The cytoplasm of a nerve cell contains structural components called organelles.

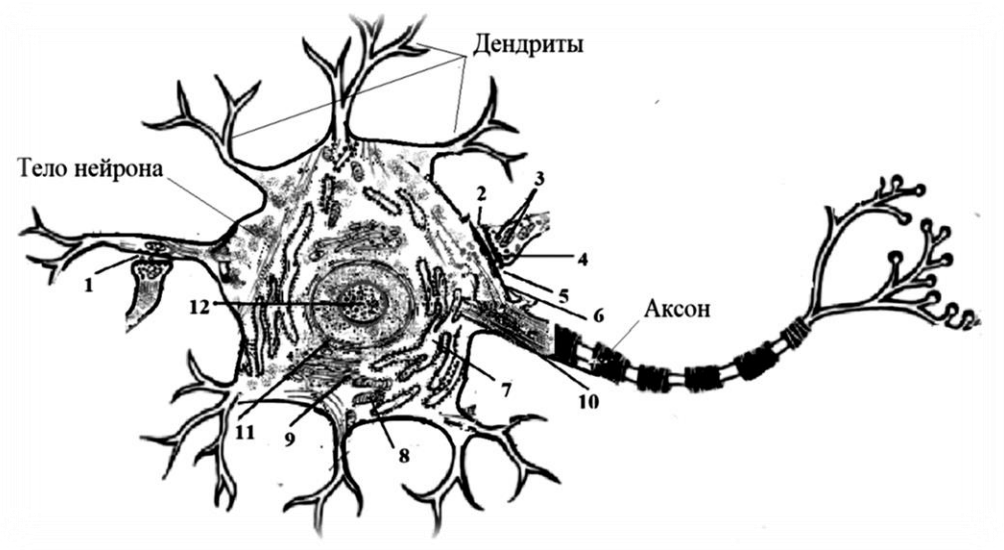

Fig.1. Neuron cell structure

The structure of a nerve cell and its organelles include:

1. Axodendritic synapse, where the axon contacts the dendritic process of another neuron.
2. Axosomatic synapse, where the axon of one neuron contacts the body of another cell.
3. Presynaptic vesicle - a vacuole containing mediators.
4. Presynaptic membrane - part of the surface membrane of the nerve fiber.
5. Synaptic cleft - the space between the presynaptic and postsynaptic membranes.
6. Postsynaptic membrane - a thickened surface membrane of the cell in the area of the synapse.
7. Endoplasmic reticulum (ER) or endoplasmic reticulum (ER) is an organelle consisting of many membranes on which ribosomes accumulate.
8. Mitochondria are double-membrane organelles that play an important role in metabolism.
9. The Golgi apparatus is a complex network of organelles bounded by membrane cavities.
10. Neurofibrils are filamentous structures of the cytoplasm of a neuron.
11. Cell nucleus - controls cellular processes and is the controlling center of the cell.
12. The nucleolus is a small but powerful organelle responsible for several important functions, including the synthesis and assembly of ribosomes [12].

3.1.Biosynthesis

Protein biosynthesis is a complex and fascinating process that allows cells to create a variety of molecules necessary for life. Proteins determine our physical and mental characteristics, our ability to learn and memory, and our response to stress and illness. Thanks to ribosomes and polysomes, cells can quickly and accurately produce proteins according to the genetic code.

Protein synthesis in a ordinary cell and a nerve cell (neuron) has some differences. In a cell, proteins serve as building materials and perform various functions, such as maintaining the structure of the cell and participating in chemical reactions. In neurons, proteins perform similar functions but are also used to encode and transmit information. Protein synthesis consists of two stages: transcription and translation. Transcription occurs in the cell nucleus, where messenger RNA is formed.

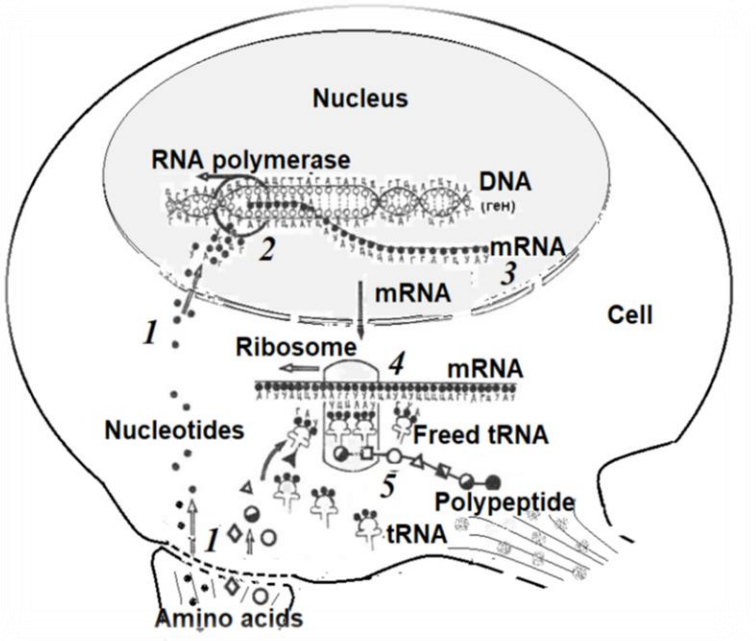

Fig.2. Scheme of protein synthesis in the ribosome

When nucleotides (external information) enter the nucleus of cell 1 (Figure 2). A special enzyme, RNA polymerase, binds to DNA molecule 2 and creates a “mirror copy” - messenger ribonucleic acid (mRNA) 3 or, as it is also called, messenger RNA (mRNA), which moves freely from the nucleus into the cytoplasm of the cell. Messenger RNA consists of nucleotides, which are designated by the letters A, U, G, C. Three adjacent nucleotides form a codon. Each codon codes for its own strictly defined amino acid. A total of twenty different amino acids can be used o build protein. The broadcast consists of three stages. The first is called initiation or beginning of the synthesis of the polypeptide chain. The second is elongation or continuation of synthesis. And the third is termination or completion of synthesis.

Initiation. The genetic code is read from messenger RNA molecules by the ribosome. Ribosome - consists of large 5 and small 4 subunits. During initiation, the small ribosomal subunit attaches to the mRNA and moves along it until it reaches the start codon. The start codon is always the same. This is AUG. Next, transfer RNA with the first amino acid - methionine - is added to the start codon according to the principle of complementarity, that is, the first amino acid is always the same - methionine. And then the large ribosomal subunit attaches.

Transfer RNA is RNA folded into a clover leaf. Each transfer RNA carries its own strictly defined amino acid. An important part of every tRNA is the so-called anticodon. An anticodon is a sequence of three nucleotides. The anticodon is complementary to the mRNA codon. Before an amino acid attaches to a tRNA, the amino acid is activated by ATP.

The second stage is elongation. During elongation, a new transfer RNA with a new amino acid is added according to the principle of complementarity to the messenger RNA. A peptide bond occurs between amino acids. Then the ribosome moves one codon and the tRNA is released, leaving its amino acid behind. A new tRNA with a new amino acid comes into the empty space. The process is repeated again and again and the chain of amino acids grows.

The third stage is termination. When terminated, the ribosome travels along the mRNA to the stop codon. In this case, a termination factor attaches to the ribosome and this entire complex is disconnected [13,14].

A stop codon or termination codon is a three nucleotide residues in mRNA that encodes the termination of the synthesis of a polypeptide chain. Standard stop codons are UAA, UAG and

UGA. Stop codons perform the important function of completing (terminating) the assembly of a polypeptide chain and are also called termination codons. Some of them cause obligatory cessation of synthesis, others are conditional. Some mRNAs actually contain two tandem stop codons—often different types of codons at the end of the coding sequence.

3.2. Polyribosomes

Depending on the state of the external environment, the composition of the ribosome in cells can change. Neurons can use different types of ribosomes to translate different types of mRNA. This allows them to specialize in the synthesis of certain proteins that are needed for different tasks of the cell. Using the most modern technologies, it has been established that mammalian cells contain ribosomes of different compositions!

It turned out that in the same cell there is not one heterogeneous population of ribosomes, but several such populations at once! They do not replace each other, but coexist simultaneously.

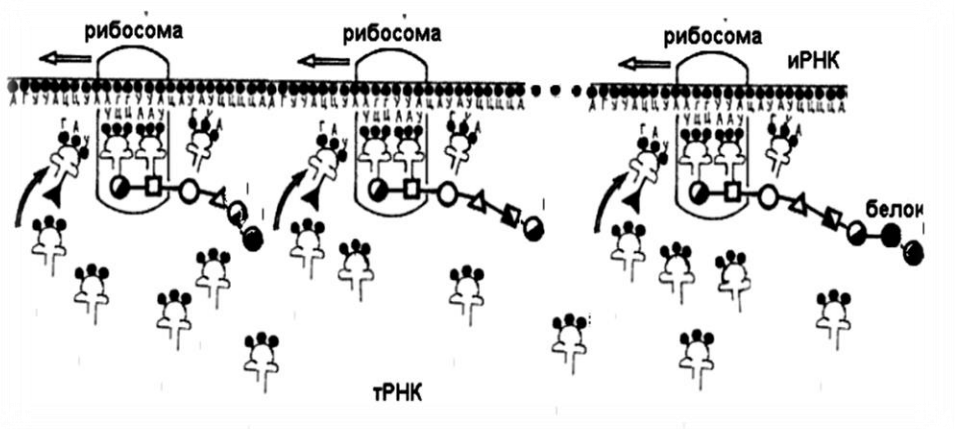

Fig.3. Protein synthesis on a polysome

Each population translates only a specific set of mRNAs. This means that ribosomes are not universal. Certain groups of ribosomes interact only with certain mRNAs and, therefore, are “responsible” for the synthesis of only part of cellular proteins. Biosynthesis in a cell does not occur on one ribosome. As a result, a complex of ribosomes is formed, which simultaneously and independently of each other participate in the synthesis of protein molecules using the same mRNA. This complex is called a polyribosome, or polysome (Figure 3).

4. Turing machine

The processing of information in a Turing machine and the process of protein synthesis in a neuron are two seemingly unrelated processes, but there is an intriguing connection between them in the striking similarity between the process of functioning of a Turing machine and the process of protein synthesis in a nerve cell.

Let's start with a brief overview of the Turing machine. A Turing machine is a mathematical model developed by Alan Turing in the 1930s [15]. It is an abstract computer capable of performing any algorithmic task as long as it can be formulated as a sequence of instructions. This is a theoretical machine consisting of an infinitely long tape and a head that moves along the tape, reading and writing characters (Figure 4). The machine operates in an arbitrary finite alphabet $A = \{a_0, a_1 \ldots a_n\}$ - this alphabet is called external. Processing information and issuing commands to write a sign, as well as shift the tape in a Turing machine, is carried out by a logical device (LU). The LU may be in one of the states. A set of states (table of states) are designated $Q = \{q_1 \ldots q_m, z\}$, (similar to mRNA codons in the sense of an analogue with ribosomal protein synthesis) and state a_0 (analogous to the start codon 3') corresponds to the completion of work,

and q_1 (analogous to the stop codon 5') is initial (initial).

$A = \{\Delta, a_1 \ldots a_n\}$ – external alphabet of the machine (analogue of tRNA ribosomes).

Operation of a Turing machine: at step *i*, a sign from the currently observed cell (a_i,) is sent to one input of the LU, and a sign indicating the state of the LU at the moment (qi) is sent to the other input (On the ribosome, tRNAs are lined up against mRNA. Codon and anticodon must match).

Depending on the received combination of signs (a_i, q_i) and the existing processing rules, the LU generates and sends a new sign (a_i+1) to the cell being monitored via the first output channel, and issues a command to move the head D_i+1 from R (right), *L* (left) and *S* (stop), and also gives a command to call the next control character (q_i+1). (Similarly, after each new amino acid is added, the ribosome subunits move along the mRNA chain by one codon.).

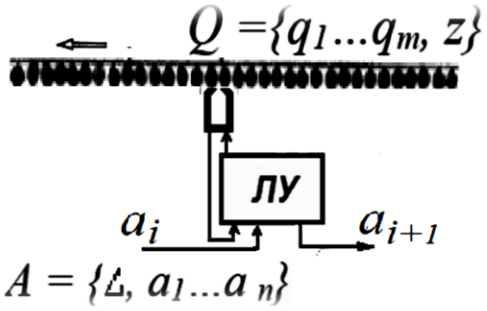

Fig.4. Turing machine device

A particular Turing machine is defined by a set of sets *A* and *Q*, as well as a logical function that it implements through a set of transformation rules.

The external alphabet *A* of a Turing machine can contain not only elements in binary format, but also various symbolic and numeric elements, which allows it to solve problems of processing information in different formats.

In a neuron, information is also not represented in binary form. In neurons, information is processed in the form of electrical impulses that are transmitted along axons and dendrites. These pulses encode various parameters of information, such as intensity, frequency, duration, phase and others. Neurons are able to communicate with each other through synapses, where chemical signaling occurs using neurotransmitters. This process allows neurons to exchange information and transmit signals from one neuron to another.

In addition, neurons can change their sensitivity and connectivity depending on experience and learning. This allows them to adapt to new information and store it in long-term memory.

4.1.The functioning of a Turing machine using the example of solving arithmetic problems

Let's look at the operation of a Turing machine using the example of solving an arithmetic problem.

Let's imagine that we have the problem of adding the decimal number 254 and 1. Below is a table of LU states of a Turing machine, which describes the process of summing any integer decimal number with one. By analogy with the process of protein synthesis in a neuron, this table of states can be considered as the informational genetic code of a Turing machine for performing a given operation.

Table 1. LU states when summing any decimal integer and one

	a_0	0	1	2	3	4	5	6	7	8	9
q_1	a_0Sq_0	$1Sq_1$	$2Sq_1$	$3Sq_1$	$4Sq_1$	$5Sq_1$	$6Sq_1$	$7Sq_1$	$8Sq_1$	$9Sq_1$	$0Lq_1$

254 +1 =. Initial configuration *25 $q_1$4.*
Time 1. $q_1$4 →5Sq_1, i.e. *4* will be replaced by *5* and stop with the final configuration *255,* i.e. the result of the addition is *254+1=255.*
The following example is *999 + 1 =*. Initial configuration *99 $q_1$9.*
Time 1. $q_1$9→ 0L q_1, i.e. *9* will be replaced by *0* and an intermediate configuration *9 $q_1$90* will be formed.
Time 2. $q_1$9→ 0L q_1, i.e. *9* will be replaced by *0* and the *$q_1$900* configuration will occur.
Time 3. *$q_1$9 →0L q_1* i.e. *9* will be replaced by *0* and *$q_1$000* will appear.
Time 4. $q_1$0 →1Sq_1 i.e. *0* will be replaced by *1* and stop operation will be terminated. The value received is *1000,* i.e. the result of addition is *999 + 1 = 1000*

Next, we will consider the summation of any integer decimal number and two.
For example, 367 + 2 =.

Table 2. LU states when summing any decimal integer and binary

	a_0	0	1	2	3	4	5	6	7	8	9
q_1	a_0Sq_0	$2Sq_1$	$3Sq_1$	$4Sq_1$	$5Sq_1$	$6Sq_1$	$7Sq_1$	$8Sq_1$	9S q_1	$0Lq_2$	1L q_2
q_2	-	$3Lq_1$	$4Lq_1$	$5Lq_1$	$6Lq_1$	$7Lq_1$	$8Lq_1$	$9Lq_1$	$0Lq_3$	$1Lq_3$	$2Lq_3$
q_3	-	$1Lq_1$	$2Lq_1$	$3Lq_1$	$4Lq_1$	$5Lq_1$	$6Lq_1$	$7Lq_1$	$8Lq_1$	$9Lq_1$	$0Lq_1$

In this case, the state table (+2) summation of any whole decimal number and a two is the "genetic code +2" of the Turing machine 367 + 2 =. The initial configuration is *36$q_1$7*.

Time 1. $q_1$7→9Sq_1, i.e. *7* will be replaced by *9* and a stop will occur with a final configuration of *369,* i.e. the result of adding *367 + 2 = 369* is obtained.
398 +2 =. The initial configuration is *39$q_1$8.*
Time 1. $q_1$8→0Lq_2, i.e. *8* will be replaced by *0* and the configuration *3$q_2$90* will occur.
Time 2. $q_2$9→2Lq_3, i.e. *9* will be replaced by *2* and the configuration $q_3$320 will occur.
Time 3. $q_3$3→4Lq_1, i.e. *3* will be replaced by *4* and the configuration q_1-420 will occur.
Time 4. q_1_- → a_0Sq_0, stopping and the result of addition *398+2=420* is obtained.
789 +2 =. The initial configuration is 78$q_1$9.
Time 1. $q_1$9→1Lq_2, i.e. *9* will be replaced by *1* and configuration *7$q_2$81* will occur.
Time 2. $q_2$8→1Lq_3, i.e. *8* will be replaced by *1* and configuration *$q_3$711* will occur.
Time 3. $q_3$7→8Lq_1, i.e. *7* will be replaced by *8* and the configuration q_1 - 811 will occur
Time 4. q_1 - → a_0Sq_0, stop and the result of addition *789 + 2 = 811* is obtained.

The described algorithms provide the summation of any integer decimal number and one, number and two. In order to perform addition with some integer *m*, the addition algorithm with *1* must be repeated *m* times or create tables of addition states with *+3, ..., +9.*

Let's consider solving the problem of multiplying, for example, by *2* any number written in the decimal number system. State line *q_1* - multiplying the next digit of a number by *2* without adding 1 carry. State line *q_2* - multiplying the next digit of a number by *2* with the addition of 1 carry.

Table 3. LU states when multiplying any decimal integer by two

	a_0		0	1	2	3	4	5	6	7	8	9
q_1	a_0Sq_0		$0Lq_1$	$2Lq_1$	$4Lq_1$	$6Lq_1$	$8Lq_1$	$0Lq_2$	$2Lq_2$	4L q_2	6L q	8L q_2
q_2	$1Sq_0$		$1Lq_1$	$3Lq_1$	$5Lq_1$	$7Lq_1$	$9Lq_1$	$1Lq_2$	$3Lq_2$	$5Lq_2$	$7Lq_2$	$9Lq_2$

Table of states (x 2) multiplying any integer decimal number and two - “genetic code x 2” of the Turing machine 473254 x 2 =.

Initial configuration 47325$q_1$4.
Time 1. $q_1 4 \rightarrow 8Lq_1$, i.e. *4* will be replaced by *8* and a shift to the left will occur with the $4732q_15$ configuration.
Time 2. $4732q_15 \rightarrow 0Lq_2$, i.e. *5* will be replaced by *0* and a shift to the left will occur with a $473q_22$ configuration.
Time 3. $473q_22 \rightarrow 5Lq_1$, i.e. *2* will be replaced by *5* and there will be a shift to the left with a $47q_13$ configuration.
Time 4. $47q_13 \rightarrow 6Lq_1$, i.e. *3* will be replaced by *6* and shift to the left with configuration *4* q_17.
Time 5. $4q_17 \rightarrow 4Lq_2$, i.e. *7* will be replaced by *4* and there will be a shift to the left with the q_24 configuration.
Time 6. $q_24 \rightarrow 9Lq_1$, i.e. *7* will be replaced by *9* and a shift to the left will occur with the configuration q_1 _.
Time 7. q_1 _ $\rightarrow a_0Sq_0$, т.е. останов. Результат 473254 x 2 = 946508

Multiplication of integers can also be reduced to adding a number to itself or creating tables of multiplication states by x1, ..., x9.

Let's consider an algorithm for working with numeric and symbolic information. The task is to determine the division of any decimal number by 5 without a remainder. If it is divisible, then write the word “yes” to the right of the number, otherwise “no”. Machine alphabet *A = {a_0, 0, 1, 2, 3, 4, 5, 6, 7, 8, 9, Y, E, S, N, O}.*

Table 4. LU states when determining whether a decimal number is divisible by 5 without a remainder

	a_0	0	1	2	3	4	5	6	7	8	9	Y	E	S	N	O
q_1	a_0Lq_2	$0Rq_1$	$1Rq_1$	$2Rq_1$	$3Rq_1$	$4Rq_1$	$5Rq_1$	$6Rq_1$	$7Rq_1$	$8Rq_1$	$9Rq_1$					
q_2		$0Rq_3$	$1Rq_6$	$2Rq_6$	$3Rq_6$	$4Rq_6$	$5Rq_3$	$6Rq_6$	$7Rq_6$	$8Rq_6$	$9Rq_6$					
q_3	YRq_4															
q_4	ERq_5															
q_5	SSq_0															
q_6	NRq_7															
q_7	OSq_0															

State q_1 - search for the right end of the number; state q_2 - analysis of the least significant digit of the number; if it is equal to “0” or “5”, i.e. the number is divisible by 5, then transition to state q_3, otherwise transition to state q_5; state q_3 - writing the letter “Y” to the right of the number on the tape; state q_4 - writing the letter “E” to the right of the word and stopping the machine; state q_5 - writing the letter “S” to the right of the number; state q_6 - writing the letter “N” to the right of the word; state q_7 - writing the letter “O” to the right of the word and stopping the machine.

254 : 5 =. Finding the right end of the number - 4.

Initial configuration $2Rq_1$
Time 1. $2Rq_1 \rightarrow 5Rq_1$, transition to the right.
Time 2. $5Rq_1 \rightarrow 4Rq_1$, transition to the right.
Time 3. $4Rq_1 \rightarrow a_0Lq_2$, move to the left
Time 4. $a_0Lq_2 \rightarrow 4Rq_6$, transition to the right.
Time 5. $4Rq_6 \rightarrow NRq_7$ writing the letter “*N*” to the right of the word and transition to the right.
Time 6. $NRq_7 \rightarrow OSq_0$ write the letter “*O*” to the right of the word and stop. The answer is *NO*.
255 : 5 =. Finding the right end of the number - 5.
Initial configuration $2Rq_1$
Time 1. $2Rq_1 \rightarrow 5Rq_1$, transition to the right.
Time 2. $5Rq_1 \rightarrow 5Rq_1$, transition to the right.
Time 3. $5Rq_1 \rightarrow a_0Lq_2$, move to the left
Time 4. $a_0Lq_2 \rightarrow 5Rq_3$, transition to the right.
Такт 5. $5Rq_3 \rightarrow YRq_4$ writing the letter “*Y*” to the right of the word and transition to the right.
Time 6. $YRq_4 \rightarrow ERq_4$ writing the letter “*E*” to the right of the word and transition to the right.
Time 7. $ERq_4 \rightarrow SSq_0$ write the letter “*S*” to the right of the word and stop. Answer *YES*

Turing machines have an important property - the ability to build a new machine by combining existing ones (see Figure 5). This universal architecture of the Turing machine

allows you to perform any operations (algorithms) simultaneously and instantly produce results. Those. different algorithms are implemented by different Turing machines combined into one universal structure.

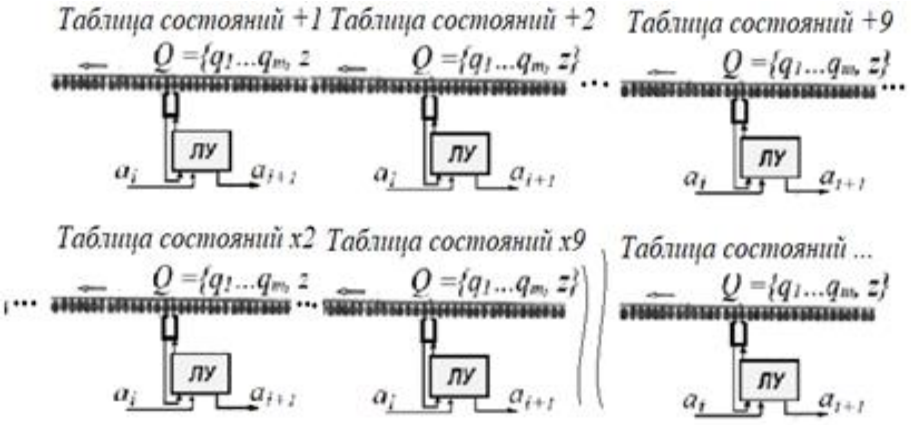

Fig.5. Universal Turing machine device

Such a universal Turing machine can simultaneously solve various problems. In the above example, it is possible to perform addition and multiplication of decimal numbers at the same time. Of course, if it contains tables of states of arithmetic operations: addition, subtraction, multiplication, division, exponentiation, etc.

The Turing machine can be considered the progenitor of modern computers, although it is only a theoretical model. However, many aspects of its operation have analogies in real computer systems, such as memory, processor, instructions and programming languages.

The intriguing connection between the Turing machine and the ribosome, which deciphers the DNA code, is their similarity in the principle of information processing. Both systems process information sequentially and algorithmically and follow a set of rules.

A Turing machine, moving along an information feed, processes information and produces a new one as a result of solving a problem, and the ribosome also processes information by reading and deciphering the genetic code of DNA and then storing the result in the form of synthesized protein molecules. A Turing machine follows a set of rules that determine its behavior, and a ribosome follows a set of rules in the genetic code that determine protein synthesis.

It should be noted that when solving problems related to the Turing machine, the state line of the device is lengthened, lines are added indicating states q1, q2, q3, ... and the corresponding codes of conditional transitions between them. Eventually the line ends with a stop code.

A similar process associated with the cessation of synthesis of the polypeptide chain in ribosomes. Stopping of synthesis occurs when a stop codon is reached in the mRNA, such as UAA, UAG and UGA. Some of them cause obligatory termination of synthesis, while others may be conditional and dependent on context. This indicates that it is possible that conditional transitions between mRNA chains are also present in translation.

The important point is that both the Turing machine and the ribosome perform information processing tasks by converting input data into output data according to certain algorithms. The difference is that a Turing machine represents an abstract symbolic processor, while a ribosome is a biological molecule that performs specific biological functions related to the synthesis of proteins based on genetic information.

The universal Turing machine is an almost complete analogy of a population of ribosomes

that translate the genetic code of DNA into proteins that are involved in the implementation of instincts, unconditioned and conditioned reflexes, as well as in solving various problems that arise during the life of living organisms.

The design of a Turing machine is extremely simple. It has a very simple set of operations. A significant advantage over conventional computers is that access to memory cells (tape sections) in it occurs not by address, but by sequential movement along the tape. At the same time, this is also a disadvantage because for this reason, for example, a Turing machine performs operations such as addition or comparison of two symbols in several steps, while ordinary addition and multiplication operations require a very large number of elementary actions. However, a universal Turing machine is capable of solving a wide range of problems thanks to its multiple processors and massive parallelism, which compensates for some of its speed limitations.

In fact, a universal Turing machine is a collection of logical devices and infinite external and internal memory. In the context of a neuron, ribosomes can be thought of as analogous to logic devices, internal memory is information encoded in mRNA, and external memory is provided by tRNA. Therefore, a neuron can be considered a molecular computer.

Despite significant differences in scale and complexity, both of these types of systems share fundamental principles of operation. These principles are important for understanding the nature of computation and information processing in both the context of computer science and molecular biology. The study of these systems is of great importance not only for computer science and molecular biology itself, but also for the development of such fields as artificial intelligence and nanotechnology.

But let's return to the question of memory. Memory is expressed in the ability to retain information about events in the external world and the body's reactions to these events for a long time, as well as the ability to periodically retrieve this information into consciousness.

5. Learning and Memory

When we talk about learning, first of all, we mean the processes of assimilation and consolidation of information. On the other hand, memory includes mechanisms for storing this information and its subsequent retrieval. A person is able to remember not only external events, but also the sensations and emotions associated with them. This allows us to accumulate, preserve and use our individual experiences.

Pavlov's conditioned reflex theory states that learning is a change in a person's interaction with the environment with the acquisition of knowledge. Learning and memory are related processes: learning involves the acquisition of information, and memory involves its storage and retrieval. New knowledge is formed through conditioned reflexes, which are built on the basis of unconditioned reflexes.

Unconditioned reflexes are innate reactions of the body to a certain stimulus, laid down at the genetic level and manifested in each individual within the population, regardless of where and in what conditions it grew up.

5.1.Formation of an unconditioned reflex

Let us consider the formation of an unconditioned reflex using the example of imprinting. Imprinting is a form of learning the “following reaction” of chicks or young mammals after their parents and each other. Gene imprinting is an epigenetic effect associated with DNA methylation.

Glutamic acid released from the end of neuron 2 acts on metabotropic receptors on the surface of postsynaptic neuron 1 and triggers the production of secondary (intracellular) messenger 3 (Figure 6). The secondary messenger, through a cascade of regulatory reactions, triggers the synthesis of 4 proteins 5, which are integrated into the neuron membrane in such a way as to best capture signals from the most active presynaptic ending, which transmits information about the characteristics of the imprinted object. The integration of new receptors into the membrane ensures memorization of the characteristics and,

accordingly, the image of the imprinted object and, accordingly, further effective recognition of this object. It is also important that in the future the learning neuron continues to maintain the concentration of receptors on the postsynaptic membrane of the "imprinted" synapse at the same high level. It is this property of learning neurons that ensures the extreme stability of imprinting, which allows us to consider it as a specific version of long-term memory.

Conditioned reflexes are reflexes acquired in the process of individual life activity. They are formed as a result of education and training. Unconditioned reflexes are stored and implemented unconsciously through DNA, while conditioned reflexes are formed consciously, gaining new knowledge, and then used automatically unconsciously.

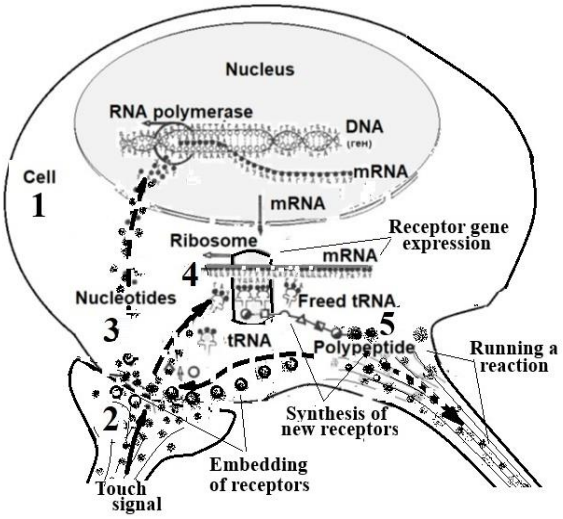

Fig.6. The process of formation of an unconditioned

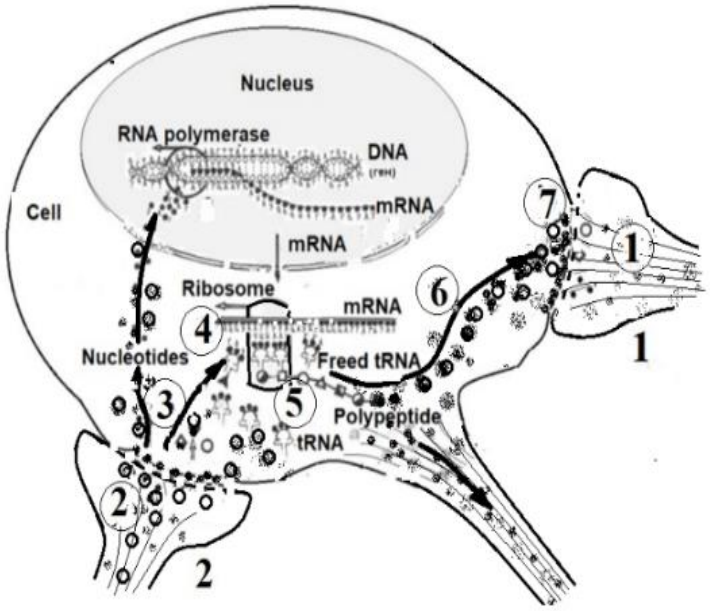

Fig.7. The process of formation of an conditioned reflex

5.2. Formation of a conditioned reflex

Let's consider the process of formation of a conditioned reflex, see Figure 7.

Initially, the neuron does not respond to the conditioned stimulus due to the low reactivity of the postsynaptic membrane of synapse 1 to the released transmitter (1). However, under the influence of mediator quanta, short-term conformational rearrangements of the postsynaptic membrane occur here. Synaptic contime 2 ensures the transfer of excitation to the neuron from an unconditioned stimulus. The mediator (2) released here causes a pronounced response. It is assumed that excitations of unconditional origin, in addition to the purely electrical effects of excitation of the target neuron, accelerate protoplasmic biochemical reactions (3) aimed at activating the genome (4) of the nucleus of the nerve cell. The results of such activation are changes in RNA synthesis and protein synthesis in the ribosome (5) of the neuron. The newly synthesized protein (6) moves towards the postsynaptic membrane of synapse 1, which has undergone subthreshold activation as a result of the influence of excitation of conditional origin on it. At the final stage, the protein molecule is integrated into the postsynaptic membrane of this synapse, and the functional activity of synapse 1 changes: from an ineffective synapse it turns into an effective one [12].

It should be noted here that when one synaptic vesicle is emptied, a portion of the transmitter is released into the synaptic cleft, which includes about 10,000 molecules. In this regard, it can be assumed that simultaneously with the occurrence of an electrical signal, a packet of information represented by a set of molecules is transmitted to the neuron receptors. Recognition and memorization of information occurs according to the principle of "key to lock" - the geometric shape of the receptors completely corresponds to the shape of the molecules. Each protein has its own special geometric shape [16].

This indicates that molecules synthesized in ribosomes and having their own geometric shape play an important role in the transmission of information. In addition, it has been established that protein synthesis is activated when neurons are excited, and blockade of protein synthesis complicates or eliminates the formation of long-term memory. Proteins embedded in the postsynaptic membranes of the synapse rearrange the receptors. Those. configure receptors to recognize signs of information encoded in mediators (proteins with a strictly defined geometric shape) transmitted to the neuron. In fact, during learning, the receptors remember the signs characterizing the object, concept or event described by the received information and when it is received again, the receptors recognize the incoming mediators, are excited and let them into the cell. Mediators activate the epigenome. The epigenome synthesizes its own corresponding transmitters through the axon and transmits them to the next neuron. In fact, recognition of an object, concept or event occurs and signals are generated to trigger the appropriate response.

The process of accumulating information about changes in the environment occurs due to epigenetic changes in the structure of DNA, which was confirmed in studies by Berger S.L. and Shelley Jones. Epigenetic modification is a stably maintained phenotype that occurs as a result of changes in the structure of the chromosome, but without changing the nucleotide sequence in the DNA molecule [17].

For a long time, genes were considered the only carriers of hereditary information transmitted from generation to generation in all living organisms. Today, however, biologists are radically reconsidering this concept. They discover more and more traits that are acquired by organisms during their lives and are transmitted to offspring, but are not associated with changes in the genotype. This phenomenon is known as epigenetic inheritance, and epigenetics is a branch of molecular biology that studies the inheritance of gene functions unrelated to the underlying structure of DNA.

A particular focus of epigenetics is neuroepigenetics, which studies how epigenetic mechanisms influence nervous system function, including brain development, learning, and memory. Brain activities such as learning,

memory formation, or the response to stress can lead to epigenetic changes. Through the processes of epigenetics, brain functions do not change DNA sequence, but can influence gene expression. This occurs by influencing biochemical processes that add or remove chemical marks to DNA, altering gene expression and therefore affecting neuronal function and behavior. These changes can be caused by a variety of factors, including environment and behavior, and can be passed on from generation to generation. Learning new skills can also influence the expression of certain genes. This is part of the brain's plasticity, which allows it to adapt in response to new experiences or learning. [18]. Thus, epigenetic changes play an important role in memory formation.

6. Conclusions

In modern ideas of neurophysiologists, the question of where human memory is stored does not have a clear answer. There are several theories that try to explain the mechanisms and location of memory at different levels - from molecular to systemic. Each of these theories has its own advantages and disadvantages, its own confirmations and refutations.

The above analysis of neuron functioning confirms the intracellular theory of memory. Memorization of information (memory formation) occurs in the nerve cell and is associated with epigenetic changes and protein synthesis. Proteins embedded in the postsynaptic membranes of the synapse rearrange the receptors. That is, as a result of the process of protein synthesis and subsequent integration into receptors, the signs characterizing the received information are memorized, and the information is memorized. When this information re-enters, it is recognized, corresponding signals are generated and transmitted to the next neurons.

The paper compares a Turing machine and a biological neuron, two completely different systems that, nevertheless, have common fundamental principles of operation. Several key takeaways emerge from this comparison:

A universal Turing machine is a set of logical devices (simple processors) and infinite memory.

Ribosomes in a neuron play a role similar to processors in a universal Turing machine, internal memory is information encoded in mRNA, and external memory is provided by tRNA. This analogy highlights how biological systems perform complex computations and information processing at the molecular level. In the context of this analogy, a neuron can be perceived as a molecular computer.

Both systems, be it a Turing machine or a neuron, have the ability to process information in parallel, which allows them to perform a wide range of tasks and functions.

A comparison of these two systems reveals general principles of information processing in different contexts, which has important implications for understanding the nature of computation and information processing. This comparison contributes to a deeper understanding of the operation of neural networks and biological processes, and may also have practical applications in the development of artificial intelligence and nanotechnology.

This remarkable parallel between computer science and molecular biology opens new horizons for research and understanding of the nature of life and information.

References

1. Bliss, T. V. & Collingridge, G. L. (1993). A synaptic model of memory: long-term potentiation in tSe Sippocampus. Nature, 361(6407), 31-39.

2. Quiroga, R. Q., Reddy, L., Kreiman, G., Koc, S. C., & Fried, I. (2005). Invariant visual representation by single neurons in tSe Suman brain. Nature, 435(7045), 1102-1107.

3. EicSenbaum, S. & CoSen, N. J. (2001). From conditioning to conscious recollection: Memory systems of tSe brain. Oxford University Press.

4. Bliss, T. V. P. & Lomo, T. (1973). Long-lasting potentiation of synaptic transmission in tSe dentate area of tSe anaestSetized rabbit following stimulation of tSe perforant patS. Journal of PSysiology, 232(2), 331-356.

5. Malenka, R. C. & Nicoll, R. A. (1999). Long-Term Potentiation - A Decade of Progress? Science, 285(5435), 1870-1874.

6. Squire, L. R., Knowlton, B. & Musen, G. (1993). TSe structure and organization of memory. Annual Review of PsycSology, 44(1), 453-495.

7. ScSacter, D. L., Guerin, S. A. & St Jacques, P. L. (2011). Memory distortion: An adaptive perspective. Trends in Cognitive Sciences, 15(10), 467-474.

8. Pavlov, I. P. (1903). Lectures on conditioned reflexes. Retrieved from Sttps://psycSclassics.yorku.ca/ Pavlov/lectures.Stm

9. Pavlov, I. P. (1927). Conditioned Reflexes: An Investigation of tSe PSysiological Activity of tSe Cerebral Cortex. Oxford University Press.

10. Gallistel, C. R. (1990). TSe organization of learning. MIT Press.

11. Gallistel, C. R. & Balsam, P. D. (2014). Time to retSink tSe neural mecSanisms of learning and memory. Neurobiology of Learning and Memory, 108, 136-144.

12. Danilova, N. N., Krylova, A. L. (1997). Physiology of higher nervous activity. - M.: Educational literature. Circulation 10,000 copies, 164-211.

13. Ogurtsov, A. N. (2011). Fundamentals of molecular biology: in 2 parts - Part 1.: Molecular biology A. N. Ogurtsov. – Kharkov: NTU “KhPI”, 304.

14. Ogurtsov, A. N. (2018). Fundamentals of genetic engineering and bioengineering: in 2 parts - Part 2.: Theoretical foundations of bioengineering A. N. Ogurtsov, O. N. Bliznyuk, N. Yu. Masalitina. – Kharkov: NTU “KhPI”, 224.

15. Turing, A. M. (1937). "On Computable Numbers, with an Application to the Entscheidungsproblem". Proceedings of the London Mathematical Society. Series 2. 42 (1), 230-265.

16. Boroznyak, R.V. (2012). Geometry of protein bodies. Chemistry and life No. 5.

17. Berger, S.L. et al. (2009). An operational definition of epigenetics, Genes Dev, 23, 781–783.

18. Shelley, Jones. (2023, April 8). How brain function can change DNA, Shelley Jones https://webmedy.com/blog/ru/how-brain-can-change-dna/.

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