Physics of the mental activity of the brain

Yuriy Zayko (https://orcid.org/0000-0002-8750-1507)

Department of Applied Informatics, Faculty of Public Administration, the Russian Presidential Academy of National Economy and Public Administration, Saratov Branch, Saratov, 410031, Russia

e-mail: zyrnick@rambler.ru

Abstract. The paper proposes a model of the brain's mental processes through the implementation of a relativistic Turing machine capable of simulating them, despite their non-computable nature. For this purpose, based on the electromagnetic nature of information transmission processes in the brain, solutions of the Maxwell equations in curved space-time were obtained and solutions of the relativistic equations of motion were found. It is shown that the corresponding Hilbert space-time belongs to a special type of singular manifolds that make it possible to model incomputable problems. A comparison is made with Malament-Hogarth manifolds known in the theory of hypercomputations.

Keywords: brain's mental activity, non-computability, hypercomputations, relativistic Turing machine, Malament-Hogarth space-time

1. Introduction

The mental activity of the brain is a subject of constant interest to a wide range of researchers – from narrow specialists to philosophers of various fields. To date, significant theoretical and experimental material has been accumulated that allows us to describe in general terms the physical foundations of the processes of mass, energy and information transfer in the brain substance. Let's briefly list the main results.

1. The main object that implements any (and presumably mental) brain activity are neurons connected to each other using axons and dendrites and forming a network of about 10^{10} neurons and 10^{14} connections between them [1].
2. The activity of neurons is carried out by transmitting electromagnetic impulses along axons, which makes it possible to explain ion transport at the cellular level. The pulse velocity calculated in this way is of the order of 10-100 *m/s*, which is confirmed by experiment [2, 3].

Hopefully, the available data is sufficient to build a picture of mental activity related to consciousness. An analogy with the work of computers can help in this.

One of the results of modeling thinking, or rather its lower forms, related to calculations was the creation of computers and the development of computational theory. In particular, so-called non-computable problems were discovered, and the development of the theory of thinking began to follow the path of separating the abilities of humans and machines to solve these problems.

R. Penrose proposed a classification of physical models of the processes underlying the mental activity of the brain. He himself is a proponent of a model based on processes that cannot be properly described using calculations.[1] At the same time, he does not exclude that the nature of these processes may be unknown to us today.[2]

The only thing he is sure of is that the mentioned process (or processes) must necessarily be of a quantum nature. Most of the arguments in the book [4] are devoted to various aspects of this idea and its consequences.

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[1] "***C***. *Appropriate physical action of the brain evokes awareness, but this physical action cannot even be properly simulated computationally*" [4, §1.3].

[2] "*According to **C**, the problem of conscious awareness is indeed a scientific one, even if the appropriate science may not yet be at hand*"[4].

In contrast, in the article [5][3], the so-called hypercomputations, specifically relativistic ones, are proposed as a candidate for the role of a tool for modeling thinking. The reason for this was that incomputable problems are separated from the set of computable ones by the so-called Turing barrier, the search for overcoming which led to the development of computational models called relativistic Turing machines (RTM).

The present work is devoted to the further development of these ideas.

2. Setting the task

Popular literature often compares the human brain to the universe. This comparison is based on the fact that the number of neurons in the brain is comparable to the number of galaxies in the universe.[4] Based on this analogy, it can be argued that, just as there is a distance in the universe that exceeds the distances between galaxy clusters, starting from which the universe looks homogeneous and isotropic, there is a distance in the brain, starting from which the brain has the same properties of uniformity and isotropy.[5] The consequence of this analogy is that there are spherically symmetric solutions to Maxwell's equations describing electromagnetic processes in the brain. These solutions are a generalization of the well-known one-dimensional solutions studied by A. L. Hodgkin and A. F. Huxley [2].

It is known that spherical electromagnetic waves (SEMW) cannot be fully described in the framework of classical electrodynamics in flat space-time due to the presence of a singularity at the SEMW focus point. There have been attempts to obtain this description by introducing fictitious sources and sinks [7]. In the works of the author [8, 9], a physical solution was proposed based on taking into account the curvature of space-time near the SEMW focus caused by the wave itself. This effect is essentially nonlinear and usually remains outside the scope of the description of the SEMW using the Maxwell equations. However, near the SEMW focus, where the wave field is extremely large, this effect cannot be ignored and the Maxwell-Einstein (ME) equations should be used instead of the Maxwell equations. A detailed course of reasoning is presented in [9, 10]. The main results are shown below.

As shown in [8] from the ME equations for an *TM*-type wave, all components of the electromagnetic tensor F_{ik} (i,k = 0,1,2,3) can be expressed through the component $F_{01}=\Psi(r,t)P_l(\theta)$, where $P_l(\theta)$ – Legendre polynomial of the order l. From the ME equations, we can obtain the equation for the radial part F_{01}

$$\frac{\partial}{\partial r}\left[e^{-\alpha}\frac{\partial f}{\partial r}\right]-e^{\alpha}\frac{\partial^2 f}{c^2\partial t^2}-\frac{l(l+1)}{r^2}f=0 \qquad (1)$$
$$f=r^2\Psi;e^{\alpha}=g_{00}=-g_{11}^{-1}$$

and the expression for the metric [9][6]

$$ds^2=g_{00}c^2dt^2+g_{11}dr^2-r^2\left(d\theta^2+sin^2\theta d\varphi^2\right)$$
$$g_{00}=e^{\alpha}=\frac{r^2}{r_0^2},g_{11}=-g_{00}^{-1}, \qquad (2)$$
$$e^{\alpha}=\pm\frac{\partial f}{\partial r}\left(\frac{\partial f}{c\partial t}\right)^{-1};r_0^2=\frac{c^2l(l+1)}{\Omega^2}$$

[3] In [5], some errors were made regarding the definition of the source of the metric under study. They are fixed in [6].

[4] The number of the latter varies depending on the change of observational equipment: about 10^{11} according to the Hubble telescope, up to 10^{12}-10^{13} according to the James Webb telescope within a radius of 14 billion light-years (data for 2014).

[5] An estimate of the order of magnitude of this distance is made in the Appendix.

[6] This metric is approximate in nature, based on the assumption that, due to the bending of light rays in a gravitational field, the energy density of the electromagnetic wave field, taking into account its own gravitational field, is spherically symmetric in contrast to the pure electromagnetic wave field.

r, θ, φ – spherical coordinates; c – light speed in vacuum.
Equation (1) has two solutions: of the wave and non-wave type [9]:

$$f(r,t) = f_0 \begin{Bmatrix} exp(\pm ir_c / r) \\ exp(\pm r_c / r) \end{Bmatrix} exp\left[e^{i\Omega(t-t_0)}\right] \tag{3}$$

These solutions are described in detail in [9].

The point of this is to use the singularities of metric (2) as an important element in creating a model of the brain MP by constructing a relativistic Turing machine operating in a singular space-time.

An example of such manifolds is the Malament-Hogarth space-time [11]. There are many equivalent definitions of MH space-times in the literature. Here is the most visual [12]:

"If an object follows a trajectory that falls into the singularity S, its journey takes forever as measured by a clock moving with the object, but external observers perceive it to have taken only a finite amount of time to complete its journey into S".

The RTM operation in MH space-time is based on the property of time dilation for an observer moving along a singular trajectory in a curved space-time. A special feature of this definition is the clear distribution of the roles of the actors involved in the calculation: the programmer (an external observer) who sets the task for the computer (a moving observer), each equipped with its own clock.

As shown in the next section by solving the equations of motion for metric (2), the resulting manifold is in some sense the inverse of the MH manifold, although it admits hypercalculations.

3. Solving the equations of motion for the metric (2)

Let us solve the radial (i.e., independent of the angles θ and φ) equations of motion of a material uncharged particle in a gravitational field with metric (2) $\dfrac{d^2x^i}{ds^2} + \Gamma^i_{kl}\dfrac{dx^k}{ds}\dfrac{dx^l}{ds} = 0$. Here $\Gamma^i_{kl} = \dfrac{1}{2}g^{im}\left(\dfrac{\partial g_{mk}}{\partial x^l} + \dfrac{\partial g_{ml}}{\partial x^k} - \dfrac{\partial g_{kl}}{\partial x^m}\right)$ - are the Christoffel symbols [13]. Let's go to the dimensionless variables $x^0 = \dfrac{ct}{r_0} = \tau, x^1 = \dfrac{r}{r_0} = \rho, \sigma = \dfrac{s}{r_0}$ and using non-zero values $\Gamma^1_{10} = -\Gamma^1_{11} = \rho^{-1}, \Gamma^1_{00} = \rho^3$ we obtain a system of equations

$$\begin{aligned} &\frac{d^2x^0}{ds^2} + 2\Gamma^0_{01}\frac{dx^1}{ds}\frac{dx^0}{ds} = 0 \\ &\frac{d^2x^1}{ds^2} + \Gamma^1_{00}\left(\frac{dx^0}{ds}\right)^2 + \Gamma^1_{11}\left(\frac{dx^1}{ds}\right)^2 = 0 \end{aligned} \tag{4}$$

Integrating the equations (4), we receive

$$\begin{aligned} &\sigma = \pm\rho_0\int\frac{dx}{\sqrt{1+x^2}} = \sigma_0 \pm \rho_0 Arshx, x = \frac{\rho}{\rho_0} \\ &\tau = \frac{1}{\rho_0}\int\frac{dx}{x^2\sqrt{1+x^2}} = -\sqrt{\frac{1}{\rho^2} + \frac{1}{\rho_0^2}} \end{aligned} \tag{5}$$

It follows from (5) that the time spent moving along the trajectory ending at the singularity $r = 0$ measured by the clock of the resting observer $t_0 = \infty$, whereas the proper time s_0 is finite, unlike the situation in the space-time MH.

Here are the expressions for calculating the time spent on changing the coordinate ρ from the value ρ_2 to the value $\rho_1 < \rho_2$ according to the clocks of the resting (τ) and moving (σ) observer calculated using formulas (5)

$$\sigma = -\rho_0 \left[arsh\left(\frac{\rho_1}{\rho_0}\right) - arsh\left(\frac{\rho_2}{\rho_0}\right) \right]$$
$$\tau = \sqrt{\frac{1}{\rho_1^2} + \frac{1}{\rho_0^2}} - \sqrt{\frac{1}{\rho_2^2} + \frac{1}{\rho_0^2}} \qquad (6)$$

3. Discussion

The proposed model of the physical realization of mental processes (MP) in the brain represents them as a certain collective property of a neural network that requires the participation of many neurons. It is based on the hypothesis of R. Penrose about the non-computable nature of MP[7], which does not allow their modeling using conventional, i.e. computable methods.

It makes sense to divide the discussion of this result into mathematical and physical ones.

The mathematical basis for modeling the brain's MP is the construction of a RTM based on solving the Maxwell equations in the corresponding Hilbert space-time and proving that it permits a hypercalculations.

Unlike R. Penrose's approach, which connects MP with quantum phenomena and processes, the proposed approach is based on classical relativistic physics.

In computational theory, the non-computability of any task is associated with an infinite number of steps or an infinite time to complete it. This fact is called the Turing barrier. Figuratively speaking, the Turing barrier separates computable and non-computable tasks. Currently, numerous papers are devoted to efforts to overcome the Turing barrier. It should be said that A. Turing himself was the first trying to solve this problem [14].

A relativistic algorithm, as was speaking above, for solving non-computable problems in MH space-time requires the presence of two actors: a programmer and a calculator. The programmer sets a task to the calculator and waits for a response within a finite time *t*. The calculator, moving along a singular world line, has infinite time *s* to solve it (see (5)). The fact that the space-time under study is not the space-time of the MH-type does not prevent the realization of the goal. You can verify this by simply swapping the positions of the programmer and the computer.

The distribution of the roles of the “programmer-computer" in the MH space-time is rather due to anthropomorphic reasons: the activity of a programmer who spends endless time obtaining the result of a calculation loses its meaning. However, this is unprincipled, after all, the computer, having received the result in a finite time, can inform a third party who will be able to use it.

R. Penrose understands computability as the existence of an algorithm that calculates a certain value, for example, the coordinates of a point on a trajectory. Therefore, he classifies chaotic phenomena as computable, because, ultimately, a chaotic trajectory is calculated on a computer [4, §1.7]. This contradicts A. Turing's view, according to which a chaotic process is non-computable, since the algorithm calculating it does not have a stopping criterion[8].

In addition, he confuses the concepts of computability and complexity. It is known that quantum algorithms (for example, Shor's algorithm or Grover's algorithm) are able to reduce the degree of complexity of a calculated task by reducing the number of steps, which is initially finite. But non-computable tasks (for example, the task of calculating the sum of a divergent series [6]) requiring an infinite number of steps are beyond their ability.

The physical part of the discussion mainly concerns the specifics of R. Penrose's interpretation of the calculation process.

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[7] “Basically the arguments of this book are making the point that what is not going on is solely a great deal of computational activity…" [4, p.395].

[8] In another place, he says "… 'non-computably', that is, in the Turing-machine-inaccessible sense that I have been using in this book'" [4, p. 394]

From a physical point of view, the important question concerns the nature of the material carrier of the very collective degree of freedom discussed above. In other words, what exactly is the particle whose equations of motion were studied in Section 3? It should be noted that it is currently not possible to obtain a definite answer to this question. All the experimental achievements of brain science discussed in the introduction relate to the microscopic, cellular level of the brain structure and say nothing about its mesostructure.[9] It is best not to imagine this carrier in the form of some compact particle and rely only on the information contained in the r coordinate appearing in the equations (2). Therefore, this work should be considered as an attempt to move in this direction. For example, we could propose a model in which r represents the size of the brain region responsible for a given thought process, the change of which reflects the dynamics of its course.

It is interesting to compare the proposed picture with the picture presented by R. Penrose [4]. Since he adheres to the quantum theory of consciousness, and the processes occurring at the neural level are classical, the source of non-computability should be located at the sub cellular level (microtubules of the cytoskeleton) and perform quantum calculations.

At the same time, in order for the final classical result to be reliable, it is necessary to ensure high coherence of both the intermediate calculation result due to the formation of a macroscopic quantum state (Bose-Einstein condensate) and the presence of an effective reduction procedure (***R***-procedure [4]) of the quantum state to the classical one. It is assumed that the non-computability of consciousness is associated with this procedure.

All this, as already emphasized in [5], is in the nature of assumptions, and although supported by references to experiments, does not make the statements given in [4] attractive in theoretical plan.

However, R. Penrose's reasoning comes to the same results as the theory of hypercalculations [4], when he includes gravity in his picture, which is capable of generating closed geodesics by changing the inclination of light cones, thereby prolonging the process of solving a non-computable problem indefinitely [4, §7.10]. If we take the event horizon surrounding the singularity as a closed geodesic, then the corresponding space-time could very likely it may turn out to be a space-time that allows for hypercalculations. We can say that R. Penrose came very close to creating a modern theory of hypercomputation.

So far, when discussing the results of the work, we have gone the direction followed by R. Penrose and which is embedded in the concept of ***C*** [4] (see the footnote on page 2). There is a place in R. Penrose's reasoning that may be a source of misunderstanding. Speaking about the non-computable nature of consciousness, inherent in understanding as the main difference between the human brain and artificial “intelligent” devices, R. Penrose speaks of “fundamental non-computability", but at the same time he is inclined to discuss just “elementary non-computability", overcome by various kinds of physical factors, for example, by quantum phenomena.

The proposal made here and in the paper [5] to use relativistic calculations instead of quantum ones actually follows the same path of overcoming elementary non-computability. A relativistic Turing machine can handle a non-computable operation, whether it is calculating the sum of divergent series [15] or proving the consistency of the Zermelo-Fraenkel set theory [16], by changing the metric of the space—time in which this operation is performed.

Can this has to do with explaining the true understanding, for example, “understanding the abstract concept of the number 3” [4, §1.19], which is indeed fundamentally non-computable?[10] This is the central question of this study, as well as the book [4], which has yet to be answered.

[9] If by macrostructure we mean the appearance of the brain, which can be seen in an anatomical theater.

[10] As R. Penrose himself writes, it, like the whole concept of a natural number, belongs to the Platonic world of ideas and a person gets acquainted with it in great childhood. Without going into philosophical disputes about the essence of the world of abstract concepts, it is safe to say that this world belongs to the field of collective human experience and it would be very rash to explore it based only on knowledge of the physical laws of the surrounding world.

5. Conclusion

The paper proposes a collective mechanism of the brain's mental processes through the implementation of a relativistic Turing machine capable of simulating them, despite their non-computable nature. For this purpose, based on the electromagnetic nature of information transmission processes in the brain, solutions of the Maxwell equations in a space-time curved by the electromagnetic wave itself were obtained and solutions of the relativistic equations of motion were found. It is shown that the corresponding singular Hilbert space-time makes it possible to model incomputable problems. Some considerations about the physical nature of the mental processes in the brain are given.

Appendix

Let's evaluate the critical distance r_c from which, i.e. for $r > r_c$ brain looks homogeneous and isotropic. Let's use the theory of similarity. Let's write down an expression for the Coulomb force (in the *CGS* system) with which two charges, q_1 and q_2 separated by a distance r in a medium with a dielectric constant ε interact with each other

$$F_c = \frac{q_1 q_2}{\varepsilon r^2}$$

It follows that the similarity factor is represented by the value of $r\sqrt{\varepsilon}$. Thus, the critical distances for the brain r_c and for the universe R_c are related by the ratio $\frac{r_c}{R_c} = \frac{1}{\sqrt{\varepsilon}} \frac{r_b}{R_u}$

where r_b and R_u – are the sizes of the brain and the universe (its visible part); ε is the dielectric constant of the brain matter, the dielectric constant of the universe is assumed to be equal to 1 with great accuracy. Assuming $r_b \approx 0.1$ *m*, $R_u \approx 1.4*10^{10}$ *ly* and evaluating $R_c \approx 10^8$ *ly*, we receive (in meters)

$$r_c = \frac{0{,}71}{\sqrt{\varepsilon}} 10^{-3}$$

Taking the value of the dielectric constant of seawater [17] for $\varepsilon \approx 50$[11], we receive the value $r_c \approx 10^{-4}$ *m* = 100 μm. For the average diameter of the neuron body $d \approx 3 \div 100$ μm, we receive that the sphere of radius r_c contains $(2r_c / d)^3$ neurons, i.e. from 8 to $3*10^5$ neurons.

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[11] Since ε (or Re ε) depends on many parameters, for example, temperature, frequency, some average value is given [12].

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