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Review Article

Relativistic Hypercomputing: Problems and Prospects from the Physicist's Point of View

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Abstract

The paper presents the main results on hypercomputing based on the use of relativistic effects. Two approaches to the problem are compared – formal-logical and physical. The basis of the physical approach is the study of the metric of curved space-time manifolds on which hypercomputing are realized, obtained either by applying the equivalence principle or by solving Einstein's equations. The properties of Malament-Hogarth spaces arising in these manifolds are discussed. The advantages of the physical approach are shown, which make it possible to verify the possibility of hypercomputing by the example of the problem of calculating the sum of the divergent Dirichlet series for the Riemann zeta function, which requires overcoming the so-called Turing barrier. It is stressed the possibility of using numerical algebras that differ from the field of real numbers, which promises significant progress in the development of modern physical theories first of all in cosmology.
The issues of relativistic theory are considered separately. The relativistic solution of the problem of motion with constant acceleration by finding the gravitational potential field of an infinite homogeneous plane is discussed. The solution of this problem by applying the equivalence principle is also discussed. The results are compared with the well-known solutions of V. Fock and R. Tolman.

1.Introduction

The last quarter of the 20th and the beginning of the 21st century were marked by the appearance of a large number of works devoted to computational models, called hypercomputing, within which the task of overcoming the so-called Turing barrier, which posits the limit of computability for classical devices modeled by a Turing machine. The concept of computability arose in connection with the discovery by A. Turing of non-computable problems, i.e. problems that cannot be solved on a Turing machine in a finite number of steps of the computing algorithm [1].

The interest in hypercomputing is due to various reasons: from purely practical ones related to the expansion of computing devices' possibilities to purely theoretical ones, for example, the violation of the Church-Turing thesis [2].

Of particular note are the works devoted to the use of the effects of general relativity for the implementation of hypercomputing (at least theoretically). The achievements of this direction include finding a class of relativistic manifolds that allow hypercomputing – the so-called Malament-Hogarth spaces [3].

One of the variants for implementing relativistic hypercomputing is the proposal to use space-time near a Kerr-Newman black hole, proposed by Nemeti et al [4], and using the effect of relativistic time dilation in its vicinity. According to this, two participants can implement hypercomputing according to the following scheme. Participant P (programmer) travels from point O in the outer region of the black hole to its inner horizon in finite time by its clock. Participant C (computer), staying at point O, performs calculations and constantly keeps in touch with P for an infinite time by his watch. During this time, he can perform an infinite number of steps of a computational algorithm and solve a problem that is not computable in the sense of Turing, for example, prove the consistency of the axiomatic of set theory ZFC [4] and send P a message about it, which he will receive at a finite (according to his watch) time. However, according to the authors, the practical implementation of this hypothetical scenario is postponed indefinitely due to the difficulties of implementation[1].

In this paper, another variant of relativistic hypercomputing is considered by the example of calculating the sums of divergent series. It is known that divergent series do not have a sum in the usual sense applicable to convergent series, and special summation methods are used to find it [5]. The reason for the divergence of the series is the failure of the necessary convergence condition – the non-decreasing or growth of the n-th term of the series a_n (if we talk about sign-constant series $a_n > 0$) with the growth of its serial number n. However, it is possible to eliminate the cause of the divergence using a computational scheme that in general resembles the one above (and formally coincides with the scheme described by Nemeti et al [6], where the role of the source of relativistic effects is played not by a black hole, but by anti–de Sitter space-time). Programmer P, being at rest, observes calculations on computer C, which moves rectilinearly and accelerated relative to it (if we are talking about a series of natural or real numbers). From the point of view of P, all a_n look like $a_n(1-v_n^2/c^2)^{1/2}$, here c – is a speed of light, and v_n – the velocity of C at the moment of adding the n-th term to the next partial sum of the series. The convergence of the series can be ensured by decreasing the relativistic factor[2]

[1] There is one weak point in the above reasoning. The important thing is not the effect of relativistic time dilation by itself, but the increase in the number of steps of the algorithm for finding a solution over a certain period of time. The latter is not obvious, because along with the relativistic time stretching on the C side, the time spent on one step of the algorithm increases in the same proportion.

[2] Note that this scheme does not use the effect of relativistic time dilation. This scheme requires improvement and is given here for illustrative purposes in the spirit of [4, 6]. Below,

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2. Calculation of series' sums of the Riemann zeta function

Consider the Dirichlet series for the Riemann zeta function $\zeta(z)$

$$\zeta(z) = \sum_{n=1}^{\infty} n^{-z}, z = u + iv \quad (1)$$

u, v – are real numbers. The series (1) converges for $u > 1$. In the article [7], relativistic effects were used to calculate $\zeta(-1)$. In this case, partial sums of the series (1)

$$\zeta_m(z) = \sum_{n=1}^{m} n^{-z} \quad (2)$$

($z = -1$) are coincident with the distance S_m, which is traveled at the time moment m by the material point (computer C) moving with constant acceleration along a straight line. The problem is reduced to determining the distance S_∞ traveled by a point in a gravitational field created by an infinite plane with a constant density of mass σ located perpendicular to a straight line of motion and providing constant acceleration in the computer's rest system. In [7], by solving the Einstein equation [8], an expression for a metric of a straight line along which C moves was found[3]

$$ds^2 = \left(1 + \frac{x}{x_c}\right)c^2 dt^2 - \left(1 + \frac{x}{x_c}\right)^{-1} dx^2 \quad (3)$$

s – is an interval, t - time, x - coordinate along a straight line, $x_c = c^2/4\pi\sigma K$, K– gravitational constant [7]. The computer C moves starting from some point on the straight line $x = x_s$, having a speed which is determined by the initial condition and stops in the point $x = -x_c$, where the metric (3) has a singularity[4]. The calculations made in [7] give the value $S_\infty = -0.08035$ which matches the exact value $\zeta(-1) = -0.08333...$ with relative error $\Delta = 0.03576$. The reason for the error is due to that metric (3) corresponds to a constant acceleration in the rest system of computer C, and not programmer P. Additional results and estimations can be found in the works [9, 10, 11].

The implementation of these methods for series (1) for complex z is of particular interest since it allows us to raise the question of using hypercomputing to prove the Riemann hypothesis. Articles [12, 13, 14] are devoted to this task. In [12] it is shown that partial sums S_m (2) in the plane of complex z for $m >> 1$ describe the vortex trajectory. This makes it possible to avoid solving Einstein's equations to find the metric in the vortex rest system, i.e. computer C, and instead use the equivalence principle (PE). Assuming the metric in the programmer's rest system P as Euclidean one and performing the transition to the computer rest system, we find the metric of the latter [12]

$$ds^2 = A(r)(cdt)^2 - dl^2 + B(r)dr^2,$$
$$A(r) = b^2 - \left(\frac{\tilde{r}}{r}\right)^2, b^2 = 1 - \left(\frac{\delta}{\omega}\right)^2, \tilde{r} = \frac{\omega}{c}, \quad (4)$$
$$B(r) = 1 - \left(\frac{r}{\tilde{r}}\right)^2 - \left(\frac{\delta}{\omega}\frac{r}{\tilde{r}} + \frac{\tilde{r}}{r'_\varphi}\right)^2 A^{-1}$$

r, φ – are polar coordinates, $dl^2 = dr^2 + r^2 d\varphi^2$, δ and ω – vortex parameters, which define radial and tangent velocities of vortex versus its radius r.

The study of solutions of relativistic equations of motion of computer C shows that depending on the argument z of the zeta function $\zeta(z)$ there are two types of computer trajectories. The trajectories of the first corresponding to the nontrivial zeros $\zeta(z)$ end at the point $r = 0$. The second type includes all other trajectories. Trajectories of the first type occur only if the argument of the zeta function locates on the critical line, i.e. if $Re(z) = u = ½$. As shown in [13], there are no trajectories of the first type outside the critical line, which proves the Riemann hypothesis.

In [14], it is stated that the proof of the Riemann hypothesis is associated with overcoming the Turing barrier.

3. Discussion

Most of the published materials on the topic of relativistic hypercomputing are anyway related to Einstein's PE, according to which "a non-inertial frame of reference is equivalent to some gravitational field" [8]. The significance of PE in A. Einstein's way of development of the theory of gravitation is well known and described in detail in the scientific literature (see, for example, [15]).
For our purposes, is of interest the role of PE in the post-relativistic era.

According to V.A. Fock [16], PE is true only locally and in this sense is inferior to the global principle of equality of inert and heavy mass. To illustrate this, V.A. Fock considers the transformation of the interval $ds^2 = c^2 dt'^2 - dx'^2$ under a nonlinear transformation of the coordinates of an inertial reference frame (x', t') to some other system (Møller coordinates [17])

$$ds^2 = c^2 dt'^2 - dx$$
$$x' = xch\frac{gt}{c} + \frac{c^2}{g}\left(ch\frac{gt}{c} - 1\right) \quad (5)$$
$$t' = \frac{c}{g}sh\frac{gt}{c} + \frac{x}{c}sh\frac{gt}{c}$$

g – is a constant having the dimension of acceleration. On condition $gt/c << 1$ V.A. Fock presents transformations (5) in the form describing the transition to an equiaccelerated reference frame [5]:

$$x' = x + \frac{gt^2}{2}; t' = t \quad (6)$$

After conversion, the interval ds takes the form

$$ds^2 = \left(c + \frac{gx}{c}\right)^2 dt^2 - dx^2 \quad (7)$$

Further, V.A. Fock gives an approximate expression for the interval corresponding to the true gravitational field (i.e. obtained by solving Einstein's equations) with a Newtonian potential $U = -gx$ under the condition $|gx| << c^2$

$$ds^2 = (c^2 - 2U)dt^2 - \left(1 + \frac{2U}{c^2}\right)dx^2 \quad (8)$$

Comparing (7) and (8), he concludes that the fields of acceleration and gravity are not fully equivalent.

R. Tolman builds his arguments in another way [18]. It proceeds from formulas (6) by converting the Galilean interval of the resting observer $ds^2 = c^2 dt^2 - dx^2$ to the form

$$ds^2 = (c^2 - g^2 t'^2)dt'^2 - dx'^2 + 2gt'dx'dt' \quad (9)$$

with which the second observer is working, moving relative to the first with acceleration g. Accordingly, solving the same covariant equations of motion for test particles, the first observer will get

relativistic effects are used to calculate specific series, which allows for more rigorous reasoning based on the solution of Einstein equations and relativistic equations of motion.

[3] For the expression for metric (3), see Appendix A

[4] Or in the opposite direction due to the invariance of the equations concerning the reversal of time.

[5] Strictly speaking, it follows from (5) $t' = t(1+xg/c^2)$. To use (6), an additional condition must be imposed, $x<<ct$, i.e. Fock's reasoning is valid away from the boundary of the light cone

$$\frac{d^2x}{ds^2}=\frac{d^2t}{ds^2}=0 \tag{10}$$

whereas for the second Tolman gets [6]

$$\frac{d^2x'}{ds^2}=\frac{g}{c^2-g^2t^2};\frac{d^2t'}{ds^2}=0 \tag{11}$$

the difference in which he (the observer) can attribute to the gravitational field, and not some absolute property of his movement, which is confirmed by PE. Despite some differences in conclusions, both authors, claim the same thing, since their research is based on the same equations.

In any case, the use of PE to justify relativistic hypercomputing is limited by the conditions mentioned above, which can be avoided by resorting to solving Einstein's equations.

Nonetheless, to obtain the metric (4) in [12], it is PE that is used, which, as shown above, does not allow, due to its incomplete equivalence to the equations of gravity, to hope for the accuracy of the result, which was noted in [13]. But in [13], as was indicated, there was no aim to perform any calculations, for example, the values of the roots of the Riemann zeta function $\zeta(z)$. Its purpose was to study the possible trajectories of a computer for different values of the argument $\zeta(z)$, i.e. we did not go beyond the kinematics limiting the applicability of PE.

We note one circumstance that was not previously paid attention to. When using PE, the real source of the curvature of space-time (gravity) is not indicated – its role is played by the acceleration of computer C. For this reason, the resulting expressions for metric (4) do not include the gravitational constant, unlike (3) where it determines the value of x_c. This once again underlines the limitations of PE - the curvature of space-time caused by acceleration does not correspond to any gravitational field. This is evidenced by turning the corresponding Riemann tensor to zero [18].

Inevitably, works on hypercomputation affect the main provisions of relativistic theory. In order not to enumerate them as the authors of the mentioned works do (see, for example, [19]), we will mention only the question of the singular structure of relativistic manifolds admitting hypercomputing. However, if in [19, 20, 21] it is speaking about manifolds identified with the Universe, then in the author's works we are talking about specific numerical manifolds (real [7, 9, 10, 11] and complex [12, 13, 14]) used in hypercomputing. Only their singular structure is common, although the nature of the singularity depends on the specific calculation.

The latter circumstance allows us to take a different look at the very possibility of hypercomputing. Firstly, it is not tied to the results of modern cosmology, which, like all objective data, can change under the influence of new facts. Secondly, it does not require huge expenditures of resources available only to future generations and allows you to use hypercomputing yet today[7].

To fit these new results into the framework of the traditional paradigm of relativistic hypercomputing, it is necessary to make sure that the structure of the manifolds used has the character of Malament-Hogarth spaces. Let's remind their definition: "A relativistic spacetime is called Malament-Hogarth (MH) if there is an event (called MH-event) in it which contains in its causal past a worldline of infinite proper length" [21]. But this follows from the very formulation of the problem of calculating the sum of an infinite divergent series as a problem of relativistic mechanics of the motion of a point, where the role of time is played by the m - number of terms of the partial sum of the series (2). In addition, as is known, no-MX spaces are globally hyperbolic [22]. This is consistent with the fact that a real number line with metric (3) cannot be completely embedded in a globally hyperbolic plane [10].

Let's start discussing the prospects of hypercomputing with a link to the work [21]: "Two major new paradigms of computing arising from new physics are quantum computing and general relativistic computing. Quantum computing challenges complexity barriers in computability, while general relativistic computing challenges the physical Church-Turing Thesis itself…
The PhCT is the conjecture that whatever physical computing device (in the broader sense) or physical thought-experiment will be designed by any future civilization, it will always be simulatable by a Turing machine."

Many questions concerning the prospects of hypercomputing are formulated in the pioneer works cited above. Most of them are related to the implementation of hypercomputing devices using black holes and, being technical, are not of interest in the context of this work. Other issues relate to the relationship of PhCT violation and the structure of MH spaces and are of a fundamental nature. Their solution, regardless of the implementation, is related to the nature of the singularities of the corresponding manifolds, cosmological or numerical.

Another feature of the mentioned works is the emphasis not on the mathematical side of the theory, but on its logical structure, to formalize it, bringing it in the form of a set of statements expressed using first-order logic. As a sample, the authors refer to the example of the axiomatization of geometry by Euclid, Hilbert, and Tarski. Here we could add D. Hilbert's axiomatic approach to the main problems of physics (Hilbert's 6th problem), which led him to the successful conclusion of relativistic equations of gravity simultaneously with A. Einstein [23].

It should be said about the difference in the approaches of D. Hilbert and of Nemeti et al [19, 20, 21, 24]. Hilbert did not set the axiomatization of a particular field of physics as his ultimate goal and obtained the final result by physical methods or, if you like, by methods of computational mathematics, whereas the aforementioned authors seek to give the results of relativistic theory the character of theorems proving by methods of logic.

Perhaps the increased interest in the logical foundations of the theory was stimulated by the historical fact that in the subsequent analysis of the hypotheses underlying the special theory of relativity (the principle of relativity extended to electromagnetic phenomena and the principle of the constancy of the speed of light) their dependence became clear.

Although according to the authors of the mentioned works, their goal is to clarify the logical connection between the statements underlying the general theory of relativity, it seems that they are aiming at something more, namely, complete axiomatic construction of the theory. Judging by the results, the authors have not yet managed to achieve the final goal. Moreover, it is possible to express a certain doubt about its reality[8].

On this occasion, it is worth making one more remark. The relativistic theory is constantly evolving, which must be considered when trying to axiomatize it. It is difficult to expect new results, such as the finding of non-wave solutions of the Maxwell-Einstein equations [25] and the instability of the electromagnetic vacuum under the horizon of a black hole [26] [9] can be obtained as consequences of the axioms laid down in the basis of the theory in the works [19, 20, 21, 24].

Of particular interest is the question of the relationship between the properties of space-time and the properties of numbers describing it [27]. The existence of such a connection has been suspected for a long time. F. Klein wrote about the justification of Euclidean geometry in his Lectures [28]: "Riemann notes that all previous studies are based

[6] Regarding the accuracy of formulas (11) borrowed from [18], see Appendix B.

[7] For this reason, those ingenious scenarios of using Kerr-Newman black holes to test the consistency of the axiomatic of ZFC set theory lose their relevance. Humanity will have enough time to find less costly ways to test it.

[8] Indeed, if this were possible for the general theory of relativity, then why not set the same goal for the simpler theory of Newton's gravitation, for example, to try logically deduce Newton's law of gravitation from the Kepler's laws, taken as axioms.

[9] The fact that in [24] we are talking about a Schwarzschild black hole, and not a Kerr one, does not remove the question.

on the assumption that straight lines have infinite length…"[10]. E. Rosiner [29] indicates the possibility of using numerical algebras that differ from the field of real numbers, which promises significant progress in the development of modern physical theories:

" • Obtaining an easy to construct and use large setup within which we can consider the further extension and deepening of the Principle of Relativity, and do so this time not only with respect to reference frame transformations or the usual background independence of the type encountered in General Relativity, but also within the significantly more general concept of background independence with respect to the mathematical models which give the scalars used in the theories of Physics.

• Doing away with the long ongoing and difficult issue of" infinities in physics", a thus as well with the need for the rather ill-founded variety of methods called" renormalization"."

The latter is confirmed by solving the problem with infinities in quantum field theory by using a non-Archimedean algebra of real numbers equipped with a metric (3) [30].

Specific results are presented in the papers [10, 11, 29]. In [29], the algebraic structures of numbers generated by the theory of space-time are investigated, and the formal-logical approach described above is used. It is shown that the structure of numerical algebras strongly depends on the set of axioms of space-time theories. In [10, 11], static and dynamic non-Euclidean (non-Archimedean) numeric systems are investigated[11]. An example of a static system is given in which equality $\zeta(-1) = -1/12$ is performed. An example of a dynamical system whose properties change over time is also given, which allows an alternative interpretation of the observed "expansion of the Universe".

Thus, the analysis of the number structures used within the framework of a logical and physical approach based on the application of methods of general relativity leads to the same conclusions, although the latter is richer in results.

4. Conclusion

According to the current trend in the development of mathematics, physics is considered as a source of new ideas that require strict justification and development (E. Witten). An example of this is the field of relativistic hypercomputing, to which this article is devoted. Within the framework of the traditional direction, the main attention is paid to the consideration of the works of I. Nemeti, H. Andreka and others. In addition to their proposed model of hypercomputing based on the effect of time dilation in the vicinity of a black hole, their attempts to formulate the main provisions of relativistic theory (both special and general) in the form of first-order logic with the allocation of basic axioms and the subsequent application of purely logical procedures to them are also discussed. This direction can be conditionally called formal-logical. The disadvantages of this approach in the study of hypercomputing are noted. In this regard, it is appropriate to mention F. Klein's statements about the correlation of formal-logical and intuitive-contemplative principles in the study of arithmetic, which preceded the modern works on the axiomatization of relativistic theory mentioned above [28].

Another direction, which can be conditionally called as physical one, is represented by the works of the author. The basis of the physical approach is the study of the metric of curved spacetime manifolds on which hypercomputing is realized, obtained either by applying the equivalence principle or by solving Einstein's equations. The properties of Malament-Hogarth spaces arising in these manifolds are discussed. The advantages of the physical approach are shown, which make it possible to verify the possibility of hypercomputing by the example of the problem of calculating the sum of the divergent Dirichlet series for the Riemann zeta function, which requires overcoming the so-called Turing barrier.

Declaration of Conflict of Interests

The author declares that there is no conflict of interest. They have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Appendix A

While writing the article, there was a small discussion about the solution of the relativistic problem of an infinite homogeneous plane, which can be found on the Quora portal [31, 32, 33]. According to the opponent (Viktor H. Toth), the author's solution of this problem is incorrect. The essence of the objections is the same as A. Einstein's objections[34] to L. Silberstein's solution[35] of the two-body problem in general relativity concerning the non-analyticity of the metric obtained in [35]. The correct approach to the study of the problem of an infinite homogeneous plane in GR, according to the opponent, is set out in the work [36][12].

In fact, A. Einstein's objections boiled down to the fact that the appearance of "extra" singularities in the metric obtained by solving the field equations should have a physical justification, for example, correspond to an extra particle, thereby contradicting the original formulation of the two-body problem. It must be said that the opinion of A. Einstein himself about the representation of particles by the singularities of the field changed throughout his activity [37]. Regarding metric (3), it should be said that the singularity in it has a completely different origin and does not correspond to any particle and does not contradict the original formulation of the problem. This only indicates that the problem of an infinite plane in GR cannot be correctly considered in the traditional algebra of real numbers, as already mentioned in the author's works, including this article.

As for the opponent's fair remark that the metric (3) should depend on $|x\text{-}x_0|$, and not on $x\text{-}x_0$, the contradiction is easily avoided by placing the plane at spatial infinity, since the final expression does not include the coordinate of the plane x_0.

Appendix B

We show that in formulas (11), borrowed from [18], an excess of accuracy is allowed. Indeed, if we proceed from the general transformations of coordinates (5), then the transition to the streaked coordinates up to the terms ~$(gt/c)^2$ would be described by formulas (far from the boundaries of the light cone)

$$x' = x\left(1+\frac{g^2t^2}{2c^2}\right)+\frac{gt^2}{2};t' = t \qquad \text{(B1)}$$

the meaning of which is not entirely clear. To use formulas (6), in the decomposition of the right parts of formulas (5), it is necessary to neglect terms of order $(gt/c)^2$ in comparison with 1. But then the first formula in (11) should not contain in the denominator a second-order term g^2t^2 in t. We show that the first-order term in t can be present. To do this, we use the expression for the interval (9) in which, under the accepted restrictions, the summand g^2t^2 should be omitted in the first term on the right.

[10] Although that these words referred to geometry, they can also be applied to the numerical continuum.

[11] The difference in terminology is insignificant if the numerical continuum is geometrized since the violation of the 2nd Euclidean principle is equivalent to the violation of the Archimedean property of a numerical system.

[12] It must be said that the authors of this work do not solve the field equations, but are only busy best fitting heuristic metrics to them.

Then the metric tensors g_{ik} and g^{ik} corresponding to the corrected interval (9) will have the form (i, k = 0, 1)

$$g_{ik} = g^{ik} = \begin{pmatrix} 1 & \frac{gt}{c} \\ \frac{gt}{c} & -1 \end{pmatrix} \tag{B2}$$

By definition $g^{ik}g_{km} = \delta^i_m$ with the specified accuracy.

Calculating the Christoffel symbols Γ^i_{kl} [8]

$$\Gamma^i_{kl} = \frac{1}{2} g^{im}\left(\frac{\partial g_{mk}}{\partial x^l} + \frac{\partial g_{ml}}{\partial x^k} - \frac{\partial g_{kl}}{\partial x^m}\right); \tag{B3}$$

$$x^0 = ct', x^1 = x'$$

we find non-zero symbols

$$\Gamma^0_{00} = \frac{g^2 t}{c^3}; \Gamma^1_{00} = -\frac{g}{c^2} \tag{B4}$$

Accordingly, the equations of motion of test particles in the accelerated coordinate system

$$\frac{d^2 x^i}{ds^2} + \Gamma^i_{kl}\frac{dx^k}{ds}\frac{dx^l}{ds} = 0 \tag{B5}$$

look as follows

$$\begin{aligned} &\frac{d^2 x^0}{ds^2} + \frac{g^2 t}{c^3}\left(\frac{dx^0}{ds}\right)^2 = 0; \\ &\frac{d^2 x^1}{ds^2} - \frac{g}{c^2}\left(\frac{dx^1}{ds}\right)^2 = 0 \end{aligned} \tag{B6}$$

and easily integrated. In the accepted approximation, expressions similar to (11), which are given in [18], have the form

$$\frac{d^2 x^0}{ds^2} = 0; \frac{d^2 x^1}{ds^2} = \frac{g}{c^2 \pm 2gct} \tag{B7}$$

The signs ± depend on the direction of movement of the test particle.

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