A Model of the Quantum-Classical and Mind-Brain Connections, and of the Role of The Quantum Zeno Effect in the Physical Implementation of Conscious Intent.

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Abstract

A simple exactly solvable model is given of the dynamical coupling between a person's classically described perceptions and that person's quantum mechanically described brain. The model is based jointly upon von Neumann's theory of measurements and the empirical findings of close connections between conscious intentions and synchronous oscillations in well separated parts of the brain. A quantum-Zeno-effect-based mechanism is described that allows conscious intentions to influence brain activity in a functionally appropriate way. The robustness of this mechanism in the face of environmental decoherence effects is emphasized.

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I. INTRODUCTION

The basic problem in the interpretation of quantum mechanics is to reconcile the fact that our observations are describable in terms of the concepts of classical (i.e., ninteenth century) physics, whereas the atoms from which our measuring devices and our physical body/brains are made obey the laws of quantum (twentieth century) physics. The direct application of the microscopic atomic laws to macroscopic aggregates of atoms is well defined, but the thus-defined aggregates of atoms are not describable in classical terms.

The basic problem of the philosophy of mind, and indeed of all philosophy, is to understand the connection of our conscious thoughts to the physically described world. No feature, configuration, or activity of the physical world, as it is conceived of and described in classical physics, *is* the experiential quality that characterizes our conscious thoughts, ideas, and feelings. Something beyond the classically conceived physical world seems to be needed in the full inventory of what exists.

The obvious solution to this second problem is to recognize that the basic precepts of classical physics were replaced during the first part of the twentieth century by those of quantum theory. This improved physical theory brings conscious human observer/agents into physics in an essential way that renders the classical conceptions of our bodies, including our brains, fundamentally deficient. The new theory accommodates a mechanism that allows our conscious thoughts to influence our bodily actions without being reducible to any physically describable feature or activity. Hence accepting the precepts of contemporary physics provides an adequate and suitable basis of a rational answer to the second question. But it leaves untouched the first question, about the basis within a quantum universe of the classical describability of our perceptions.

Mounting neuroscientific evidence indicates that our conscious intentions are closely linked to synchronous $\sim 40Hz$ oscillations of the electromagnetic field at many well-separated brain sites[1, 2]. This result points to the importance of classically describable simple harmonic oscillator (SHO) motions in the description and understanding of our conscious intentions and their physical effects. But a focus on SHO motions opens the door to a relatively simple solution of the problem of the connection between the classical character of our descriptions of our perceptions and the quantum character of our description of the physical dynamics. The so-called "coherent states" associated with SHO motions connect quantum concepts to classical concepts in just the way needed to achieve a simple, rational, simultaneous solution of the problems of the quantum-classical and mind-brain connections. The purpose of this article is to describe an exactly solvable model that exhibits in a clear way the basic elements of this resolution of these two problems.

In this model the causal effectiveness of our conscious intentions rests heavily upon the quantum Zeno effect. This is a strictly quantum mechanical effect that has been advanced elsewhere[5–9] as the dynamical feature that permits "free choices" on the part of an observer to influence his or her bodily behavior.

The intervention by the observer into physical brain dynamics is an essential feature of orthodox (von Neumann) quantum mechanics. Within the von Neumann quantum dynamical framework this intervention can, with the aid of quantum Zeno effect, cause a person's brain to behave in a way that causes the body to act in accord with the person's conscious intent. However, the previous accounts of this mechanism, although strictly based on the mathematical principles of quantum mechanics, have been directed primarily at neuroscientists and philosophers, and have therefore been largely stripped of equations. The present model is so simple that the equations and their meanings can be presented in a way that should be understandable both to physicists and to sufficiently interested nonphysicists who are not troubled by simple equations.

On the other hand, the use of quantum mechanical effects in brain dynamics might seem problematic, because it depends on the existence of a macroscopic quantum effect in a warm, wet, noisy, brain. It has been argued that *some* such effects will be destroyed by environmental decoherence[10]. Those arguments do cover many macroscopic quantum mechanical effects, but they fail, for the reasons described below, to upset the quantum Zeno effect at work here.

In section II I shall review the well known properties of a system of two coupled SHOs. In section III I shall use those results, and the closely related properties of the associated quantum "coherent states", to construct a mathematically solvable quantum mechanical model of the connection between conscious intent and brain activity. In section IV I describe the conclusions to be drawn.

II. COUPLED OSCILLATORS IN CLASSICAL PHYSICS

It is becoming increasingly clear that at least some of our normal conscious experiences are associated with $\sim 40Hz$ synchronous oscillations of the electromagnetic fields at a collection of brain sites[1, 2]. These sites are evidently dynamically coupled. And the brain appears to be, in some sense, approximately described by classical physics. So I begin by recalling some elementary facts about coupled classical simple harmonic oscillators (SHOs).

In suitable units the Hamiltonian for two SHOs of the same frequency is

$$H_0 = \frac{1}{2}(p_1^2 + q_1^2 + p_2^2 + q_2^2). \tag{1}$$

If we introduce new variables via the canonical transformation

$$P_1 = \frac{1}{\sqrt{2}}(p_1 + q_2) \tag{2}$$

$$Q_1 = \frac{1}{\sqrt{2}}(q_1 - p_2) \tag{3}$$

$$P_2 = \frac{1}{\sqrt{2}}(p_2 + q_1) \tag{4}$$

$$Q_2 = \frac{1}{\sqrt{2}}(q_2 - p_1), \tag{5}$$

and replace the above H_0 by

$$H = (1+e)(P_1^2 + Q_1^2)/2 + (1-e)(P_2^2 + Q_2^2)/2, \tag{6}$$

then this H expressed in the original variables is

$$H = H_0 + e(p_1 q_2 - q_1 p_2). \tag{7}$$

If $e << 1$ then the term proportional to e acts as a weak coupling between the two SHOs whose motions for $e = 0$ would be specified by H_0.

The Poisson bracket (classical) equations of motion for the coupled system are, for any x,

$$dx/dt \ = \ \{x, H\} = \sum_j \Big(\frac{\partial x}{\partial q_j}\frac{\partial H}{\partial p_j} - \frac{\partial x}{\partial p_j}\frac{\partial H}{\partial q_j}\Big). \tag{8}$$

They give

$$dp_1/dt \ = \ -q_1 + p_2 e \tag{9}$$

$$dp_2/dt = -q_2 - p_1 e \quad (10)$$

$$dq_1/dt = p_1 + q_2 e \quad (11)$$

$$dq_2/dt = p_2 - q_1 e. \quad (12)$$

A solution is

$$p_1 = \frac{C}{2}[\cos(1+e)t + \cos(1-e)t]$$
$$= C \cos t \cos et \quad (13)$$
$$q_2 = \frac{C}{2}[\cos(1+e)t - \cos(1-e)t]$$
$$= -C \sin t \sin et \quad (14)$$
$$p_2 = \frac{C}{2}[-\sin(1+e)t + \sin(1-e)t]$$
$$= -C \cos t \sin et \quad (15)$$
$$q_1 = \frac{C}{2}[\sin(1+e)t + \sin(1-e)t]$$
$$= C \sin t \cos et. \quad (16)$$

The second line of each equation follows from the trigonometric formulas for sines and cosines of sums and differences of their argumants. A common phase ϕ can be added to the argument of every sine and cosine in the first line of each of the four equations. This leads to the addition of this phase to the argument t, but not the argument et, in the second line of each of the four equations.

These equations specify the evolving state of the two SHO system by a trajectory in (p_1, q_1, p_2, q_2) space.

When we introduce the quantum corrections by quantizing this classical model we obtain an almost identical quantum mechanical description of the dynamics. In a very well known way the Hamiltonian H_0 goes over to (I use units where Planck's constant is 2π.)

$$H_0 = \frac{1}{2}(p_1^2 + q_1^2 + p_2^2 + q_2^2) = (a_1^\dagger a_1 + 1/2) + (a_2^\dagger a_2 + 1/2). \quad (17)$$

The connection between the classical and quantum descriptions of the state of the system is very simple: the point in (p_1, q_1, p_2, q_2) space that represents the classical state of the whole system is replaced by a "wave packet" that, insofar as the interventions associated with observations can be neglected, is a smeared out (Gaussian) structure centered for all times exactly on the point that specifies the classical state of the system. That is, the quantum mechanical representation of the state specifies a probability distribution of the form

$(exp(-d^2)$) where d is the distance from a center (of-the-wave-packet) point $(p_1, q_1, p_2, q_2$), which is, at all times, exactly the point (p_1, q_1, p_2, q_2) that is the classical representation of the state.

According to quantum theory, the operator $a_i^\dagger a_i = N_i$ is the number operator that gives the number of quanta of type i in the state.

Thus in the absence of any observations the classical and quantum descriptions are almost identical: there is, in the quantum treatment, merely a small smearing-out in (p, q)-space, which is needed to satisfy the uncertainty principle.

This correspondence persists when the coupling is included. The coupling term in the Hamiltonian is

$$\begin{aligned} H_1 &= e(p_1q_2 - q_1p_2 - p_2q_1 + q_2p_1)/2 \\ &= ie/2(a_1^\dagger a_2 - a_1a_2^\dagger - a_2^\dagger a_1 + a_2a_1^\dagger). \end{aligned} \tag{18}$$

The Heisenberg (commutator) equations of motion generated by the quadratic Hamiltonian $H = H_0 + H_1$ gives the same equations as before, but now with operators in place of numbers. Consequently, the centers of the wave packets will follow the classical trajectories also in the $e > 0$ case. The radius of the orbit is the square root of twice the energy, measured in the units defined by the quanta of energy associated with frequency of the SHO.

III. APPLICATION

With these well known results in hand, we can turn to their application. The above mathematics shows, for SHOs, a near identity between the classical and quantum treatments, insofar as there are no observations. But if observations occur, then the quantum dynamics prescribes certain associated actions on the quantum state.

The essential point here is that quantum theory, in the von Neumann/Heisenberg formulation, describes the dynamical connection between conscious observations and brain dynamics. [Von Neumann[3] brought the mind-brain connection into the formulation in a clear way, as an application of the orthodox quantum precept that each increment in our classically describable knowledge is represented in the mathamatical language of quantum mechanics by the action of associated projection operators on the prior state. Heisenberg[4] emphasized that if one wants to understand what is really happening then the quantum state should be regarded as a "potentia" (objective tendency) for a real psycho-physical event to occur.] To apply this theory, the classically described brain must first be converted to its quantum form. By virtue of the relationships described in section II, this conversion is direct when the classical state that is connected to consciousness is a SHO state. And if no observations occur the classical and quantum descriptions are essentially the same: the tiny smearing out of the classical point to the narrow gaussian centered on the classical point is of negligible significance.

The observer, in order to get information about what is going on about him into his stream of consciousness, must, according to orthodox quantum mechanics, initiate probing actions. According to the development of the theory of von Neumann[3] described in Refs[5–9], the brain does most of the work. It creates, in an essentially mechanical way based on trial and error learning, and also upon the current quantum state of the brain, a query/question. Each possible query is associated with a psychological projection into the future that specifies the brain's computed "expectation" about what the feedback from the query will be. [My idea here is to assume/postulate that if $P1, P2, P3, ...$ is the set of $P's$ corresponding to all the questions that could be posed at time t, and $P(t)$ is the PN that maximizes $Trace\ PN\rho(t)$, then the only question that could be asked at time t is $P(t)$. But whether this question will in fact be posed at time t could be influenced by experiential qualities. This would allow the *timings* of the probing actions to be determined in part by features of nature not represented in the physically described part.]

The physical manifestation of this query is called "process 1" by von Neumann. It is a key and necessary element of the quantum dynamics: it resolves ambiguities that are not resolved by the physical laws of quantum mechanics, and it ties the physical description expressed in terms of the quantum mathematics to our communicable descriptions of our perceptions. This process 1 probing action is *not* the famous statistical element in quantum theory! It is needed both in order to specify what the statistical predictions will be *about*, and also to tie the abstract quantum mathematics to human perceptual experience, and hence to science.

In order to bring out the essential point, and also to tie the discussion comfortably into the common understandings of neuroscientists, who are accustomed to thinking that the brain is well described in terms of the concepts of classical physics, I shall consider first an approximation in which the brain is well described by classical ideas. Thus the two SHO states that we are focusing on are considered to be aspects of possible states of a classically described brain, which is also providing the potential wells in which these two SHOs move. It is the degrees of freedom of the brain associated with the first of these two SHOs that are, in the simple model being considered here, the possible brain correlates of the consciousness of the observer during the period of the experiment. Hence it is they that are affected by von Neumann's process 1. The second SHO, described by the pair of variables (p_2, q_2), represents environmental degrees of freedom. One sees from the second lines in each of the four equations (13-16) that in a period of duration $t = \pi(2e)^{-1}$ starting from time $t = 0$ the energy of the first SHO will, for $e << 1$, be fully transferred to the second SHO, provided no probing actions are made.

If no probing actions are made then the conserved energy will oscillate with period $t = 2\pi(e)^{-1}$ back and forth between the two SHOs. Our interest here is in the effect upon this transfer of energy from the first SHO to the second SHO of a sufficiently rapid sequence of probing actions. What will be shown is that if the probing actions are sufficiently rapid on the scale of time $t = e^{-1}$ then the trajectory of (p_1, q_1) will tend to follow the uncoupled $(e = 0)$ trajectory.

The point, here, is that quantum mechanics has a built-in connection between a conscious intent and its physical effects. This connection is tied to the process 1 probing actions, whose dynamical effects are specified by the quantum dynamical rules. Therefore our conscious intentions do not stand outside the dynamics as helpless, impotent witnesses, as they do in classical physics, but have *specified* dynamical effects. We are now in a position to examine what these effects are.

I assume that there is a rapid sequence of queries at a sequence of times $\{t_1, t_2, t_3, ...\}$. These queries will be based on expectations constructed by the brain on the basis of past experiences. These queries are represented in the quantum mathematics by a series of projection operators $\{P(t_1), P(t_2), P(t_3), ...\}$ [A *projection* operator P satisfies $PP = P$] This sequence of projection operators represents a sequence of questions that ask whether the current state is on the "expected" track. This track is specified by the $e = 0$ trajectory, which represents expectations based on past experiences in which the holding-in-place effects of similar efforts have been present.

Up until now I have spoken as if the projection operators associated with the observations are projections onto a single quasi-classical state (i.e., onto one of the so-called "coherent' states.) A projection upon such a state would involve fantastic precision. Each such state is effectively confined to a disc of unit size relative to an orbit radius C of about 10^6 in the units employed in equation (1). [This number 10^6 is roughly the square root of the thermodynamic energy per degree of freedom at body temperature, in energy units associated with equation (1), in which Planck's constant is 2π, and the angular velocity is one radian per unit of time. The unit of time in these units is about 4ms for 40 Hertz oscillations. An actual excited brain state should have energy significantly *greater* than thermal, but a higher energy makes our approximation even better]. However, it it is possible (for our SHO case) to define more general operators that are projection operators (i.e., satisfy $PP = P$) apart from corrections of order, say, $< 10^{-3}$, by using the von Neumann lattice theorem.[11]

If one represents by $[P, Q]$ the projection operator that projects onto the Gaussian state centered at $(p, q) = (P, Q)$, then the lattice theorem says that the following identity holds:

$$\sum [mf, nf] = I \tag{19}$$

where $f = (2\pi)^{1/2}$, I is the identity operator, and the sum is over all integer values of m and n except $m = n = 0$. Moreover, the decomposition into different Gaussian components effected by this identity is unique. If one restricts the sum to the lattice points in a very large square region in (p_1, q_1) space then the resulting operator P' is very nearly a projection operator.

For example, if the square region $S(C, 0)$ is centered at the SHO point $(C, 0)$ in the (p_1, q_1) space that we have been discussing, and has sides of length, say, one percent of the radius C of the unperturbed orbit, then each side of the square will be $10^4 f^{-1}$ units compared to the unit size associated with the Gaussian fall off, $\exp(-d^2)$. In this case the associated quasi-projection operator $P' = P(C, 0)$ is essentially a projection operator onto the square region $S(C, 0)$ of (p_1, q_1) space: it will take any state vector, uniquely decomposed into the sum of terms specified in equation (19), approximately into the sub-sum over the terms occurring in P'.

Let $S(C \cos\phi, C \sin\phi)$ be the square, centered on $(C \cos\phi, C \sin\phi)$, obtained by rotating $S(C, 0)$ by ϕ, so that the line from its center point to the origin is parallel to two of its sides. The action of the unperturbed ($e = 0$) Hamiltonian will take $S(C, 0)$ to $S(C \cos\phi, C \sin\phi)$ in time ϕ. It will also take $P(C, 0)$ to the quasi-projection operator $P(C \cos\phi, C \sin\phi)$ associated with the square $S(C \cos\phi, C \sin\phi)$. These results follow from the simple SHO dynamics in the unperturbed (decoupled) $e = 0$ case.

The collapse rules of orthodox quantum dynamics are compactly stated in terms of the $Trace$ operation. [The $Trace$ operation acting upon operators/matrices is defined by allowing the matrix (or operator) multiplication operation occurring in, say, $TraceAB$ to be extended cyclically, so that B acting to the right acts back on A. This means that for any pair of matrices/operators A and B, $Trace\ AB = Trace\ BA$. This property entails also that $Trace\ ABC = Trace\ BCA$. For any X, $Trace\ X$ is a number. In our case, $Trace\ P(P, Q)$ is essentially the area of the square S(P, Q), measured in units of action given by Planck's constant, and $Trace\ P(P, Q)P(P', Q')$ is the area of the intersection of $S(P, Q)$ and $S(P', Q')$.]

The $Trace$ of the product of the "projection" operator $P(p_1(t, e), q_1(t, e))$ centered on the perturbed orbit [where the two arguments are defined by equations (13) and (16)] with the "projection" operator $P(p_1(t, 0), q_1(t, 0)) = P(C \cos t, C \sin t)$ centered on the unperturbed orbit is, to lowest order in t, $1 - \frac{1}{2}((et)^2 100)$, where for a 40 Hertz SHO the time unit is about 4 ms. The term $\frac{1}{2}((et)^2 100)$ is the ratio of the displacement [of the perturbed square relative to the unperturbed square, namely $\frac{C}{2}(et)^2$], to the length of the side of the square, which is one percent of the radius C of the unperturbed orbit. The unperturbed square rotates rigidly with angular velocity unity, under the action of the unperturbed Hamiltonian, and the lowest-order $e > 0$ displacement is toward the origin $(p_1, q_1) = (0, 0)$. Consequently, the dynamics is essentially unchanged by rotations: the initial condition $(C, 0)$ plays no essential role.

According to the basic precepts of quantum theory, the (physical) "state" of the system at time t is specified by a "density matrix" (or "density operator"), usually denoted by $\rho(t)$. If the answer is 'Yes', then the state immediately *after* the probing action at time t_i is $\rho(t_i+) = P(t_i)\rho(t_i-)P(t_i)$, where $\rho(t_i-)$ is the state immediately *before* the time t_i at which the question is posed. The operators $P(t_i)$ that occur on the right and left in $\rho(t_i+)$ project onto states that in our case are evolving at time t_i according to the unperturbed ($e = 0$) SHO motion. Hence for our case the first-order evolution forward in time from the probing time t_i is the same as the *unperturbed* ($e = 0$) evolution. This means that the small-time evolution forward in time by the time interval t from the time t_i of the i^{th} probing action is given by the second lines of equations (13) and (16) with the arguments t in those two equations replaced by $t + t_i$ but the arguments et left unchanged.

The basic statistical law of quantum theory asserts that, *given the query specified by the projection operator* $P(t)$, the probability that the answer will be 'Yes' is $Trace\ \rho(t+)$ divided by $Trace\ \rho(t-)$.

Note that the query, specified by $P(t)$ and by the time t at which $P(t)$ acts, must be specified *before* the statistical postulate can be applied!

If $\rho(t-)$ is, for the first probing time $t = t_1$, slowly varying over the square domain in (p_1, q_1) space, in the sense that $Trace\ [P, Q]\rho(t-)$ is essentially constant as (P, Q) varies over the square $S(C, 0)$, then the state immediately after the initial observation will be essentially the projection operator $P(C, 0)$ associated with that initial process 1 probing action.

Under these conditions our equations show that for any (large) time T the density matrix $\rho(T)$ will be nearly equal to $P(C \cos T, C \sin T)$, provided the interval T is divided by observations into N equal intervals $t_{i+1} - t_i$, and $N(10eT)^2 N^{-2} << 1$. This condition entails both that *all* the answers will be 'Yes' with probability close to unity, and also that the final $\rho(T)$ will be almost the same as the unperturbed "projection" operator $P(C \cos T, C \sin T)$.

Thus the rapid sequence of probing actions effectively holds the sequence of outcomes to the *expected* sequence. The affected brain states are constrained to follow the *expected* trajectory! This is the quantum Zeno effect, in this context.

This result means that if the probing actions come repetitiously at sufficiently short time intervals then the probability that the state will remain on the unperturbed orbit for, say, a full second will remain high even though the perturbed $e > 0$ classical trajectory moves away from the unperturbed orbit by an amount of order C in time T of order e^{-1}.

The drastic slowing of the divergence of the actual orbit from the computed/expected (circular-in-this-case) orbit is a manifestation of the quantum Zeno effect. The representation in the physically described brain of the probing action corresponding to the query "Is the brain correlate of the occurring percept the computed/expected state" is von Neumann's famous process 1, which lies at the mathematical core of von Neumann's quantum theory of the relationship between perception and brain dynamics.

IV. CONCLUSIONS

The bottom line is that orthodox quantum mechanics has a built-in dynamical connection between conscious intent and its physically describable consequences. This connection fills a dynamical gap in the purely physically described quantum dynamical laws, and it allows certain specific mind-brain connection to be *deduced from the basic physics precepts relating mind and brain.* If a person can, by mental effort, *sufficiently increase the rate at which his process 1 probing actions occur* [this is something not under the control, even statistically, of the physical laws of quantum mechanics] then that person can, by mental effort, quantum dynamically *cause* his brain/body to behave in a way that follows a pre-programmed trajectory, specified, say, by "expectations", instead of following the trajectory that it would follow if the von Neumann process 1 probing actions do not occur in rapid succession. Because the causal origin of the process 1 probing actions *is not specified, even statistically, by the presently known laws of physics,* there is in quantum mechanics a rational place for the experiential aspects of our description of nature to enter, irreducibly and efficaciously, into the determination of the course of certain physically described events.

I have focused here on the leading powers in t, in order to emphasize, and exhibit in a relatively simple way, the origin of the key result, which is that for small t on the scale, not of the exceedingly short period of the quantum mechanical oscillations, nor even on the $\sim 25ms$ period of the $\sim 40Hz$ scale of the classical oscillations, but on the much longer time scale of the *difference* of the periods of the two coupled modes, there will be, in this model, by virtue of the quantum mechanical effects associated with a rapid sequence of repeated probing actions, a strong tendency for the brain correlate of consciousness to follow the *expected* trajectory, in contrast to what would happen if only infrequent probing actions were made.

This analysis is based on a theory of the mind-brain connection that resolves in principle the basic interpretational problem of quantum theory, which is the problem of reconciling the classical character of our perceptions of the physical world with the non-classical character of the state of the world generated by the combination of the Schroedinger equation and the uncertainty principle. The theory resolves also the central problem of the philosophy of mind, which is to reconcile the apparent causal power of our conscious efforts with the laws and principles of physics. This relatively simple theory allows us to understand within the *dynamical framework* of orthodox (knowledge-associated-collapse) quantum physics the evident capacity of our conscious thoughts to influence our physical actions, and to become thereby integrated into the process of natural selection.

The discussion has focused so far on one very small region of the brain, or rather on one small region together with an environment into which it would, in the absence of probing observations, dissipate its energy. But the possible experiences of the relevant kind are associated with synchronous excitations in a large collection of such localized regions[1, 2]. Following the principles of quantum *field* theory the associated quantum state is represented by a *tensor product* of states associated with the individual tiny regions.

There has been a lot of detailed theoretical work examining the effects of the fact that for a system that extends over an appreciable region of spacetime, the parts of the systen located in different regions are coupled effectively to different degrees of freedom of the environment[10]. Insofar as these aspects of the environment are never observed, the predictions of quantum theory are correspondingly curtailed. In particular, *relative phases* of the wave function of the system associated with different regions becomes impossible to determine, and a "superposition" of spatially separated components becomes reduced to a "mixture".

In the model under consideration here the components in different space-time regions are different *factors* of a tensor product, rather than different terms of a superposition. In this case, the fact that different regions of the system are coupled to different degrees of freedom of the environment does not produce the usual quantum decoherence effects.

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