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Research Article

Quantum-Classical Interactions: Calcium Ions and Synchronous Neural Firings

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Abstract

Background: Previous work by the author has developed a statistical mechanics of neocortical interactions (SMNI) describing short-term memory (STM) and electroencephalographic (EEG) data, using the author's Adaptive Simulated Annealing (ASA) to fit such data. A closed-form time-dependent derivation of a quantum path-integral for calcium-ion wave-packets generated at tripartite neuron-astrocyte-neuron synaptic sites was used for interactions with Classical-physics SMNI. SMNI has used path-integral calculations with the author's numerical PATHINT code, to understand short-term memory (STM).

Objective: Better fits to EEG data will be a strong indication that STM neocortical information processing in some subjects involves synchronous interaction between Quantum calcium-ion waves and Classical neural firings (also synchronous, but just among the neurons).

Method: Comparison will be made with Quantum computers and the author's N-dimensional path-integral algorithm for quantum systems, qPATHINT, which runs on Classical computers: Quantum computers propagating calcium-ion wave-packets will be synchronized with Classical computers propagating SMNI via PATHINT. qPATHINT for calcium wave-packets also will be synchronized with PATHINT for SMNI, both running on Classical computers.

Results: If successful, there should be modest improvement of cost/objective functions used to fit EEG data with these models.

Conclusion: Quantum and Classical computers can run synchronized computations to investigate Quantum-Classical phenomena such as interactions between calcium ions and synchronous neural firings. Classical computers may deliver similar results using qPATHINT synchronized with PATHINT.

Keywords: Path Integral; Quantum Systems; Neuron Astrocyte Interactions; Multiscale Modeling; Quantum-Classical Computers

Introduction

This project calculates synchronous quantum systems and macroscopic systems with well-defined interactions. This paper is a summary report of work published, with a view to future research; there are no new research results in this paper.

The project was mapped out in several publications [6], performed with the help of six yearly grants from The Extreme Science and Engineering Discovery Environment (XSEDE.org) using their supercomputer resources from Feb 2013 through Dec 2018. This Communication describes current work beginning where that work finished. Previous publications, including the one above, also have calculated spin-off features of this research, such as nano-robotic drug-delivery and correlates of Consciousness.

That project calculated quantum Ca^{+2} interactions with electroencephalographic (EEG) data, in the theoretical context of the author's Statistical Mechanics of Neocortical Interactions (SMNI), which has explicitly calculated phenomena across a range of experimental data. Only very specific calcium ions, Ca^{+2}, are considered, those arising from regenerative calcium waves generated at tripartite neuron-astrocyte-neuron synapses. Astrocytes comprise most glial cells. which are larger in number than neurons; astrocytes play a fundamental role in neocortex [23]. It is important to note that Ca^{+2} ions, and specifically Ca^{+2} waves, influence many processes in the brain [11], but this study focuses on free waves generated at tripartite synapses [24] because of their calculated direct interactions with large synchronous neuronal firings. Similarly, other ions such as potassium are very influential in neocortical phenomena also at quantum scales [8,25], but here stress is put on Ca^{+2} waves which may multiply their effects.

This project does not rely on metaphors to quantum systems to describe large-scale neural activity. Rather, explicit mechanisms and calculations that support these mechanisms are invoked. In all applications to date, only a minimal set of parameters have been adjusted to data, and in those case only within reasonable experimental ranges of those parameters.

In this context, it is important to note that mechanisms invoked here such as the Zeno/"bang-bang" effect may exist only in special contexts [12,13,17,26-31], albeit decoherence among particles is known to be very fast, e.g., faster than phase-damping of macroscopic classical particles colliding with quantum particles [2].

However, previous Classical physics calculations support these extended SMNI models and are consistent with experimental data. Quantum physics calculations also support these extended SMNI models and, while they too are consistent with experimental data, it is quite speculative that they can persist in neocortex. Admittedly, it is surprising that detailed calculations continue to support this model, and so it is worth continued examination it until it is theoretically or experimentally proven to be false.

- Section 2 itemizes assumptions and mechanisms invoked, after a brief discussion of SMNI, including successful mathematical physics calculations, both Classical [32] and Quantum [6,7,33].
- Section 3 describes research in progress to further examine the proposed Classical-Quantum synchronous interactions.
- Section 4 is the Conclusion.

Note that using common variable names require using the same root Latin or Greek letters. Therefore, the convention is used that variables are additionally identified by their subscript and/or superscript indices.

Previous mechanisms and calculations

Statistical mechanics of neocortical interactions (SMNI)

SMNI has been developed since circa 1980, scaling aggregate synaptic interactions to neuronal firings, up to minicolumnar-macrocolumnar columns of neurons to mesocolumnar dynamics, up to columns of neuronal firings, up to regional macroscopic sites [4,18,34-37].

This development is described below to give context to Classical SMNI, which contains the algebra of synchronous neural firings which interacts with Quantum calcium ions further described below.

Multiple scales

SMNI scales aggregate synaptic interactions, from neuronal firings, to minicolumnar-macrocolumnar columns of neurons to mesocolumnar dynamics, to columns of neuronal firings, to regional macroscopic sites [4,18,34-37]. By scaling SMNI across neocortical regions fits to EEG data were tested [1,6,38,39] using the author's Adaptive Simulated Annealing (ASA) importance-sampling optimization code [5].

SMNI spans many orders of magnitude, from synaptic gaps with scales of $10^{-2}\,\mu$m to regional scales of $10^{-4}\,\mu$m, e.g., 6 orders of magnitude, which has been noted by other investigators who understand the necessity of treating multiple neocortical scales when dealing with many neocortical phenomena [40].

Synaptic interactions

Experimental data of chemical and electrical intra-neuronal interactions are used to develop the short-time conditional probability distribution of firing of a given neuron firing given just-previous firings of other neurons [18,34], i.e., interactions with k neurons within τ_j of 5-10 msec give rise to the conditional probability that neuron j fires (σ_j=+1) or does not fire (σ_j=-1) is

$$p_{\sigma_j} = \Gamma\Psi = \frac{\exp(-\sigma_j F_j)}{\exp(F_j)+\exp(-F_j)}$$

$$F_j = \frac{V_j - \sum_k \; a^*_{jk} v_{jk}}{(\pi \; \sum_{k'} \; a^*_{jk'}(v^2_{jk'} + \phi^2_{jk'}))^{1/2}}$$

$$a_{jk} = \frac{1}{2} A_{|jk|}(\sigma_k + 1) + B_{jk} \quad (1)$$

Above, Γ is the "intra-neuronal" probability distribution, the contribution to polarization achieved at an axon given activity at a synapse. Ψ is the "inter-neuronal" probability distribution of thousands of quanta of neurotransmitters released at one neuron's presynaptic site effecting a (hyper-)polarization at another neuron's postsynaptic site. This derivation holds for Γ Poisson, and for Ψ Poisson or Gaussian.

Vj is the depolarization threshold, v_{jk} is the induced synaptic polarization of *E* or *I* type at the axon, and ϕ_{jk} is its variance. The efficacy a_{jk} is a sum of A_{jk} from the connectivity between neurons, from impinging *k*-neuron firings, and B_{jk} is spontaneous background noise.

Neuronal interactions

The mesoscopic probability P is developed by aggregating to the mesoscopic scale from the microscopic synaptic scale,

$$P = \prod_G P^G[M^G(r;t+\tau)|M^{\bar{G}}(r';t)]$$
$$= \sum_{\sigma_j} \delta\big(\sum_{jE} \sigma_j - M^E(r;t+\tau)\big)\delta\big(\sum_{jI} \sigma_j - M^I(r;t+\tau)\big)\prod_j^N p_{\sigma_j} \quad (2)$$

Here, *M* represents mesoscopic scales of columns of *N* neurons, in terms of subsets *E* and *I*, represented by p_{qi}. The "delta"-functions *δ*-constraint represents many neurons in a column, labeled by *G* to represent excitatory (*E*) and inhibitory (*I*) contributions.

Columnar interactions

In the prepoint (Ito) representation the SMNI Lagrangian *L* is

$$L = \sum_{G,G'} (2N)^{-1}(\dot{M}^G - g^G)g_{GG'}(\dot{M}^{G'} - g^{G'})/(2N\tau) - V'$$
$$g^G = -\tau^{-1}(M^G + N^G \tanh F^G) \quad (3)$$
$$g^{GG'} = (g_{GG'})^{-1} = \delta_G^{G'}\tau^{-1}N^G \mathrm{sech}^2 F^G$$
$$g = \det(g_{GG'})$$

The threshold factor F^G is derived as;

$$F^G = \sum_{G'} \frac{v^G + v^{\ddagger E'}}{\left((\pi/2)[(v_{G'}^G)^2 + (\phi_{G'}^G)^2](\delta^G + \delta^{\ddagger E'})\right)^{1/2}}$$
$$v^G = V^G - a_{G'}^G v_{G'}^G N^{G'} - \frac{1}{2}A_{G'}^G v_{G'}^G M^{G'}, v^{\ddagger E'} = -a_{E'}^{\ddagger E} v_{E'}^E N^{\ddagger E'} - \frac{1}{2}A_{E'}^{\ddagger E} v_{E'}^E M^{\ddagger E'}$$
$$\delta^G = a_{G'}^G N^{G'} + \frac{1}{2}A_{G'}^G M^{G'}, \delta^{\ddagger E'} = a_{E'}^{\ddagger E} N^{\ddagger E'} + \frac{1}{2}A_{E'}^{\ddagger E} M^{\ddagger E'}$$
$$a_{G'}^G = \frac{1}{2}A_{G'}^G + B_{G'}^G, a_{E'}^{\ddagger E} = \frac{1}{2}A_{E'}^{\ddagger E} + B_{E'}^{\ddagger E} \quad (4)$$

Here, $A^G_{G'}$ is the columnar-averaged direct synaptic efficacy, $B^G_{G'}$ is the columnar-averaged background-noise contribution to synaptic efficacy. The "‡" parameters arise from regional interactions across many macrocolumns.

While the midpoint Stratonovich representation, described most recently in [6], is required to understand and derive useful measures, this also requires a lot more algebra, as a Riemannian geometry is induced by a multivariate nonlinear variance, effectively a curvature of this neural space which multiplies second-derivative terms in the Fokker-Planck representation, mathematically equivalent to this path integral development (also mathematically equivalent to sets of coupled stochastic differential equations) [6,18,34,41].

SMNI parameters from experiments

All values of parameters and their bounds are taken from experimental data, not arbitrarily fit to specific phenomena.

N^G = {N^E=160, N^I=60} was set for for visual neocortex, {N^E=80, N^I=30} was set for all other neocortical regions, $M^{G'}$ and $N^{G'}$ in F^G are afferent macrocolumnar firings scaled to efferent minicolumnar firings by $N/N^* \approx 10^{-3}$. N^* is the number of neurons in a macrocolumn, about 10^5. *V'* includes nearest-neighbor mesocolumnar interactions. Other values also are consistent with experimental data, e.g., V^G=10 mV, $v_{G'}^G$ = 0.1 mV, $\phi_{G'}^G = 0.03^{1/2}$ mV.

The wave equation cited by EEG theorists, permitting fits of SMNI to EEG data [19], was derived using the variational principle applied to the SMNI Lagrangian.

This creates an audit trail from synaptic parameters to the statistically averaged regional Lagrangian. Such audit trails are a prime virtue of models of reality, e.g., in contrast to machine learning, etc [6].

Verification of basic SMNI hypothesis

The core SMNI hypothesis first developed circa 1980 [4,18,34] that highly synchronous patterns of neuronal firings process high-level information, has been verified experimentally only since 2012 [20,42].

SMNI Calculations of short-term memory (STM)

SMNI calculations agree with observations [7,9,18,32-39,43-48]; This list includes:

- Capacity (auditory 7±2 and visual 4±2) [35]
- Duration [36]
- Stability [36]
- Primacy versus recency rule [36,49]
- Hick's law (reaction time and g factor) [44]

- Nearest-neighbor minicolumnar interactions => mental rotation of images [18,34]
- Derivation of basis for EEG [19,21].

Pathint

The folding in time of short-time probabilities P give rise to relatively long-time probabilities encompassing the time periods during which STM experiments are conducted while measuring P300 electromagnetic waves, which in turn are fit to SMNI parameters within their experimentally determined ranges.

To get the sense of the path-integral histogram algorithm used, it suffices to consider a one-dimensional path-integral in variable *q*, developed in terms of the kernel/propagator *G*, for each of its intermediate integrals, as

$$P(q;t+\Delta t) = \int dq'[g^{1/2}(2\pi\Delta t)^{-1/2}\exp(-L\,\Delta t)]P(q';t) = \int dq' G(q,q';\Delta t)P(q';t)$$
$$P(q;t) = \sum_{i=1}^{N} \pi(q-q^i)P_i(t)$$
$$\pi(q-q^i) = 1, (q^i - \tfrac{1}{2}\Delta q^{i-1}) \le q \le (q^i + \tfrac{1}{2}\Delta q^i); 0, \text{otherwise} \quad (5)$$

This yields

$$P_i(t+\Delta t) = T_{ij}(\Delta t)P_j(t)$$
$$T_{ij}(\Delta t) = \frac{2}{\Delta q^{i-1}+\Delta q^i}\int_{q^i-\Delta q^{i-1}/2}^{q^i+\Delta q^i/2} dq \int_{q^j-\Delta q^{j-1}/2}^{q^j+\Delta q^j/2} dq' G(q,q';\Delta t) \quad (6)$$

T_{ij} is a banded matrix representing the Gaussian nature of the short-time probability centered about the drift.

Several projects have used this algorithm [14,50-54]. Special 2-dimensional codes were developed for specific projects in Statistical Mechanics of Combat (SMC), SMNI and Statistical Mechanics of Financial Markets (SMFM) [15,50,55].

Interaction between calcium-ion waves and neural magnetic vector potential

Classical interactions

Circa 2010, Classical physics calculations supported the interaction between Ca^{2+} -ion waves [11] and large-scale synchronous neural firings, e.g., STM attentional states [9,32,39,45-48].

Experimental data used for vector potential source

The neocortical electric current is taken directly from experimental data, not theoretical calculations. Thus, they include much of the contribution from several sources, e.g., including ephaptic coupling [23].

The magnitude of the current is based on dipole moments $Q=|I|\hat{z}$ where $\hat{z}$ is the direction of the current I with the dipole spread over z. Q ranges from 1 pA-m = 10^{-12} A-m for a pyramidal neuron [56], to 10^{-9} A-m for larger neocortical mass (like mesocolumns considered here) [22], giving rise to currents leading to $qA \approx 10^{-28}$ kg-m/s. The velocity of a Ca^{2+} wave can be ≈20-50 μm/s. A typical Ca^{2+} wave of 1000 ions, with mass $m=6.655\times10^{-23}$ kg times a speed of ≈20-50 μm/s, gives $p \approx 10^{-27}$ kg-m/s, i.e., within an order of magnitude by this Classical calculation.

Note that, unlike short-ranged electric and magnetic fields in vivo which are derivatives of A, A itself has a long-ranged logarithmic dependence on distance.

Therefore, 10^4 synchronous firings in a macrocolumn gives a dipole moment |Q| = 10^{-8} A-m. With z = 10^2 μm $=10^{-4}$ m, $|qA| \approx 2\times10^{-19}\times10^{-7}\times10^{-8}/10\text{-}4 = 10^{-28}$ kg-m/s.

Quantum interactions

Circa 2014, Quantum physics calculations supported the interaction between Ca^{2+} -ion waves and large-scale synchronous neural firings, e.g., STM attentional states, and explicit wave functions were developed for Ca^{2+} waves that interacted with the magnetic vector potential of highly synchronous neural firings [7,10,33,45,47], and a closed-form time-dependent path-integral expression explicitly dependent on the Planck constant, $\hbar$, was derived to test fits to EEG data [6]. The wave function ψ_e contains interaction of A with p of Ca^{2+} wave packets. A closed-form expression was derived from the Feynman representation of the path integral [3], modified to include A.

$$\psi_e(t) = \int d\mathbf{r}_0\psi_0\psi_F = \left[\frac{1-i\hbar t/(m\Delta\mathbf{r}^2)}{1+i\hbar t/(m\Delta\mathbf{r}^2)}\right]^{1/4}[\pi\Delta\mathbf{r}^2\{1+[\hbar t/(m\Delta\mathbf{r}^2)]^2\}]^{-1/4}$$
$$\times\exp\left[-\frac{[\mathbf{r}-(\mathbf{p}_0+q\mathbf{A})t/m]^2}{2\Delta\mathbf{r}^2}\frac{1-i\hbar t/(m\Delta\mathbf{r}^2)}{1+[\hbar t/(m\Delta\mathbf{r}^2)]^2}+i\frac{\mathbf{p}_0\cdot\mathbf{r}}{\hbar}-i\frac{(\mathbf{p}_0+q\mathbf{A})^2t}{2\hbar m}\right]$$
$$\psi_F(t) = \int\frac{d\mathbf{p}}{2\pi\hbar}\exp\left[\frac{i}{\hbar}\left(\mathbf{p}(\mathbf{r}-\mathbf{r}_0)-\frac{\mathbf{\Pi}^2t}{(2m)}\right)\right] = \left[\frac{m}{2\pi i\hbar t}\right]^{1/2}\exp\left[\frac{im(\mathbf{r}-\mathbf{r}_0-q\mathbf{A}t/m)^2}{2\hbar t}-\frac{i(q\mathbf{A})^2t}{2m\hbar}\right]$$
$$\psi_0 = \psi(\mathbf{r}_0,t=0) = \left(\frac{1}{\pi\Delta\mathbf{r}^2}\right)^{1/4}\exp\left(-\frac{\mathbf{r}_0^2}{2\Delta\mathbf{r}^2}+i\frac{\mathbf{p}_0\cdot\mathbf{r}_0}{\hbar}\right) \quad (7)$$

Where ψ_0 is the initial Gaussian packet, ψ_F is the free-wave evolution operator, $\hbar$ is the Planck constant, q is the electronic charge of Ca^{2+} ions, m is the mass of a wave-packet of 1000 Ca^{2+} ions, Δr^2 is the spatial variance of the wave-packet, the initial momentum is p_0, and the evolving canonical momentum is $\Pi=p+qA$. Calculations show that p of the Ca^{2+} wave packet and qA of the EEG field make about equal contributions to Π [45].

Tripartite influence on synaptic $B_{G'}^{G}$ was measured by the ratio of packet's $<p(t)>_{(\psi^*\psi)}$ to $<p_0(t_0)>_{(\psi^*\psi)}$ at the onset of each attentional task. Here $<p(t)>_{(\psi^*\psi)}$ is taken over $\psi_e^* \psi_e$.

$$< \mathrm{p} >_{\psi*\psi} = m \frac{<\mathrm{r}>_{\psi*\psi}}{t-t_0} = \frac{q\mathrm{A}+\mathrm{p}_0}{m^{1/2}|\Delta\mathrm{r}|} \left(\frac{(\hbar t)^2 + (m\Delta\mathrm{r}^2)^2}{\hbar t + m\Delta\mathrm{r}^2} \right)^{1/2} \quad (8)$$

A changes slower than p, permitting a static approximation of A to derive ψ_e and $<p>_{(\psi^*\psi)}$ within P300 EEG epochs, resetting $t=0$ at the onset of each classical EEG measurement (1.953 ms apart), using the current A. These forms were used in fits to EEG data to test of interactions across scales in a classical context [6].

Note the presence of time-dependence and $\hbar$ in $\hbar$t, making this description of calcium waves quite sensitive to Quantum effects. Accordingly, the SMNI synaptic parameters were set to be proportional to $<p>_{(\psi^*\psi)}$ in previous fits to EEG [6].

Zeno bang-bang interactions

The wave-packet wave function ψ can "survive" multiple collisions due to their regenerative processes over long durations of hundreds of ms. Therefore, Ca^{2+} waves may support a Zeno or "bang-bang" effect promoting long coherence times [12,13,17,26-31].

In momentum space, the wave function ϕ(p,t) is

$$\begin{aligned} \phi(\mathrm{p},0) &= (2\pi(\Delta\mathrm{p})^2)^{-3/4} e^{-(\mathrm{p}-\mathrm{p}_0)^2/(4(\Delta\mathrm{p})^2)} \\ U(\mathrm{p},t) &= e^{-i((\mathrm{p}+q\mathrm{A})^2 t)/(2m\hbar)} \\ \phi(\mathrm{p},t) &= \phi(\mathrm{p},0)U(\mathrm{p},t) \end{aligned} \quad (9)$$

The wave packet ϕ(p,t) is "kicked" from p to p+δp. Random repeated kicks of δp result in $<\delta p>\approx 0$; each kick keeps the variance $\Delta(p+\delta p)^2 \approx \Delta(p)^2$. Then, the overlap integral at the moment t of a kick to the new from the old state is

$$\begin{aligned} < \phi^*(\mathrm{p}+\delta\mathrm{p},t)|\phi(\mathrm{p},t) > &= \exp\left(\frac{i\kappa+\rho}{\sigma}\right) \\ \kappa &= 8\delta\mathrm{p}\Delta\mathrm{p}^2\hbar m(q\mathrm{A}+\mathrm{p}_0)t - 4(\delta\mathrm{p}\Delta\mathrm{p}^2 t)^2 \\ \rho &= -(\delta\mathrm{p}\hbar m)^2 \\ \sigma &= 8(\Delta\mathrm{p}\hbar m)^2 \end{aligned} \quad (10)$$

Where ϕ(p+δp,t) is the normalized wave function in p+δp momentum space.

Then the survival time amplitude A(t) and survival probability p(t) is calculated as [17].

$$\begin{aligned} A(t) &= < \phi^*(\mathrm{p}+\delta\mathrm{p},t)|\phi(\mathrm{p},t) > \\ p(t) &= |A(t)|^2 \end{aligned} \quad (11)$$

These numbers yield

$$< \phi^*(\mathrm{p}+\delta\mathrm{p},t)|\phi(\mathrm{p},t) > = \exp\left(i(1.67 \times 10^{-1}t - 1.15 \times 10^{-2}t^2) - 1.25 \times 10^{-7}\right) \quad (12)$$

Where, after substitution for numerical values of all variables except time, the numerical coefficient of time t is in units of time^{-1} and the numerical coefficient of time t^2 is in units of time^{-2}, thereby simply presenting the dependence on time. Thus, thousands of small repeated kicks do not appreciably affect the real part of ϕ, and the projections do not appreciably destroy the original wave packet, giving a survival probability per kick as $p(t) \approx \exp(-2.5\times10^{-7}) \approx 1-2.5\times10^{-7}$.

As emphasized in the Introduction, note that the Zeno/"bang-bang" effect may exist only in special circumstances. Decoherence among particles is known to be very fast, e.g., faster than phase-damping of macroscopic classical particles colliding with quantum particles [2].

qPATHINT

Standard Monte Carlo techniques generally are not useful to numerically calculate the time-dependent path integral. qPATHINT is an N-dimensional histogram-based code that calculates propagation of quantum variables, e.g., in the presence of shocks. qPATHINT is based on the Classical-physics code PATHINT. The PATHINT C code of about 7500 lines of code using the GCC C-compiler was rewritten for double complex variables and further developed for arbitrary N dimensions.

qPATHINT was tested in SMNI and SMFM calculations [7,16,33].

Current research

Synchronous quantum-classical computers

Although qPATHINT has been developed and tested [7], it is important to further study the Zeno/"bang-bang" effect for Ca^{2+} wave-packets in the presence of serial regenerative collisions.

For more detailed exploration of the Zeno effect in SMNI, accounts on quantum computers have been established, i.e., on D-Wave, IBM and Rigetti.

As in previous publications, fits to EEG data will be a useful measure of Quantum-Classical physics interactions in neocortex, likely requiring synchronized calculations between quantum and classical computers during the ASA fitting process to EEG over a range of subjects during STM attentional tasks. Quantum computer calculations will also be compared with results from Classical computer calculations using qPATHINT.

Conclusion

Previous studies over the past decade have established a rationale to consider Quantum-Classical scales of interaction in neocortex, specifically between Ca^{2+} wave-packets generated via regenerative collisions at tripartite neuron-astrocyte-neuron synaptic sites and the magnetic vector potential A arising from highly synchronous neural firings, e.g., as experimentally determined by EEG during STM tasks.

Current research is geared towards further investigating the Quantum physics aspects of evolving Ca^{2+} wave-packets, to further study their prolonged existance due to Zeno/"bang-bang" effects. Quantum computers, as well as Classical computers running qPATHINT, will be used for this purpose. Id: https://www.ingber.com/smni19_quantum-classical.pdf 1.26 2019/11/25 22:34:45

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