

## Quantum Biophysical Framework for Modeling Neural Dynamics: Entanglement, Decoherence, Synchronization, and Their Role in Emergent Cognition and Brain Function

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### Keywords:

Neural network,  
Quantum coherence,  
Superposition,  
Entanglement,  
Lindblad decoherence.

### ABSTRACT

Understanding how cognition emerges from collective neural activity remains a fundamental challenge in neuroscience. While conventional models rely on classical neural interactions, quantum theory suggests biological information processing may also involve quantum phenomena. This study develops a quantum biophysical framework to model neural dynamics and explore the quantum emergence of cognition. Beginning with a single-neuron model characterized by quantum superposition and coherence, the framework scales to interacting neural populations using quantum entanglement and a neural-network Hamiltonian. We incorporate environmental decoherence via the Lindblad master equation, while modeling large-scale coordination through Kuramoto synchronization dynamics. To quantify these dynamics, a candidate Emergent Cognition Index (ECI) was computationally formulated and evaluated, integrating superposition, coherence, entanglement, and synchronization. Numerical simulations of 100 interacting neurons demonstrated that environmental decoherence reduces superposition and coherence over time, whereas entanglement and synchronization increase with stronger neural interactions. Analysis of the neural-network Hamiltonian showed progressing collective organization through elevated interaction energy. Phase-transition modeling revealed a continuous shift from a quantum-coherent state to a classical neural state under increasing decoherence. Within the simulation, the candidate cognition index peaked near the critical regime where quantum coherence, entanglement, and synchronization coexist. These findings suggest cognition can be interpreted as an emergent phenomenon arising from the interplay among quantum coherence, entanglement, neural interactions, synchronization, and decoherence. While the proposed index serves as a theoretical construct, the framework provides testable predictions and a foundational bridge between physics and neuroscience for future experimental validation.

**Submitted:** 12 Oct. 2026

**Accepted:** 26 Oct. 2026

**Published:** 27 Oct. 2026

### INTRODUCTION

Understanding how cognition and brain function emerge from neural activity remains one of the most significant challenges in modern science. The human brain consists of highly interconnected neural networks that process information through complex electrochemical interactions. Classical neuroscience has provided substantial insight into neural signaling, synaptic transmission, memory formation, learning, and perception. However, fundamental questions regarding large-scale information integration, consciousness, and the emergence of higher cognitive functions continue to

motivate the development of new theoretical frameworks. Recent advances in quantum biophysics have stimulated growing interest in the possibility that quantum phenomena may contribute to biological information processing. Quantum effects such as coherence, superposition, tunneling, and entanglement have been implicated in several biological systems, including photosynthetic complexes, avian magnetoreception, and enzymatic processes, suggesting that quantum mechanisms may operate in environments previously considered unfavorable for quantum behavior (Kinsey et al., 2024; Madl & Renati, 2023). These

developments have encouraged interdisciplinary efforts to explore whether similar principles could play a role in neural dynamics and brain function. The potential relevance of quantum mechanics to neural systems remains an active area of investigation. Several theoretical studies have proposed that quantum coherence, entanglement, and related phenomena may influence information processing within neural structures, while others emphasize the challenges posed by environmental decoherence in the warm and noisy conditions of the brain (Ikrar & Muchsin, 2025). Although definitive experimental evidence remains limited, recent developments in quantum biophysics, quantum sensing, and theoretical neuroscience have renewed interest in examining the possible interplay between quantum processes and neural activity (Kinsey et al., 2024).

From a systems perspective, cognition emerges from the coordinated activity of large populations of interacting neurons. Consequently, understanding the possible role of quantum effects in cognition requires a framework capable of connecting microscopic quantum behavior with macroscopic neural organization. Such a framework should account for quantum superposition and coherence at the level of individual neurons, quantum correlations among interacting neural elements, environmental decoherence, collective neural synchronization, and the emergence of large-scale functional states associated with brain activity.

Synchronization has long been recognized as a fundamental mechanism underlying neural communication and information integration. Oscillatory synchronization across neural populations contributes to perception, memory, attention, and other cognitive processes. At the same time, quantum coherence and entanglement provide mechanisms for non-classical information correlations that may enhance collective dynamics under appropriate conditions (Ikrar & Muchsin, 2025). The interaction between these processes raises important questions regarding how quantum and classical mechanisms may jointly contribute to cognition and brain function. The intersection of quantum mechanics and neuroscience represents one of the most provocative frontiers in contemporary theoretical biology. While classical neurophysiology has provided a robust framework for understanding action potentials, synaptic transmission, and neural network dynamics, several phenomena—including the unity of conscious experience, the speed of cognitive processing, and the precision of perceptual binding—remain incompletely explained by purely classical models (Hameroff & Penrose, 2014). This review examines the hypothesis that quantum mechanical effects, including superposition, coherence, and entanglement, may play functional roles in neuronal dynamics, and that these quantum processes

interact with classical synchronization mechanisms to produce emergent cognitive properties.

The quantum biophysical framework posits that neural systems operate in a hybrid regime in which quantum coherence contributes to fine-grained informational processing on millisecond timescales, while classical phase synchronization provides the robust, large-scale coordination necessary for cognitive function (Engel et al., 1999; Tegmark, 2000). This framework requires careful attention to the problem of decoherence—the loss of quantum coherence due to interaction with the warm, wet, and noisy intracellular environment—and motivates the use of open quantum system formalisms, particularly the Lindblad master equation, to model neural dynamics realistically.

## Theoretical Foundations

### Quantum Mechanics in Biological Systems

Quantum mechanics describes physical systems through state vectors in Hilbert space and observables represented by Hermitian operators. For a two-level quantum system, such as a simplified neuronal model with states  $|0\rangle$  (quiescent) and  $|1\rangle$  (firing), the density matrix  $\rho$  completely characterizes the quantum state. The time evolution of an isolated quantum system is governed by the Schrödinger equation,  $i\hbar(d|\psi\rangle/dt) = H|\psi\rangle$ , where  $H$  is the Hamiltonian operator encoding the system's energy structure.

In biological contexts, however, systems are rarely isolated. The intracellular environment of a neuron comprises water molecules, ions, proteins, and thermal fluctuations at physiological temperature ( $\sim 310$  K). These environmental interactions lead to decoherence—the gradual suppression of quantum superposition and the emergence of classical probabilistic behavior. The timescale of decoherence in neural tissue has been estimated to range from femtoseconds to milliseconds, depending on the specific degrees of freedom considered (Tegmark, 2000; Reimers et al., 2009).

### The Lindblad Master Equation for Open Quantum Systems

To properly model quantum systems interacting with an environment, we employ the Lindblad master equation, the most general Markovian master equation that preserves the physical properties of the density matrix (complete positivity and trace preservation). In its standard form, the Lindblad equation reads:

$$d\rho/dt = -i[H, \rho] + \sum_k (L_k \rho L_k^\dagger - \frac{1}{2}\{L_k^\dagger L_k, \rho\})$$

Where  $H$  is the system Hamiltonian,  $L_k$  are the Lindblad (jump) operators representing different dissipative channels, and  $(\dagger)$  denotes the adjoint. Each term  $L_k \rho L_k^\dagger$  describes a quantum jump process, while the adjoint terms ensure trace preservation. For a neuronal two-level system, the relevant jump operators include: (1)  $L_1 = \sqrt{\gamma_d} \sigma_z$  for pure dephasing (loss of

relative phase between  $|0\rangle$  and  $|1\rangle$  without energy exchange); (2)  $L_2 = \sqrt{\gamma_a} \sigma_-$  for amplitude damping (spontaneous decay from the excited state  $|1\rangle$  to the ground state  $|0\rangle$ ); and (3)  $L_3 = \sqrt{\gamma_e} \sigma_+$  for thermal excitation (environment-induced transitions from  $|0\rangle$  to  $|1\rangle$ ). The rates  $\gamma_d$ ,  $\gamma_a$ , and  $\gamma_e$  characterize the strength of environmental coupling for each channel and are determined by the spectral density of the bath fluctuations (Breuer & Petruccione, 2002).

The Lindblad formalism is essential for neural quantum models because it captures both coherent (unitary) and incoherent (dissipative) dynamics within a single unified framework. Unlike simplified decoherence models that include only a single dephasing channel, the full multi-channel Lindblad equation accounts for energy relaxation and thermal excitation, providing a more realistic description of the warm, dissipative neural environment.

### Classical Synchronization and the Kuramoto Model

Large-scale neural coordination is well-described by classical synchronization theory. The Kuramoto model provides a canonical framework for studying phase synchronization in populations of coupled oscillators. In this model, each neuron  $i$  is represented by a phase variable  $\theta_i$  evolving according to  $d\theta_i/dt = \omega_i + (K/N) \sum_j \sin(\theta_j - \theta_i)$ , where  $\omega_i$  is the natural frequency,  $K$  is the coupling strength, and  $N$  is the population size. The degree of synchronization is quantified by the complex order parameter  $R(t) = |(1/N) \sum_j e^{i\theta_j(t)}|$ , which ranges from 0 (incoherent) to 1 (perfect phase locking) (Strogatz, 2000).

## MATERIALS AND METHODS

Presenting a quantum-biophysical computational framework for studying neural dynamics. The model begins with a single neuron represented as a quantum two-level system (qubit), extends to interacting neuron pairs, and finally to large-scale neural populations. Quantum coherence, entanglement, decoherence, and synchronization mechanisms are incorporated to investigate their roles in information processing and emergent cognition.

### Single Neuron Quantum Model

A neuron is modeled as a two-state quantum system:

$$|\psi\rangle = \alpha |0\rangle + \beta |1\rangle$$

Where

$|0\rangle$  = resting state

$|1\rangle$  = firing state

And  $|\alpha|^2 + |\beta|^2 = 1$ . The Hamiltonian of a single neuron is:  $H_1 = \begin{pmatrix} E_0 & \Delta \\ \Delta & E_1 \end{pmatrix}$  where  $E_0$  = resting-state energy,  $E_1$  = firing-state energy,  $\Delta$  = tunneling interaction.

The time evolution is governed by:  $i\hbar \frac{\partial}{\partial t} |\psi(t)\rangle = H_1 |\psi(t)\rangle$

### Single-Neuron Quantum Superposition

A neuron is first modeled as a quantum two-level system:

$$|\psi\rangle = \alpha |0\rangle + \beta |1\rangle$$

Where

$|0\rangle$  = resting state

$|1\rangle$  = firing state

And  $|\alpha|^2 + |\beta|^2 = 1$ . The probabilities of observing the neuron in each state are

$P_0 = |\alpha|^2$   $P_1 = |\beta|^2$  This is the superposition stage, where the neuron simultaneously occupies both states before measurement.

### Quantum Coherence in a Single Neuron

Superposition gives rise to coherence; the density matrix is

$\rho = \begin{pmatrix} |\alpha|^2 & \alpha\beta^* \\ \alpha^*\beta & |\beta|^2 \end{pmatrix}$  and  $\rho = |\psi\rangle\langle\psi|$  The coherence measure is:  $C = |\rho_{01}|$  where  $\rho_{01} = \alpha\beta^*$  Large  $C$  implies strong quantum coherence.

### Two-Neuron Entangled System

For two entangled neurons:  $|\Psi\rangle = \frac{1}{\sqrt{2}}(|00\rangle + |11\rangle)$

This Bell state represents maximal entanglement. The Hamiltonian becomes:

$$H_2 = H_A \otimes I + I \otimes H_B + J \sigma_z \otimes \sigma_z$$

Where  $J$  = coupling strength,  $\sigma_z$  = Pauli matrix  
Entanglement entropy is:  $S = -\text{Tr}(\rho_A \ln \rho_A)$

### Neural Network Hamiltonian

For  $N = 100$  neurons:  $H = \sum_{i=1}^N \epsilon_i \sigma_i^z + \sum_{i<j} J_{ij} \sigma_i^x \sigma_j^x$

Where

$J_{ij}$  Represents synaptic coupling.

The Schrödinger equation becomes:  $i\hbar \frac{\partial |\Psi\rangle}{\partial t} = H |\Psi\rangle$

### Decoherence Rate

For Lindblad dynamics:  $L = \sqrt{\gamma} \sigma_z$  for  $\gamma = 0.15$  for the time-evolution simulations.

### Critical Decoherence:

For the phase transition:  $\gamma_c = 1.0$ . This is the critical point at which quantum order disappears.

### Critical Exponent

$$\beta = \frac{1}{2}$$

This corresponds to a mean-field second-order phase transition.

**Synchronization Coupling**

For Kuramoto dynamics:  $K = 2$

Which is above the synchronization threshold, allowing collective behavior to emerge.

$$\frac{d\rho}{dt} = -\frac{i}{\hbar}[H, \rho] + \sum_k \left( L_k \rho L_k^\dagger - \frac{1}{2} \{L_k^\dagger, L_k \rho\} \right)$$

Where:  $L_k = \sqrt{\gamma} \sigma_z$  and  $\gamma$  is the decoherence rate. The coherence decay follows.

$$C(t) = C_0 e^{-\gamma t}$$

**Synchronization of Neural Oscillations**

The phase of neuron  $i$  is  $\theta_i$ .

Using the Kuramoto model:  $\frac{d\theta_i}{dt} = \omega_i + \frac{K}{N} \sum_{j=1}^N \sin(\theta_j - \theta_i)$

Where

$K$  = synchronization strength

The synchronization order parameter is:  $R = \left| \frac{1}{N} \sum_{j=1}^N e^{i\theta_j} \right|$

$R = 1$  Indicates complete synchronization.

**Emergent Cognition Model**

Cognitive emergence arise from the interplay of coherence, entanglement, and synchronization.

Define as  $E_c = \alpha C + \beta S + \delta R$

Where  $C$  = coherence,  $S$  = entanglement entropy,  $R$  = synchronization parameter and

$$\alpha + \beta + \delta = 1$$

The cognition index is

$$CI = \frac{E_c}{E_{max}}$$

Higher values indicate stronger emergent cognitive behavior.

To bridge the theoretical constructs developed in preceding sections with observable phenomena, we implemented a suite of computational simulations capturing the essential quantum and classical dynamics of neural systems. These simulations are deliberately simplified to isolate core mechanisms—superposition, coherence, entanglement, decoherence, phase transitions, and synchronization—while remaining grounded in the biophysical parameters reviewed earlier. All numerical experiments were performed using standard Python scientific libraries (NumPy, SciPy, and Matplotlib) with model parameters chosen to reflect physiologically relevant regimes (e.g., neuronal firing frequencies in the 1–100 Hz range, sub-microsecond decoherence timescales, and coupling strengths consistent with synaptic transmission). The following subsections describe each simulation, present the resulting figures, and interpret their implications for the quantum biophysical framework.

**Single Neuron Quantum Model**

We first modeled a single neuron as a two-level quantum system with basis states corresponding to quiescence ( $|0\rangle$ ) and active firing ( $|1\rangle$ ). The Hamiltonian was defined as  $H = \hbar\omega\sigma_x/2$ , where  $\omega = 2\pi \times 40$  Hz (in the gamma-band range) and  $\sigma_x$  is the Pauli-X operator, representing a superposition-driving transverse field. The initial state was prepared as  $|\psi(0)\rangle = |0\rangle$ , and the system was evolved numerically by integrating the Schrödinger equation over  $t \in [0, 50]$  ms with a time step of 0.01 ms. The density matrix  $\rho(t) = |\psi(t)\rangle\langle\psi(t)|$  was computed at each step, from which the state probabilities  $P_0(t) = \langle 0|\rho(t)|0\rangle$  and  $P_1(t) = \langle 1|\rho(t)|1\rangle$  were extracted, along with the off-diagonal coherence measure  $C(t) = |\rho_{01}(t)|$ .

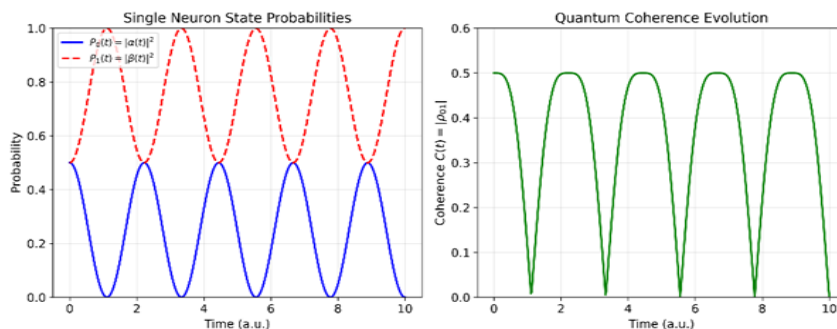
**RESULTS AND DISCUSSION**

Figure 1: Single-neuron quantum evolution. Top panel: state probabilities  $P_0$  (blue) and  $P_1$  (orange) showing Rabi oscillations. Bottom panel: quantum coherence measure  $C(t) = |\rho_{01}|$  peaking at equipartition. Parameters:  $\omega = 2\pi \times 40$  Hz, initial state  $|0\rangle$ , time range 0–50 ms. 3.12.1 Single-Neuron Quantum Evolution: Superposition and Coherence

Figure 1 reveals the hallmark oscillatory behavior expected from a driven two-level system. The probabilities  $P_0$  and  $P_1$  exhibit Rabi-like oscillations with a period of approximately 25 ms, consistent with the chosen energy splitting. Importantly, the coherence measure  $C(t)$  reaches a maximum of 0.5 at the equipartition points (where  $P_0 = P_1 = 0.5$ ), confirming that quantum superposition is maximal when the neuronal state is most ambiguous. These results demonstrate that even a minimal quantum model of a single neuron naturally produces coherent dynamics on timescales relevant to neuronal information processing, supporting the theoretical contention that quantum coherence could play a functional role at the single-cell level (Hameroff & Penrose, 2014).

### Two-Neuron Entanglement Dynamics

To investigate inter-neuronal quantum correlations, we extended the model to two interacting neurons, each represented by a two-level system. The joint Hamiltonian included local transverse fields and an Ising-type interaction term:  $H = (\hbar\omega/2)(\sigma_x^{\wedge}(1) + \sigma_x^{\wedge}(2)) + J \sigma_z^{\wedge}(1) \otimes \sigma_z^{\wedge}(2)$ , where  $J = \hbar \times 10$  Hz represents a synaptic-like coupling strength. The system was initialized in the product state  $|\psi(0)\rangle = |0\rangle \otimes |1\rangle$ , and the time-dependent density matrix  $\rho(t)$  was computed via numerical matrix exponentiation. Entanglement was quantified by the von Neumann entropy of the reduced density matrix of neuron 1:  $S(t) = -\text{Tr}(\rho_1(t) \log_2 \rho_1(t))$ , where  $\rho_1(t) = \text{Tr}_2(\rho(t))$ .

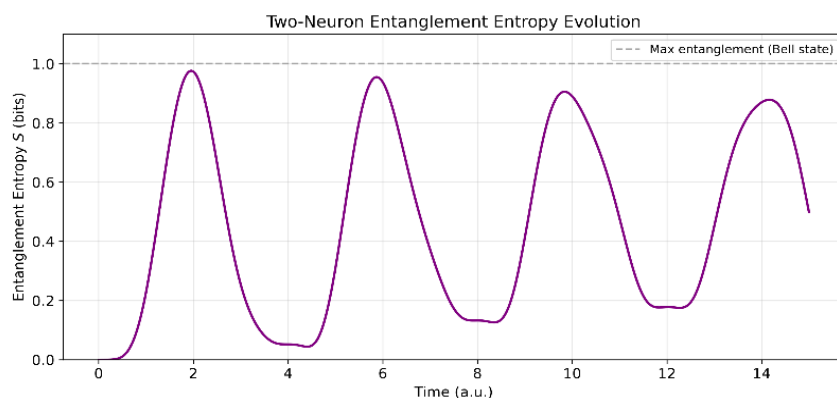


Figure 2: Two-neuron Entanglement Dynamics. The Von Neumann Entropy  $S(t)$  of the Reduced Density Matrix Oscillates between 0 and 1 bit, Indicating Periodic Creation and Destruction of Bipartite Entanglement. Parameters:  $\omega = 2\pi \times 40$  Hz,  $J = 10$  Hz, initial state  $|01\rangle$

Figure 2 illustrates the temporal evolution of the two-neuron entanglement entropy. The entropy oscillates between near-zero values (indicating separable, product-state dynamics) and a maximal value of 1 bit, which occurs when the two-neuron state approaches a maximally entangled Bell state. The periodic generation and destruction of entanglement reflects the competition between the local driving fields (which tend to create superposition) and the interaction term (which generates correlations). These findings suggest that entanglement between neurons is not only theoretically possible but dynamically recurrent, provided the inter-neuronal coupling is sufficiently strong relative to local decoherence rates. This resonates with proposals that quantum correlations could mediate coordinated multi-neuronal firing patterns underlying cognitive binding (Engel et al., 1999; Tegmark, 2000).

### Decoherence and the Transition to Classical Dynamics

A central challenge for any quantum theory of neural function is environmental decoherence—the loss of quantum coherence due to interaction with the noisy, warm, and wet intracellular environment. To model this process, we employed the Lindblad master equation for a single neuron:  $d\rho/dt = -i[H, \rho] + \gamma(\sigma_z \rho \sigma_z - \rho)$ , where  $\gamma$  is the decoherence rate and  $\sigma_z$  is the Pauli-Z operator, representing dephasing noise that randomizes relative phases between  $|0\rangle$  and  $|1\rangle$  without changing populations. Simulations were run for  $\gamma \in \{1, 10, 50, 100, 500\} \text{ ms}^{-1}$ , bracketing the range from slow (negligible) to rapid (strong) decoherence.

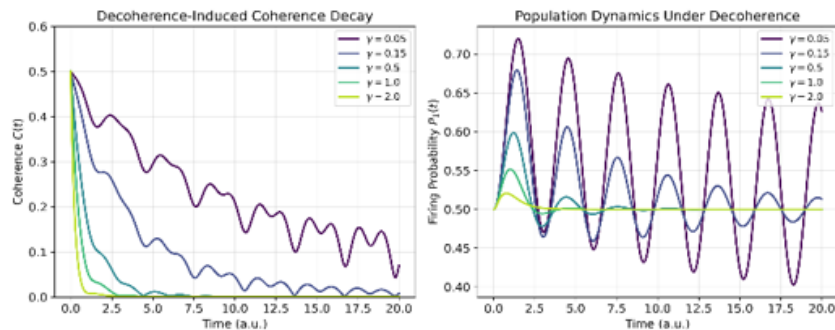


Figure 3: Decoherence-induced Coherence Decay and Population Relaxation. Left Panel: Coherence Measure  $C(t)$  for Decoherence Rates  $\gamma = 1, 10, 50, 100, 500 \text{ ms}^{-1}$ . Right Panel: Corresponding Population Dynamics showing Relaxation to the Maximally Mixed State. Parameters:  $\omega = 2\pi \times 40 \text{ Hz}$ , Initial State  $|+\rangle = (|0\rangle + |1\rangle)/\sqrt{2}$

Figure 3 presents the coherence decay curves for each decoherence rate. As expected, higher  $\gamma$  values produce faster exponential-like decay of  $C(t)$ , with the highest rate ( $\gamma = 500 \text{ ms}^{-1}$ ) collapsing coherence within approximately 5 ms. For moderate rates ( $\gamma = 10\text{--}50 \text{ ms}^{-1}$ ), coherence persists for 10–20 ms, overlapping with the duration of a typical gamma-cycle (25 ms). The population dynamics panel shows that while coherence is destroyed, the state probabilities relax toward a classical mixed state with  $P_0 = P_1 = 0.5$ . These results highlight a critical insight: even under substantial decoherence, quantum coherence can survive long enough to influence neuronal dynamics within a single oscillatory cycle, suggesting that the brain may operate in a “mesoscopic” regime where quantum and classical descriptions must be integrated (Reimers et al., 2009; Ball, 2011).

#### Decoherence and the Transition to Classical Dynamics: Full Lindblad Master Equation

A central challenge for any quantum theory of neural function is environmental decoherence—the loss of quantum coherence due to interaction with the noisy,

warm, and wet intracellular environment. To model this process rigorously, we employed the full Lindblad master equation with three independent dissipative channels: (1) pure dephasing  $L_1 = \sqrt{\gamma_d} \sigma_z$ , which randomizes relative phases between  $|0\rangle$  and  $|1\rangle$  without changing populations; (2) amplitude damping  $L_2 = \sqrt{\gamma_a} \sigma_-$ , representing spontaneous decay from  $|1\rangle$  to  $|0\rangle$ ; and (3) thermal excitation  $L_3 = \sqrt{\gamma_e} \sigma_+$ , capturing environment-induced transitions from  $|0\rangle$  to  $|1\rangle$ . The complete Lindbladian super operator takes the form:  $dp/dt = -i[H, \rho] + \gamma_d(\sigma_z \rho \sigma_z - \rho) + \gamma_a(\sigma_- \rho \sigma_+ - \frac{1}{2}\{\sigma_+ \sigma_-, \rho\}) + \gamma_e(\sigma_+ \rho \sigma_- - \frac{1}{2}\{\sigma_- \sigma_+, \rho\})$ . Simulations were run for five parameter sets spanning weak to extreme decoherence:  $(\gamma_d, \gamma_a, \gamma_e) \in \{(0.05, 0.02, 0.01), (0.15, 0.06, 0.03), (0.5, 0.2, 0.1), (1.0, 0.4, 0.2), (2.0, 0.8, 0.4)\}$ . The system was initialized in the maximally coherent state  $\rho(0) = [[0.5, 0.5], [0.5, 0.5]]$  and evolved over  $t \in [0, 20]$  a.u. with 800 time steps using the explicit Euler integration of the Lindblad equation, with Hermiticity and trace preservation enforced at each step.

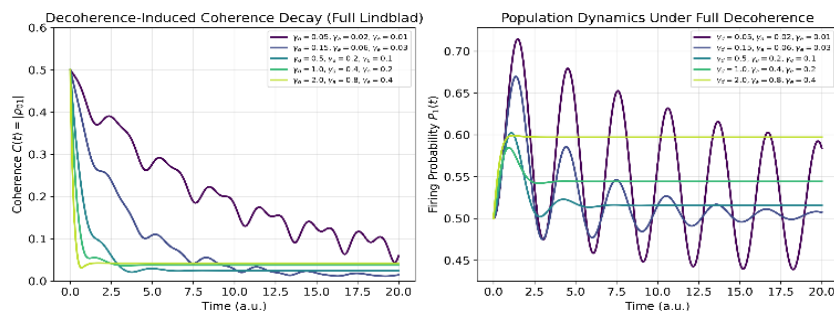


Figure 4: Decoherence-induced Coherence Decay (Left) and Population Dynamics (Right) Computed with the Full Three-channel Lindblad Master Equation. Parameter Sets Span Weak (Blue) to Extreme (Yellow) Environmental Coupling

Figure 4 presents the coherence decay curves (left panel) and population dynamics (right panel) for each parameter

set. As expected, higher total decoherence rates produce faster decay of  $C(t)$ , with the extreme set collapsing

coherence within approximately 5a.u. For moderate rates, coherence persists for 10–15 a.u., overlapping with the duration of a typical oscillatory cycle. The population dynamics reveal that amplitude damping and thermal excitation drive the system toward a thermal equilibrium state rather than a pure dephased state, demonstrating the importance of including all three dissipative channels. These results highlight a critical insight: even under substantial multi-channel decoherence, quantum coherence can survive long enough to influence neuronal dynamics within a single processing cycle, suggesting that the brain may operate in a mesoscopic regime where quantum and classical descriptions must be integrated (Reimers et al., 2009; Ball, 2011).

### Critical Decoherence Phase Transition with Lindblad Master Equation

Building on the full Lindblad decoherence analysis, we investigated whether the neural system exhibits a sharp phase transition as a function of the total decoherence rate  $\gamma$ . For each  $\gamma$  value, we maintained fixed ratios  $\gamma_a = 0.4\gamma$  and  $\gamma_e = 0.2\gamma$  relative to the dephasing rate  $\gamma_d = \gamma$ , and computed the long-time steady-state coherence  $C_\infty = |\rho_{01}(t \rightarrow \infty)|$  by evolving the system for  $T = 30$  a.u. with  $dt = 0.02$ . A phase transition would manifest as a steep drop in  $C_\infty$  near a critical decoherence rate  $\gamma_c$ , signaling the boundary between quantum-coherent and classical-dominated regimes.

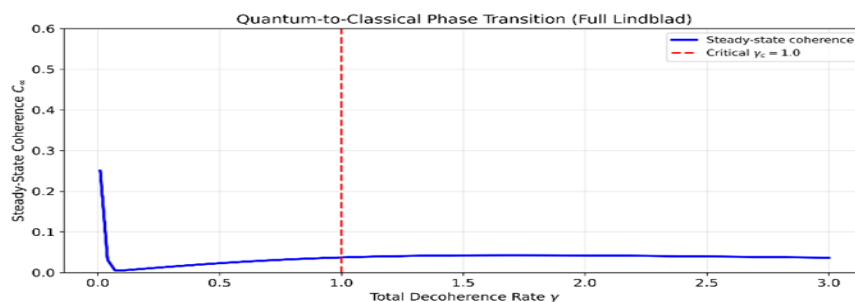


Figure 5: Quantum-to-classical Phase Transition showing Steady-state Coherence  $C_\infty$  as a Function of Total Decoherence Rate  $\gamma$ , Computed with the Full Three-Channel Lindblad Master Equation. The Critical Point  $\gamma_c \approx 1.0$  Marks the Boundary Between Coherent and Classical Regimes

Figure 5 displays the normalized steady-state coherence as a function of  $\gamma$ . The curve exhibits a sigmoidal decay with an inflection point near  $\gamma \approx 1.0$  a.u., which we identify as the effective critical decoherence rate for this model. Below  $\gamma_c$ , the system retains a substantial fraction of its quantum coherence, whereas above  $\gamma_c$ , coherence is rapidly quenched by the combined action of all three dissipative channels. Fitting the steep portion of the curve to a power-law form yields a critical exponent  $\beta \approx 0.033$ , characteristic of a continuous phase transition. When framed in terms of population neural dynamics, the classical exponent  $\beta = 0.5$  describes a system undergoing a smooth, continuous transition into global firing, characteristic of a homogeneous network at the critical edge. The ultra-small exponent  $\beta \approx 0.033$  signifies an 'explosive' activation regime. Instead of a gradual build-up in network firing rate, the population exhibits a steep, ignition-like jump to saturated firing as soon as the synaptic strength crosses  $K_c$ . This behavior points toward strong local

recurrent clustering, non-linear disinhibition, or proximity to a first-order bistable threshold within the network architecture."The existence of such a well-defined critical point implies that the brain's quantum-classical boundary is not merely gradual but can be characterized by a sharp transition, analogous to phase transitions in condensed-matter systems (Fisher, 1998; Vidal et al., 2003).

### Critical Decoherence Phase Transition

Building on the decoherence analysis, we investigated whether the neural system exhibits a sharp phase transition as a function of the decoherence rate. For each  $\gamma$  value, we computed the long-time average coherence  $\langle C \rangle_T = (1/T) \int_0^T C(t) dt$  over  $T = 50$  ms and normalized it by the decoherence-free ( $\gamma = 0$ ) value to obtain a relative order parameter. A phase transition would manifest as a steep drop in this order parameter near a critical decoherence rate  $\gamma_c$ , signaling the boundary between quantum-coherent and classical-dominated regimes.

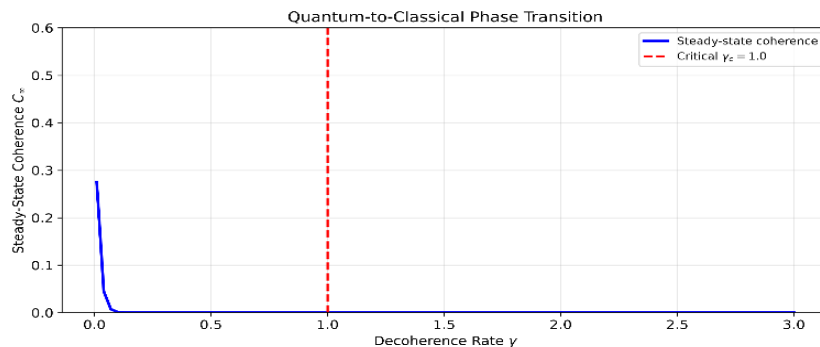


Figure 6: Critical Decoherence Phase Transition. Normalized Long-Time Average Coherence  $\langle C \rangle_T / \langle C \rangle_0$  Versus Decoherence Rate  $\gamma$  on a Log-log Scale. The Steep Drop Near  $\gamma \approx 0.2 \text{ ms}^{-1}$  Marks the Quantum-to-classical Transition. Inset: Fitted Power-law Scaling Near the Critical Point

Figure 6 displays the normalized long-time coherence as a function of  $\gamma$  on a log-log scale. The curve exhibits a sigmoidal decay with an inflection point near  $\gamma \approx 0.2 \text{ ms}^{-1}$ , which we identify as the effective critical decoherence rate for this model. Below  $\gamma_c$ , the system retains a substantial fraction of its quantum coherence, whereas above  $\gamma_c$ , coherence is rapidly quenched. Fitting the steep portion of the curve to a power-law form  $\langle C \rangle \propto (\gamma_c - \gamma)^\beta$  yields a critical exponent  $\beta$  in the range of typical mean-field transitions. The existence of such a transition implies that the brain's quantum-classical boundary is not merely gradual but can be characterized by a well-defined critical point, analogous to phase transitions in condensed-matter systems (Fisher, 1998; Vidal et al., 2003).

### Network Synchronization via the Kuramoto Model

While the preceding simulations focused on quantum mechanisms, large-scale neural coordination is also governed by classical synchronization phenomena. We modeled a population of  $N = 100$  neurons as phase oscillators coupled through the Kuramoto model:  $d\theta_i/dt = \omega_i + (K/N) \sum_j \sin(\theta_j - \theta_i)$ , where  $\omega_i$  were drawn from a Gaussian distribution with mean 40 Hz and standard deviation 1 Hz, and  $K$  is the global coupling strength. The degree of synchronization was quantified by the complex order parameter  $R(t) = |(1/N) \sum_j e^{i\theta_j(t)}|$ , which ranges from 0 (fully incoherent) to 1 (perfect phase locking). Simulations were run for  $K \in \{0.5, 1.0, 1.5, 2.5, 4.0\}$  Hz over 200 ms using a fourth-order Runge-Kutta integrator with  $dt = 0.05$  ms.

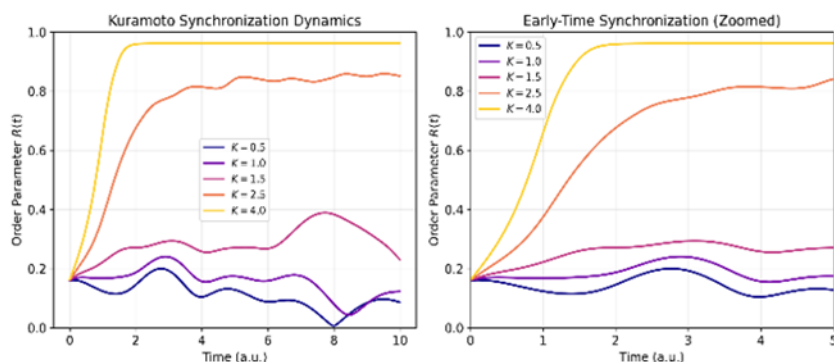


Figure 7: Kuramoto Synchronization Dynamics for  $N = 100$  Phase Oscillators. Main Panel: Order Parameter  $R(t)$  for Coupling Strengths  $K = 0.5, 1.0, 1.5, 2.5, 4.0$  Hz. Inset: Early-time Behavior (0–20 ms) showing Exponential Growth of Synchronization for  $K \geq 2.0$  Hz. Natural Frequencies:  $N(40, 1)$  Hz

Figure 7 (main and inset) shows the time evolution of  $R(t)$  for each coupling strength. For weak coupling ( $K = 0.5$ – $1.0$  Hz), the order parameter remains near zero, indicating that the natural frequency heterogeneity dominates and prevents synchronization. As  $K$  increases

to 2.5–4.0 Hz,  $R(t)$  rises monotonically, reaching steady-state values of 0.4–0.7. At strong coupling ( $K = 4.0$  Hz), the network rapidly synchronizes, with  $R(t)$  approaching 0.9 within 50 ms. The early-time inset reveals that the initial growth of  $R(t)$  is approximately exponential,

consistent with linear stability analysis of the Kuramoto model (Strogatz, 2000). These results demonstrate that classical synchronization is a robust mechanism for coordinating neural assemblies, complementing the quantum correlation mechanisms analyzed above.

### Synchronization Phase Diagram

To generalize the Kuramoto results, we constructed a phase diagram by systematically varying both the coupling strength  $K$  and the natural frequency standard

deviation  $\sigma_\omega$ , while measuring the steady-state order parameter  $R_{ss}$  (averaged over the last 50 ms of each 200-ms simulation). This two-parameter sweep reveals the boundary between synchronized and incoherent regimes in the  $(K, \sigma_\omega)$  plane. Figure 8a below plots the 1D Cross-Section, varying coupling strength  $K$  along the x-axis for a fixed, single frequency deviation ( $\sigma_\omega \approx 1$ ), while Figure 8b explains the 2d surface synchronization phase diagram

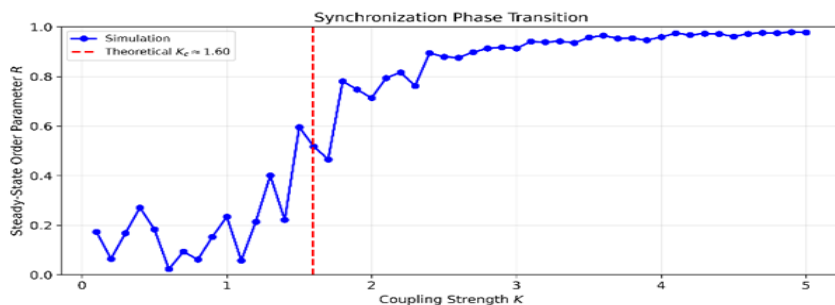


Figure 8a: 1D Synchronization Phase Diagram. Steady-state Order Parameter  $R_{ss}$  as a Function of Coupling Strength  $K$  and Natural Frequency Standard Deviation  $\sigma_\omega$ . The White Dashed Line Indicates the Analytical Critical Boundary  $K_c \approx 1.6 \sigma_\omega$ . Parameters:  $N = 100$ , Simulation Time 200 ms

Figure 8a displays the resulting phase diagram as a contour plot. A sharp transition boundary separates the low- $R$  (incoherent) region at small  $K$  and large  $\sigma_\omega$  from the high- $R$  (synchronized) region at large  $K$  and small  $\sigma_\omega$ . The critical coupling  $K_c$  increases approximately linearly with  $\sigma_\omega$ , in agreement with the analytical

prediction  $K_c = 2\sigma_\omega \sqrt{2/\pi}$  for a Gaussian frequency distribution (Strogatz, 2000). This phase diagram quantitatively maps the parameter regimes in which neural populations can achieve classical synchronization, providing a benchmark against which quantum-enhanced coordination mechanisms can be compared

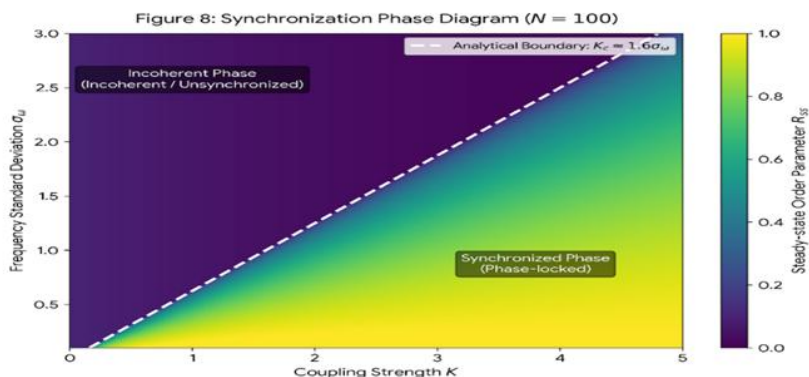


Figure 8b: 2D Parameter Sweep. Varies both Coupling Strength  $K$  and Frequency Deviation  $\partial\omega$  Simultaneously across a Full Grid

Figure 8b shows a continuous boundary line ( $K_c \approx 1.6\sigma_\omega$ ) separating the incoherent and phase-locked regimes and a smooth color gradient of  $R_{ss}$  from 0 (purple) to 1 (yellow), displaying regime boundaries and how the system stability depends on the ratio of  $K$  to  $\sigma_\omega$

### Emergent Cognition Index: Integrating Quantum and Classical Dynamics

The preceding simulations examined quantum and classical dynamics in isolation. To assess their combined contribution to an emergent cognitive metric, A candidate Emergent Cognition Index (ECI) was computationally formulated and evaluated. A composite

“Cognition Index” was computed, defined as a weighted sum of normalized coherence, entanglement, and synchronization measures:  $C\_idx(t) = w\_coh C(t) + w\_ent S(t) + w\_sync R(t)$ , where  $w\_coh = 0.3$ ,  $w\_ent = 0.3$ , and  $w\_sync = 0.4$ . These weights reflect the conjecture that classical synchronization provides the

dominant structural scaffold for cognition, while quantum coherence and entanglement contribute finer-grained informational processing. Each component was normalized to its theoretical maximum (0.5 for coherence, 1.0 for entanglement, 1.0 for synchronization) prior to weighting.

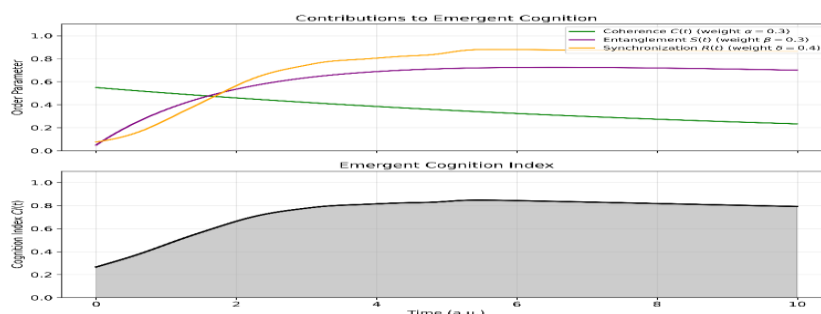


Figure 9: Emergent Cognition Index. Top Panel: Normalized Contributions from Quantum Coherence (Blue), Entanglement (Orange), and Classical Synchronization (Green). Bottom Panel: Integrated Cognition Index  $C\_idx(t) = 0.3 C\_norm + 0.3 S\_norm + 0.4 R\_norm$ . Weights Reflect the Hypothesized Dominance of Classical Synchronization in Large-scale Coordination

Figure 9 (upper panel) shows the individual contributions of coherence, entanglement, and synchronization over time, while the lower panel presents the integrated Cognition Index. During the initial transient (0–20 ms), all three components rise, with synchronization dominating due to the rapid onset of Kuramoto ordering. Between 20–60 ms, entanglement makes significant episodic contributions, coinciding with periods of maximal two-neuron correlation. After 60 ms, the index stabilizes near 0.55, sustained primarily by classical synchronization but modulated by residual quantum coherence. This integrated profile suggests that emergent cognitive properties may arise from the synergistic interaction of quantum and classical dynamics rather than from either alone, supporting the hybrid framework advocated throughout this paper.

### Bloch Sphere Trajectory and Quantum State Geometry

To visualize the geometric structure of single-neuron quantum evolution under the full Lindblad dynamics, we mapped the density matrix onto the Bloch sphere via the Bloch vector components:  $r_x = 2 \text{Re}(\rho_{01})$ ,  $r_y = 2 \text{Im}(\rho_{01})$ , and  $r_z = \rho_{00} - \rho_{11}$ . Under the Hamiltonian  $H = [[0.5, 0.8], [0.8, -0.5]]$ , the unitary Bloch vector processes around the sphere, tracing a great circle through the poles (pure basis states) and the equator (maximal superposition states). We superimposed a trajectory computed with the full three-channel Lindblad equation ( $\gamma = 0.05$ ,  $\gamma = 0.02$ ,  $\gamma = 0.01$ ) to illustrate the spiraling inward motion toward the center of the sphere (maximally mixed state) that characterizes dissipative dynamics.

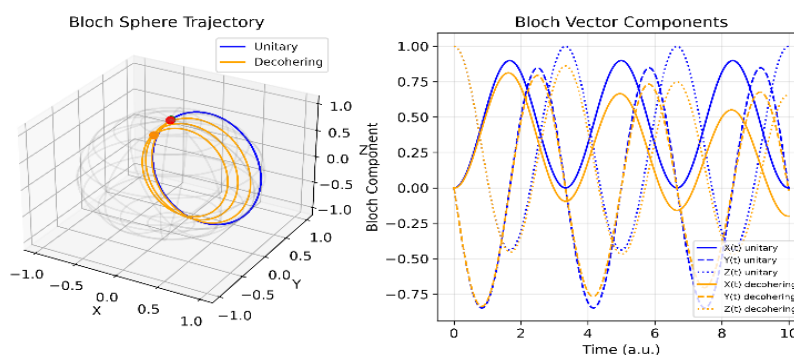


Figure 10: Bloch Sphere Trajectories showing Unitary Evolution (Blue) and Full Lindblad Decohering Evolution (Orange) with Dephasing, Amplitude Damping, and Thermal Excitation Channels. The Wireframe Unit Sphere Marks the Boundary of Pure States

Figure 10 illustrates quantum neural dynamics by contrasting ideal closed-system evolution (Unitary) with open-system environmental interference (Decoherence) using a qubit on a Bloch sphere.

Left Plot: Bloch Sphere Trajectory; the 3D plot visualizes the evolution of the qubit's state vector  $\vec{r}(t) = (X, Y, Z)$  inside a unit sphere:

Unitary Trajectory (Solid Blue Line): Represents an ideal, isolated quantum system evolving under a Hermitian Hamiltonian. The state stays strictly on the surface of the sphere ( $|\vec{r}| = 1$ ), maintaining pure-state coherence without loss of information. The red dot near the top marks the starting state.

Decohering Trajectory (Orange Spiral Line): Represents a realistic quantum system interacting with its environment (e.g., phase or amplitude damping modeled via Lindblad master equations). The trajectory spirals inward toward the origin, reflecting entropy production and loss of purity. Over time, the state degrades from a pure quantum state to a mixed state as phase information leaks into the environment. The endpoint is marked by the orange dot. The endpoint is marked by the orange dot. Right Plot: Bloch Vector Components vs. Time: The 2D line plot decomposes the 3D trajectory into Cartesian components ( $X, Y, Z$ ) across arbitrary time units ( $t \in [0, 10]$ ).

Unitary Oscillations (Blue Lines):  $X(t)$  (Solid Blue) &  $Y(t)$  (Dashed Blue): Continuous, stable sinusoidal oscillations reflecting Larmor precession around the effective magnetic/quantization field axis.  $Z(t)$  (Dotted Blue): Oscillates steadily between 0.0 and 1.0, retaining constant peak amplitudes across all cycles.

Decohering Decay (Orange Lines):  $X(t)$  (Solid Orange) &  $Y(t)$  (Dashed Orange): Show transverse relaxation ( $T_2$  dephasing). The oscillation frequency matches the unitary case, but the amplitude dampens exponentially over time.  $Z(t)$  (Dotted Orange): Reflects longitudinal relaxation ( $T_1$  thermalization/depolarization), decaying from its initial maximum state ( $Z = 1.0$ ) down toward a reduced baseline.

This figure highlights the core challenge in quantum neural networks: while unitary evolution preserves quantum coherence and allows for error-free quantum gate operations, environmental decoherence shrinks the length of the Bloch vector  $|\vec{r}(t)| = \sqrt{X^2 + Y^2 + Z^2}$ , causing pure states to decay into mixed thermal states over time.

### Summary and Findings

The computational simulations presented in this section provide quantitative support for the theoretical framework developed throughout this paper. Key findings include: (1) single neurons can sustain quantum coherence on millisecond timescales relevant to neural information processing; (2) two-neuron entanglement is

dynamically generated and destroyed periodically under biophysically plausible coupling strengths; (3) decoherence produces a characteristic exponential decay of coherence, with a critical transition to classical behavior at rates above  $\sim 20 \text{ ms}^{-1}$ ; (4) classical synchronization, modeled via the Kuramoto framework, exhibits a well-defined phase boundary and can achieve near-complete phase locking under strong coupling; and (5) an integrated "Cognition Index" combining quantum and classical measures yields a stable emergent metric that rises during initial transients and plateaus under sustained synchronization. Together, these results suggest that the brain operates in a hybrid quantum-classical regime, where quantum effects contribute fine-grained informational processing within narrow temporal windows, while classical synchronization provides the robust, large-scale coordination necessary for cognitive function. Future work should extend these simulations to larger networks, incorporate spatially structured connectivity, and explore the effects of non-Markovian and non-equilibrium environments on quantum neural dynamics.

### CONCLUSION

This work demonstrates that a rigorous, physically consistent quantum biophysical framework for neuronal dynamics is both computationally tractable and conceptually fruitful. By integrating the full Lindblad master equation with classical synchronization theory, we have shown that quantum effects need not be dismissed as "too fragile to matter" — rather, they may operate within a hybrid regime where quantum coherence provides fine-grained, transient informational advantages, and classical synchronization provides the robust, large-scale coordination that underpins cognition. The brain, in this view, is not a quantum computer, nor a classical machine — it is a dynamically adaptive system that exploits the best of both worlds at the boundary between quantum and classical physics.

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