Quantum Simulation of Synaptic Plasticity Mechanisms in Neural Circuits

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***Abstract*—Synaptic plasticity—the capacity of neural circuits to strengthen, weaken, or reconfigure connections in response to activity—is fundamental to learning, memory formation, and adaptive behavior. Classical computational models have advanced the understanding of plasticity, but they struggle to fully capture the high-dimensional, nonlinear, and quantum-biophysical processes that shape synaptic dynamics at molecular and network scales. This study explores a quantum simulation framework for modeling synaptic plasticity mechanisms by leveraging variational quantum circuits, Hamiltonian-based learning rules, and quantum state representations of neuronal interactions. The proposed approach encodes synaptic weight updates, spike-timing–dependent plasticity (STDP), and Hebbian/anti-Hebbian processes within quantum operators capable of expressing richer correlation structures than classical models. Preliminary results demonstrate that quantum simulations can represent multi-synapse entanglement, non-Markovian memory traces, and complex attractor transitions that approximate biological synaptic behaviors with enhanced precision. These findings highlight the emerging role of quantum computational tools in uncovering new aspects of neural adaptability and advancing next-generation computational neuroscience.**

Synaptic plasticity lies at the core of neural computation, enabling biological systems to learn from experience, encode memory, and adapt to environmental demands [1]. At the cellular level, plasticity emerges from a diverse set of biophysical mechanisms—including calcium signaling, neurotransmitter dynamics, receptor trafficking, and structural remodeling—that collectively shape how synaptic strengths evolve over time [5]. At the circuit level, these changes give rise to emergent properties such as associative learning, pattern completion, and attractor-based memory retrieval. Despite extensive progress in computational neuroscience, existing classical models often simplify these processes due to the inherent complexity and high dimensionality of synaptic interactions [7].

Classical approaches such as rate-based learning rules, spike-timing–dependent plasticity (STDP) models, and biophysically motivated differential equations have provided important insights into neural behavior [2]. However, they face several limitations: they may struggle to capture long-range correlations across synapses, represent non-linear and stochastic molecular phenomena, or scale efficiently to large, multi-layered neural systems. As biological evidence accumulates for multiscale interactions and potential

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