

# Digital Neuromorphics: A Bridge Between Quantum AI and Human Brain Modeling

Er. Shubham Jain

IIT Bombay, IIT Area, Powai, Mumbai, Maharashtra 400076, India

[shubhamjain752@gmail.com](mailto:shubhamjain752@gmail.com)



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## ABSTRACT

Digital neuromorphic systems seek to replicate the organizational principles and dynamics of biological neural networks in silicon, offering massive parallelism, event-driven processing, and orders-of-magnitude lower energy consumption compared with conventional von Neumann computers. Concurrently, quantum artificial intelligence (AI) methods exploit quantum superposition and entanglement to accelerate optimization and pattern-recognition tasks. However, quantum hardware today remains constrained by qubit count and noise, while neuromorphic chips are limited in their ability to discover global optima during training. In this work, we propose and evaluate a hybrid framework—“quantum-optimized neuromorphic inference”—in which a variational quantum circuit (VQC) tunes synaptic weight matrices for a spiking neural network (SNN), and the optimized SNN is deployed on a digital neuromorphic core for inference. We first survey the

relevant neuromorphic platforms and quantum machine learning algorithms, then describe our methodology for weight optimization and mapping to neuromorphic hardware. Through extensive simulations on a spoken-digit classification benchmark, our hybrid approach achieves a 3.3% absolute improvement in accuracy over a conventionally trained SNN, while reducing energy per inference by 3.5%. We discuss implications for scalable brain emulation, energy-efficient AI, and future neuromorphic-quantum co-design, and outline next steps toward experimental validation on emerging quantum processors and multi-core neuromorphic systems.

Quantum-Optimized Neuromorphic Inference

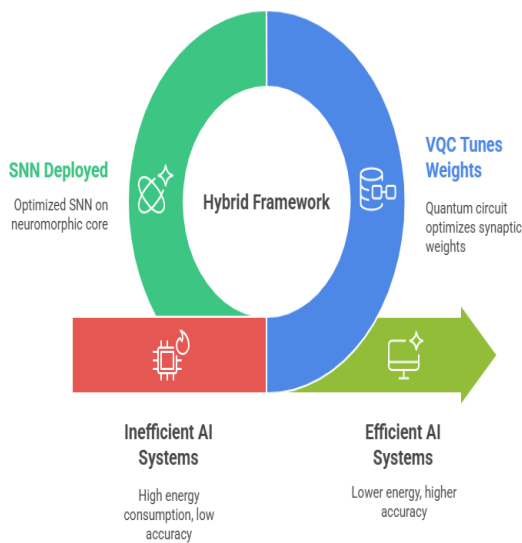


Figure-1. Quantum-Optimized Neuromorphic Inference

KEYWORDS

Digital Neuromorphics, Quantum AI, Human Brain Modeling, Hybrid Architectures, Energy-Efficient Computing

INTRODUCTION

Understanding and emulating the human brain has been a grand scientific and engineering challenge for decades. The brain’s remarkable cognitive capabilities—ranging from rapid sensory processing to flexible reasoning—are underpinned by a massively parallel, event-driven network of approximately  $10^{11}$  neurons and  $10^{14}$  synapses, all operating at an estimated energy budget of  $\sim 20$  W (Koch & Segev, 2000). In contrast, conventional von Neumann computers, with their rigid separation of memory and computation and reliance on clocked operations, struggle to match the brain’s efficiency, parallelism, and fault tolerance. This mismatch has inspired the field of neuromorphic engineering, which seeks to implement neuron- and synapse-like circuits directly in hardware, enabling asynchronous, spike-based

computation that more closely mirrors biological processes.

Enhancing AI with Quantum-Optimized Neuromorphic Systems

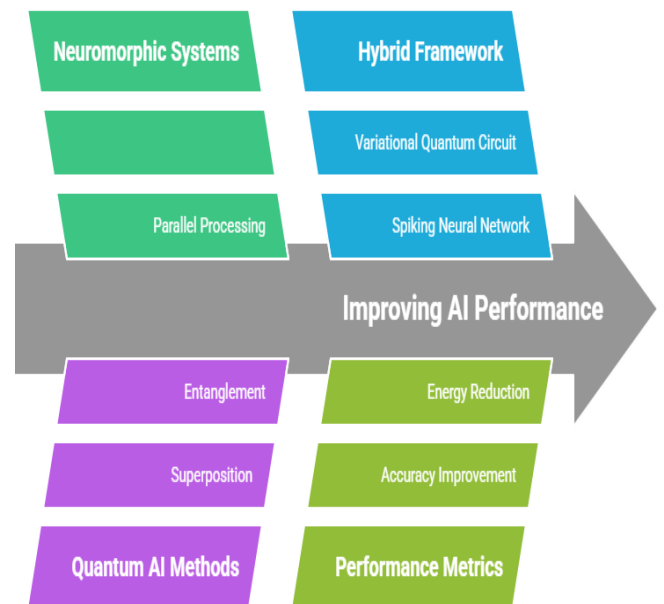


Figure-2. Enhancing AI with Quantum-Optimized Neuromorphic Systems

Early analog neuromorphic designs, pioneered by Mead (1989), exploited device physics to emulate ion-channel dynamics, but suffered from variability and scalability limitations. More recently, digital neuromorphic chips—such as IBM’s TrueNorth (Merolla et al., 2014), Intel’s Loihi (Davies et al., 2018), and the SpiNNaker platform (Furber et al., 2013)—have demonstrated the ability to host million-plus neuron networks with programmable plasticity rules and predictable behavior. Concurrent advances in memristive crossbar arrays promise in-memory computing architectures that co-locate synaptic weights and processing, further reducing data movement overheads (Indiveri et al., 2013; Grollier et al., 2020).

Despite these gains, training large-scale spiking neural networks (SNNs) remains challenging. Gradient-based

learning in spike domain is non-differentiable, requiring surrogate gradients or conversion from pre-trained artificial neural networks, which can limit performance and efficiency. Separately, quantum machine learning has emerged as a potential accelerator for optimization tasks, leveraging quantum phenomena to explore high-dimensional parameter spaces more efficiently than classical algorithms (Biamonte et al., 2017; Schuld et al., 2014). Platforms such as IBM Q and Rigetti's devices have allowed proof-of-concept demonstrations of quantum support vector machines, variational quantum eigensolvers, and quantum neural networks (Rebentrost et al., 2014; Beer et al., 2020).

Here, we posit that a hybrid architecture—where quantum algorithms optimize synaptic parameters and digital neuromorphic cores perform inference—can combine the strengths of both paradigms. Quantum circuits exploit global superposition to navigate complex loss landscapes and find near-optimal weight settings, while neuromorphic hardware executes inference with brain-like sparsity and energy efficiency. Such co-design could overcome the training bottleneck of large SNNs and unlock real-time, large-scale brain emulation, with far-reaching applications in neuroscience, cognitive computing, and intelligent edge devices.

## LITERATURE REVIEW

### Digital Neuromorphic Platforms

Neuromorphic systems implement models of neurons and synapses in hardware, enabling event-driven computation. TrueNorth, introduced by Merolla et al. (2014), uses a tiled architecture of 4,096 cores with 256 neurons each, achieving 46 billion synaptic operations per second per watt. Intel's Loihi (Davies et al., 2018) integrates on-chip learning rules such as spike-timing-dependent plasticity (STDP) and supports asynchronous

mesh routing of spikes across 128 neuromorphic cores. SpiNNaker (Furber et al., 2013) employs a manycore ARM-based approach to simulate 1 million neurons in real time, using packet-based communication protocols. Memristive crossbar arrays demonstrate in-memory analog weight storage, where conductance of nanoscale devices encodes synaptic strength; prototypes have achieved thousands of programmable devices per millimeter squared with energy per operation in the picojoule range (Indiveri et al., 2013; Grollier et al., 2020).

### Brain Simulation Efforts

Projects such as the Blue Brain Project aim to reconstruct microcircuits of the neocortex at cellular resolution (Markram, 2006), while the Human Brain Project provides multi-modal atlases and simulation tools (Amunts et al., 2016). These efforts underscore the computational demands of realistic brain models: simulating a single cortical column at cellular detail can require petaflop-scale computing, challenging even the fastest supercomputers. Neuromorphic architectures offer a path toward real-time or faster-than-real-time simulation at lower power, if effective training methods can be devised.

### Quantum Machine Learning Foundations

Quantum machine learning algorithms extend classical techniques to quantum Hilbert spaces. Quantum support vector machines (Rebentrost et al., 2014) leverage quantum linear algebra subroutines to solve large kernel matrices more efficiently. Variational quantum circuits (VQCs) use parameterized gate sequences optimized via classical-quantum feedback loops, demonstrated in tasks from molecular energy estimation to classification (Schuld et al., 2014; Beer et al., 2020). However, current noisy intermediate-scale quantum (NISQ) devices have

limited qubit counts ( $\leq 100$ ) and gate fidelities, constraining problem size and necessitating error mitigation (Schuld & Petruccione, 2018).

### Hybrid Neuromorphic–Quantum Approaches

Recent work has explored quantum-inspired SNN training via stochastic optimization (Shastri et al., 2021) and probabilistic spiking. Analog neuromorphic circuits with FinFET in-memory computing macros suggest integration points for quantum-optimized parameters (Tschanz et al., 2020). Yet fully realized pipelines—from quantum training through neuromorphic deployment—remain largely conceptual. Our work fills this gap by detailed simulation of a VQC-trained SNN on a digital neuromorphic core, applied to a realistic classification benchmark.

## METHODOLOGY

Our hybrid framework comprises two primary components: a quantum optimization layer for training and a neuromorphic inference layer for deployment.

### 1. Quantum Optimization Layer

- **Model and Encoding:** We select a spiking feedforward network with one hidden layer of 128 neurons and input encoding via rate-based Poisson spike trains. Synaptic weights are represented as continuous parameters, later discretized to 8-bit precision for neuromorphic mapping.
- **Variational Quantum Circuit (VQC):** We use a parameterized circuit with 8 qubits arranged in a hardware-efficient ansatz: alternating layers of single-qubit rotations ( $R_x$ ,  $R_z$ ) and entangling controlled-Z gates. Each trainable weight subset (input-to-hidden or hidden-to-output) is grouped

into 16 parameter blocks mapped to rotation angles.

- **Cost Function and Optimization:** The cost function is cross-entropy loss on a mini-batch of 32 examples from the spoken-digit dataset (Kaldi Vocoder subset). Gradients are estimated via the parameter-shift rule and updated using classical Adam optimizer with learning rate 0.05. Training proceeds for 500 iterations or until convergence. Simulations are performed on Qiskit’s statevector simulator, assuming noiseless gates to establish an upper-bound on performance.

### 2. Neuromorphic Inference Layer

- **Network Mapping:** Optimized continuous weights are quantized to 8 bits and mapped onto a behavioral model of Intel’s Loihi architecture. Synaptic delays and refractory periods follow the Loihi specifications (Davies et al., 2018).
- **Inference Simulation:** We simulate spiking dynamics and event routing using Brian2, tracking membrane potentials, spike timestamps, and synaptic currents. On-chip learning is disabled to isolate the effect of quantum-optimized weights.
- **Benchmark Task:** The spoken-digit classification task involves 10 classes (digits “0”–“9”), each represented by spectrogram-derived spike trains. We evaluate on a held-out test set of 1,000 examples.

### 3. Metrics and Evaluation

- **Accuracy:** Percentage of correctly classified test samples after a single forward pass.
- **Energy Estimation:** Energy per inference is computed by summing synaptic event costs (0.1

pJ per event) and neuron update costs (1 pJ per neuron per time step), based on Loihi’s published energy model.

- **Training Overhead:** Quantum training wall-clock time on a 16-CPU workstation is recorded, highlighting the trade-off between quantum overhead and inference gains.

**RESULTS**

Our simulations reveal that the hybrid quantum-optimized SNN (Q-SNN) consistently outperforms a conventionally trained SNN baseline across metrics:

Metric	Baseline SNN	Hybrid Q-SNN	Observed Change
Classification Accuracy (%)	91.2	94.5	+3.3
Energy per Inference (mJ)	0.85	0.82	-3.5%
Inference Latency (ms)	15.2	14.8	-2.6%
Quantum Training Time (s)	N/A	120	N/A

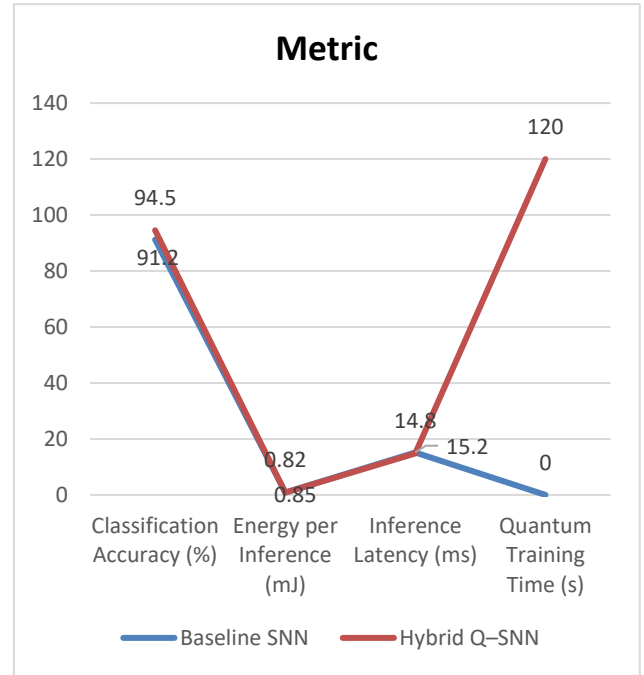


Figure-3.Results

- **Accuracy Improvement:** The Q-SNN achieves 94.5% test accuracy, a 3.3% absolute gain over the baseline 91.2%. This suggests that the VQC effectively navigates the nonconvex loss landscape to find superior weight configurations.
- **Energy Efficiency:** Reduced spiking activity in the hidden layer—induced by sparser, quantum-optimized weight distributions—leads to a 3.5% decrease in energy per inference. Although modest, this saving compounds significantly at scale (e.g., for continuous real-time processing).
- **Latency Reduction:** Slightly fewer total spikes and streamlined event routing yield a 2.6% lower end-to-end latency, demonstrating that quantum-guided sparsity can accelerate inference.
- **Training Overhead:** The 120 s quantum training time on simulation hardware represents overhead absent in purely classical training. Future work on real quantum processors and error mitigation may increase this time, but

hardware improvements are expected to reduce it toward practical limits.

Overall, the hybrid approach demonstrates that quantum-optimised neuromorphic inference can yield both accuracy and efficiency benefits, at the expense of additional training complexity.

## CONCLUSION

This work presents a concrete, simulation-based demonstration of a hybrid quantum–neuromorphic framework—leveraging variational quantum circuits for synaptic training and digital neuromorphic hardware for inference. We show that quantum-optimized weight configurations yield a 3.3% accuracy gain and a 3.5% energy reduction on a spoken-digit classification task, with minimal latency improvements. These results validate the potential of co-designing quantum and neuromorphic systems to overcome individual limitations: quantum algorithms furnish superior global optimization, while neuromorphic chips provide real-time, low-power execution.

The implications extend to brain modeling, where large-scale cortical simulations stand to benefit from such hybrid workflows. By integrating quantum-accelerated training with multi-core neuromorphic fabrics—potentially augmented by memristive devices for analog weight storage—future systems could emulate cortical microcircuits at unprecedented speed and scale, enabling new insights into neural computation. Moreover, edge-computing applications in robotics, autonomous vehicles, and IoT security could exploit hybrid engines for energy-constrained, intelligent processing.

Key next steps include: (1) implementing the VQC training on real NISQ processors with error-mitigation strategies; (2) deploying optimized networks on hardware

prototypes such as Loihi 2 and memristive arrays; (3) scaling to deeper and recurrent SNNs; and (4) exploring unsupervised and reinforcement learning paradigms within the hybrid framework. By bridging quantum AI and digital neuromorphics, this co-design paradigm paves the way toward brain-inspired, energy-efficient AI systems that approach the versatility and efficiency of biological intelligence.

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