NeuroQuantum Nexus Global Industry Challenge: Decoding Neural Circuits with NISQ-Based Spike Analysis

Introduction

The NeuroQuantum Nexus brings together the National Capital Region's strengths in quantum computing, AI/ML, and neuroscience to establish the U.S. as a leader in these converging fields, and to build global collaborations. By focusing on the complex challenges of neuroscience, the Nexus accelerates both quantum research and neuroscience, driving innovation in neurotechnology and broader quantum applications that address critical market needs and improve patient outcomes.

Statement:

Understanding the complex dynamics of neural circuits is crucial for unraveling brain function and developing effective treatments for neurological disorders. Neural spike trains, which capture the electrical activity of neurons, offer key insights into these dynamics. Analyzing spike trains derived from calcium imaging or electrophysiological recordings can reveal patterns of neural connectivity and activity, aiding in the diagnosis and treatment of diseases like epilepsy, Alzheimer's, and Parkinson's. However, the high dimensionality and complexity of these neural data pose significant challenges for classical computing methods, particularly when inferring connectivity or identifying intricate spike patterns.

These analytical tasks often involve complex optimization problems, where the number of possible solutions grows exponentially with the size of the neural network. Quantum algorithms, such as Variational Quantum Algorithms (VQAs) and Quantum Approximate Optimization Algorithm (QAOA), are particularly well-suited to address these challenges. They hold the potential to efficiently explore vast solution spaces and identify globally optimal solutions—those that truly represent the underlying neural dynamics—which classical methods may struggle to find. Furthermore, inferring neural connectivity (the "neural wiring" problem) is inherently probabilistic and iterative. Quantum computing's ability to naturally handle probabilistic models and perform complex iterative calculations with potential speedups makes it a uniquely promising approach for unraveling the brain's intricate communication networks.

Background and Context:

Brain networks are highly connected, with each neuron forming thousands of synapses with other cells is one of the fundamental differences between information processing in biological neural networks and in classical computing. Understanding the higher order dynamics of neural circuits is crucial for unraveling brain function and developing effective treatments for neurological disorders.

Neural spike trains, captured with microelectrodes or calcium imaging, offer key insights into these dynamics. Technological breakthroughs in the last decade have yielded commercial devices capable of simultaneous recordings on thousands of neural cells. The high dimensionality of the neural information poses a unique opportunity for discoveries on such datasets with quantum computing approaches.

Challenge:

This challenge invites participants to develop quantum computing-based algorithms to discover higher-order features in neural network activity. The challenge will provide both calcium signal and electrical signal data on neural networks, for which the existence of collective structures is well known.

The rationale for this search for collective signals is the recent discovery of several BRAIN initiative teams that sensory information is encoded in collective firing events of small groups of neurons. Since the nature of quantum computing is well-suited for processing collective behavior, the primary goal of this challenge is to extract meaningful insights into neural circuit activity and connectivity that classical methods may have missed.

Participants may explore relevant quantum algorithms such as VQA, QAOA, Quantum Neural Networks (QNNs), or Quantum Graph Neural Networks (QGNNs). Developed quantum or hybrid algorithms will be rigorously compared against classical state-of-the-art higher-order analysis methods, e.g. multivariate autoregressive modeling.

We expect that participants will have the opportunity to demonstrate some algorithms on NISQ devices or hybrid quantum-classical approaches to analyze a provided neural network calcium signals dataset.

Evaluation Criteria:

Performance will be evaluated based on factors such as accuracy in spike detection, efficiency in processing large datasets, and the ability to uncover complex patterns in the calcium signals that may be missed by traditional methods. The challenge aims to demonstrate the potential of NISQ computing to enhance our understanding of neural dynamics beyond the capabilities of current classical techniques.

(i) Use NISQ to distinguish data with known higher-order correlations from control data.

(ii) Develop quantum cellular automaton simulations that can yield higher-order correlations.

Resources Available

- There are two data sets, one corresponding to calcium imaging, and the other to electrophysiology, i.e., electrical activity.
- The first one pertains to the experiments and results reported in the paper by Bowen et al., Fractured columnar small-world functional network organization in volumes of L2/3 of mouse auditory cortex, PNAS Nexus, Volume 3, Issue 2, February 2024, pgae074, https://doi.org/10.1093/pnasnexus/pgae074.

Data for this paper can be found in https://gcell.umd.edu/

- The second one corresponds to the paper by Buccino et al., Spike Interface, a unified framework for spike sorting, eLife 9:e61834, https://doi.org/10.7554/eLife.61834

Data for this paper can be found in https://gui.dandiarchive.org/#/dandiset/000034