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KIND Project proposal: Quantum Circuit Representation of Neuronal Activity

1. Applicants

Dimphna Meijer, assistant professor, Dept. of Bionanoscience

Three relevant publications:
[1] Burbach, JPH and Meijer DH: Latrophilin's Social Protein Network, Front Neurosci. (2019)
[2] Jackson VA*, Meijer DH*, Carrasquero M, van Bezouwen LS, Lowe ED, Kleanthous C, Janssen BJC, Seiradake E.: Structures of Teneurin adhesion receptors reveal an ancient fold for cell-cell interaction, Nature Communications 9(1):1079 (2018)
[3] Meijer DH, et al: An amino terminal phosphorylation motif regulates intranuclear compartmentalization of Olig2 in neural progenitor cells. J.Neurosci. 34:8507-8518.

Eliska Greplova, assistant professor, Dept. of Quantum Nanoscience

Three relevant publications:
[1] Durrer R, Kratochwil B, Koski JV, Landig AJ, Reichl C, Wegscheider W, Ihn TM, Greplova E: Automated tuning of double quantum dots into specific charge states using neural networks, Phys. Rev. Applied 13, 054019 (2020)
[2] Greplova E, Valenti A, Boschung G, Schäfer F, Lörch N, Huber SD: Unsupervised identification of topological order using predictive models, New J. Phys. 22 045003 (2020)
[3] Valenti A, van Nieuwenburg EPL, Huber SD, Greplova E: Hamiltonian learning for quantum error correction; Phys. Rev. Research 1, 033092 (2019).

2. Abstract

Given the enormous computing power of biological neurons, it is currently believed that this computational power cannot be explained merely by biochemical and biophysical principles. For example, quantum physics might be needed for precise modelling of information transfer in intricate neuronal circuits. In this project we provide a concrete testbed for this hypothesis by applying quantum machine learning tools to neurobiological data. Specifically, we employ generative adversarial training to build a quantum circuit whose outputs would reproduce the neuronal network activity of primary mouse neurons. The resulting circuit will then be simulated on Quantum Inspire provided by TU Delft or on IBM cloud quantum computers and its performance tested on both quantum and classical data. Thus, we open an avenue toward understanding connections between quantum and neurobiological information processing.

3. Benefit to the synergy of KIND

This proposal will enable collaboration between bionanoscience (Meijer lab) and quantum nanoscience (Greplova lab) in a concrete and feasible way that promises an advancement in understanding for both disciplines.
This proposal aims to open a completely new interdisciplinary field of 'quantum network neurobiology', therefore it is challenging for us to apply for larger funding without having a simple toy model with accompanying preliminary data, such that we can provide concrete experimental design to move forward in a larger multi-year project. To obtain this initial benchmark, we need funding for the researcher that will collect the data of various neuronal networks as well as a qualified student assistant to numerically model quantum circuits.
KIND funding will give us a concrete benchmark that will allow us to evaluate the feasibility of a bigger project. If a toy model of a limited number of mouse neurons mapped on a small qubit circuit succeeds, we will be able to formulate a proposal on (a) modelling neuronal network signals using quantum machine learning and (b) investigate quantum correlations in the neuronal circuits and quantify the potential quantum speedup they provide. Additionally, this project will establish a new line of collaborative research between Quantum Nanoscience and Bionanoscience that prospective KIND postdoctoral fellows can apply for.

4. Description of the proposed research

Introduction: In a healthy brain, functional neural circuits are the essential framework for learning and memory. Outstanding questions in cognitive research include: What defines a functional neural network? How is information transferred within these networks? Can we build synthetic neuronal networks and model synaptic transfer? In the Meijer lab, we are now capable of visualizing and analyzing small but complete neurobiological circuits by combining state-of-the-art high content confocal microscopy and graph theory.
In the Greplova lab, we have developed a class of machine learning driven methods that are able to collect experimentally accessible data from quantum devices and find the physical model that best describe their behavior. We have successfully applied these methods in a range of nanomaterial domains.
Combining the expertise available in Meijer and Greplova labs, we are now in the position to build a quantum physics-based model for neural activity based on experimentally obtained data.
Aim of the project: Design a quantum model for neuronal activity. We will measure and visualize electrical signals transmitted in living neuronal networks. We use these as an input of quantum machine learning model that will be trained in adversarial manner until it produces the same data as biological neurons. The quantum machine learning model we train will be represented by a quantum circuit whose quantum correlation properties will be studied.
Approach: We will set up small scale neuronal cell cultures using primary mouse neurons isolated from brain hippocampus (the area of memory formation). We have recently equipped our high content confocal microscope with a live cell incubator that enables live cell imaging. We will extract cell-specific network parameters and visualize neuronal activity using chemical or genetically encoded calcium sensors. The imaging format will be downscaled to enable complete network imaging as well as live calcium acquisition. We will use the first 90% of frames for training of the novel hybrid generative adversarial machine learning model, where biological neurons will serve as a generator and simulated quantum circuit as a discriminator. The 10% of the measured frames will be used as test dataset to apply our new algorithms on and test their predictive power. Once we construct a quantum model for the transfer of neuronal signals we can take a step further and analyze it from a quantum physics point of view. Specifically, we can describe the quantum correlations that

the model generates by studying how it acts on different types of input states. Analyzing the long-range correlations generated by the quantum model as it acts on different types of quantum states will help us conjecture the level in which quantum physics play a role in neuronal network activity.

5. Budget*

Category	Clarification	Costs in euros
Personnel	Technician NWP, 7 months, 1 FTE, schaal 8.0 (Neurobiological assay set up and data collection)	44,298
	Student Researcher NWP, 10 months, 1 FTE, schaal 7.0 (Data management and formatting)	44,013
Material	Reagents for neuronal cell culture (€500/month)	4,000
Computing	GPU computing hours SURFSARA	8,000
Rounded Total		100,000

- We are requesting €50k * 2, because this is a collaborative project between two extremely diverse research disciplines that requires a realistic investment to result in actual preliminary data for future grant opportunities.