Tutorial on QuantumFlow+VACSEN: A Visualization System for Quantum Neural Networks on Noisy Quantum Devices

Abstract: As one of the most popular machine learning algorithms, neural networks have been applied in a wide variety of applications, such as autonomous vehicles, simultaneous translation, and diagnostic medical imaging. With the increasing requirement on analyzing the large-scale data (e.g., 10^8 pixels for one 3D-CT medical image), neural networks encounter both memory-wall and compute-bound on classical computers. With the extremely high parallelism in representing and processing information, Quantum Computing is promising to address these limitations. But, how to make full use of the powerful quantum computers to accelerate neural networks is still unclear. QuantumFlow, published at Nature Communications this year, is an end-to-end framework to optimize neural networks onto a given quantum processor. Importantly, following the co-design philosophy, the developed quantum neurons in QuantumFlow demonstrate the quantum advantage. Meanwhile, *VACSEN* [1] is an online visualization system which provides the "easy to understand" visualization of the noise status on all available quantum computing nodes, recommends the most robust transpilation of circuit on the selected quantum computing node, and allows the real-time execution for a given quantum algorithm with noise awareness. In this tutorial, we will introduce how to conduct the co-design of neural networks and quantum circuits with QuantumFlow and *VACSEN*. We will have hands-on experience in implementing the neural network on the quantum circuit. Finally, targeting the near-term quantum computers, we will present the current solution in QuantumFlow, discuss the existing challenges, and show our perspective of quantum machine learning in the NISQ-Era. All attendees will leave with code examples that they can use as the backbone implementation to their own projects.

Keywords: Quantum Machine Learning, Neural Network, Quantum Circuits, Co-Design Optimization, Quantum Accelerator, Quantum Advantage, Hands-On Programming.

Contents Level: The content of this tutorial is aimed at 60% beginner and 40% intermediate level attendees, but materials should be interesting and useful even for advanced level attendees. We expect the typical attendee to be a beginner in quantum computing or machine learning, and be familiar with Python.

Target Audience: This tutorial aims to bridge the gap between neural network design and quantum circuit design, and therefore, it is appropriate for both the computer scientists or hobbyists with interests in applying their machine learning model to quantum computing and the quantum computing hobbyists with the interests in quantum machine learning. The first session of the tutorial will cover background on both machine learning and quantum computing to synchronize all attendees on the same page. Additionally, we will present the co-design approach applied in QuantumFlow to enable the quantum neuron achieving quantum advantage. In the second session, attendees will have the opportunity to implement the quantum neurons on IBM Qiskit using Google Colab. The third session will introduce the developed mapping optimizer in QuantumFlow, the challenge and perspective of quantum neural network in the near-term quantum computers through *VACSEN*.

Goals: The first goal of this tutorial is to enable attendees to use the QuantumFlow framework to solve their own problems. The hands-on experiences and coding will be the backbone implementation for their future studies or research. Also, attendees will have the opportunity to understand how the co-design can be applied in the design of quantum applications in order to achieve a quantum advantage. Moreover, attendees could explore the *VACSEN* system, revealing some insights about the hidden noise in the quantum computers and compiled circuits, and further mitigate the quantum noise based on the visual evidences.

Relevance: Quantum machine learning is a popular branch of quantum computing. It has direct relevance to quantum computing practitioners and researchers. In addition, software and hardware co-design is an important approach in quantum computing to achieve a quantum advantage. This tutorial shows a case study on machine learning applications, which can provide more insights for quantum computing practitioners and researchers in designing their own quantum applications.

Format: There are three sessions in this tutorial: (1) The first session will be a *slides-based talk*. We will make an introduction to quantum gates, machine learning, and the co-design approach proposed in QuantumFlow. (2) The format of the second session will be *hands-on coding*. We will implement the design presented in the first session using Qiskit. (3) The format of the third session will be *slides-based talk with on-line materials*. We will prepare the logical-to-physical mapping algorithm on Github, and we will introduce the details of the algorithm in the slides.

Regarding the *internet access* of the hands-on session, we expect that the attendees will have internet access to Google Colab. Since Colab provides the environment on the cloud, all environment installations will have no cost for the local network bandwidth. Instruction on how to use Colab will distribute to attendees before the tutorial. For people who have no or weak internet access, we will also have plan B to provide the local running environment. The required packages will be sent to attendees before the tutorial. Regarding the *projected load* of the hands-on session, we will simplify the dataset to be used (e.g., using 2 out of 10 digits from the MNIST dataset). We will provide the trained neural network model to make attendees focus on the implementation of a quantum neural network. But, we will also provide the detailed training algorithm implementation on GitHub. End-to-end implementation of a neural network on the quantum circuit will be conducted in this session with a simplified example. Attendees can easily extend the built tool in the tutorial to a larger dataset or neural network.

Biography of Weiwen Jiang: Dr. Jiang joined the ECE department at George Mason University as an Assistant Professor in Fall 2021. He was a Postdoctoral Associate at the University of Notre Dame. He received the Ph.D. degree from Chongqing University in 2019. From 2017 to 2019, he was a research scholar at the University of Pittsburgh. His research works have won Best Paper Awards in IEEE TCAD'21, ICCD'17, and NVMSA'15. He is the receipt of four Best Paper Nominations in ASP-DAC'16, DAC'19, CODES+ISSS'19, ASP-DAC'20, and the Top Winning Awards at IEEE Services Hackathon. He built the first co-design framework, QuantumFlow, to demonstrate the quantum advantage in designing neural network onto a quantum computer, which was published in Nature Communications. On the quantum topic, he was invited to give a contribution talk at IBM Quantum Summit 2020 and host tutorials at QuantumWeek-21, CODES+ISSS'21, ICCAD'21, and will host tutorials at DAC'22.

Biography of Qiang Guan: Dr. Guan is an assistant professor in Department of Computer Science at Kent State University, Kent, Ohio. Dr. Guan is the direct of Green Ubiquitous Autonomous Networking System lab (GUANS). He is also a member of Brain Health Research Institute (BHRI) at Kent State University. He was a computer scientist in Data Science at Scale team at Los Alamos National Laboratory before joining KSU. His current research interests include fault tolerance design for HPC applications; HPC-Cloud hybrid system; virtual reality; quantum computing systems and applications.

Biography of Yong Wang: is currently an assistant professor in School of Computing and Information Systems at Singapore Management University. He obtained his Ph.D. in Computer Science from Hong Kong University of Science and Technology in 2018. His research interests include information visualization, visual analytics and explainable machine learning. His research has won the Best Paper Award in IUI 2017, Best Paper Honorable Mention Awards in CHI 2022 and IEEE VIS 2021, and Best Poster Award in IEEE VIS 2019. For more details, please refer to `http://yong-wang.org`.

Tutorial on QuantumFlow+*VACSEN*:

Although the concept of quantum learning [2] can be traced back to the 1990s, how to realize a quantum neuron (i.e., the quantum version of the fundamental operation in a neural network) with an achievable quantum advantage is still not clear, not to mention the acceleration of the neural network.

To achieve quantum advantage, we need to implement one artificial neuron with the input size of $O(N)$ to a quantum circuit with at most $O(\text{polylog}N)$ complexity for both number of qubits and circuit length. Y. Cao et al. proposed the very first quantum neuron [3], which requires $O(N)$ qubits and $O(N)$ circuit length. Tacchino et al. optimize the quantum neuron to use $O(\log N)$ qubits [4] but the circuit length is still $O(N)$. In this year, based on the co-design philosophy, we propose a novel quantum neuron in the QuantumFlow framework [5], which utilizes $O(\log N)$ qubits and the circuit length is $O(\log^2 N)$. As a result, the time-space complexity of quantum neurons is reduced to $O(\log^3 N)$ from $O(N)$ with the classical computing scheme. This demonstrates the quantum advantage can be achieved for the fundamental operation in a neural network.

To provide users with an intuitive way to perceive the quantum noise, *VACSEN* leverages multiple novel visual designs to visualize the quantum noise of quantum computers and compiled circuits. Meanwhile, *VACSEN* supports the real-time compilation and execution for a given quantum algorithm with noise awareness. Users can assess and mitigate the quantum noise via selecting the optimal quantum computers and compiled circuits with less quantum noise. Specifically, for quantum computer selection, users can assess the noise through the decoherence time and error rate of basic building blocks (i.e., qubits and quantum gates) via the Computer Evolution View. For compiled circuit selection, *VACSEN* extracts all compiled circuits and then provides coupled bar charts to portray the noise hidden in each compiled circuit. *VACSEN* guarantees that the reliable quantum computer and compiled circuits can be prioritized via the intuitive quantum computing-specific visualization.

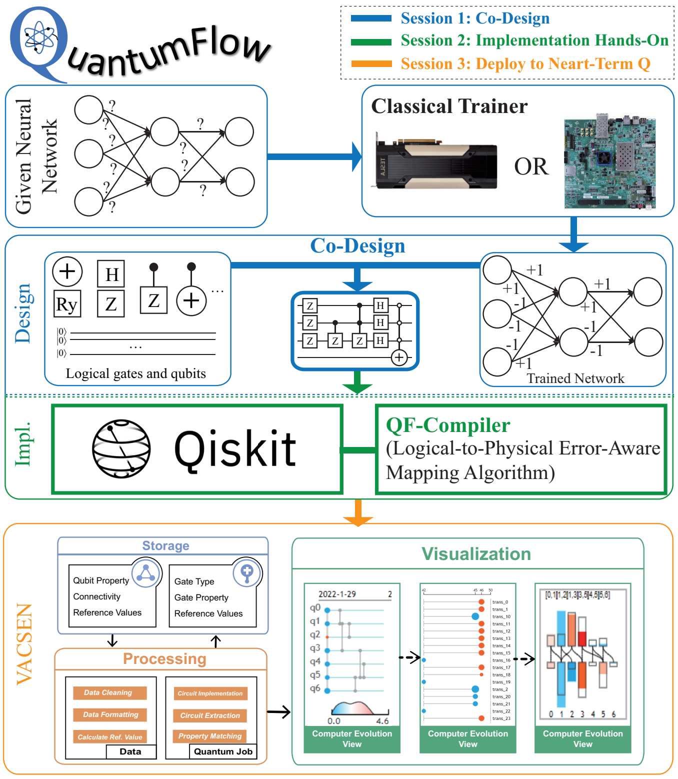

Figure 1: Three Sessions in the tutorial on QuantumFlow with session 1 in blue color, session 2 in green color, and session 3 in orange color.

In this tutorial, we aim to provide attendees the design and implementation details of QuantumFlow and *VACSEN*. Figure 1 shows that the tutorial will be organized into three sessions, each of which corresponds to one layer in the framework. In the following texts, we will introduce the organization of each session.

Session 1: Backgrounds, fundamentals, and network-circuit co-design

[Content] This session is slides-based presentation. The 45-minute content is organized as follows:

- Introducing the background and fundamental mathematics of neural networks and quantum computing.
- Presenting the design of quantum circuits to perform the exact same function as neural networks.
- Demonstrating how to optimize the quantum circuit to achieve quantum advantage via co-design.

[Related Experience] (1) The content is based on the QuantumFlow paper published at Nature Communications; (2) Part of the contents are presented in IBM Quantum Summit 2020; (3) Dr. Jiang was the guest lecture of 2 courses at Notre Dame during 2020-2021 Winter break.

Session 2: Assessing and mitigating the quantum noise using VACSEN.

[Content] The session consists of slides-based presentation and hands-on implementation. The 45-minute content is organized as follows:

- Introducing the background of visualization and the fundamental knowledge of Visual Analytics Science and Technology (VAST).

- Presenting the visual designs of *VACSEN* via a real-time demo.
- Conducting the hands-on experiments to operate on *VACSEN* based on the pre-defined quantum algorithm (e.g., Quantum Fourier Transform algorithm).

[Related Experience] (1) The content is based on the *VACSEN* paper submitted to *IEEE VIS 2022*. The online demo of *VACSEN* can be accessed via the URL: `https://vacsen.github.io/`; (2) Dr. Guan was the lecturer of graduate level course "Quantum Computing" at Kent State University and Dr. Wang is an expert in data visualization from Singapore Management University.

Session 3: Integrating the QuantumFlow and VACSEN for quantum neural networks.

[Content] This session consists of slides-based presentation and hands on implementation. The 45-minute content is organized as follows:

- Introducing the optimization algorithm to perform Logical-to-Physical mapping in QuantumFlow
- Conducting the hands-on experiment on using *VACSEN* to select the backend and transpilation mappings in QuantumFlow.
- Discussing the challenge and outline our perspective of accelerating neural networks on near-term quantum computers and the user feedback on using *VACSEN*.
- Q&A.

[Related Experience] The content is from QuantumFlow, where our previous talk at other conferences covers these contents.

Sample Contents: In addition to our previously published papers [5, 6], we have already prepared related materials on QuantumFlow, listed as follows:

- Official Website: `https://jqub.github.io/categories/QF/`.
- QuantumFlow was invited and presented at IBM Quantum Summit 2020. The slides can be accessed via `https://wjiang.nd.edu/2020/06/29/quantumflow/QuantumFlow_IBM_Summit.pdf`.
- Teaching slides at the University of Notre Dame. The slides can be accessed via the following two addresses: `https://wjiang.nd.edu/categories/teaching/Course1_Framework.pdf` and `https://wjiang.nd.edu/categories/teaching/Course2_QuantumFlow.pdf`.
- QuantumFlow is open-sourced at github `https://github.com/weiwenjiang/QuantumFlow`.
- We have made a tutorial-like repo at github `https://github.com/weiwenjiang/QuantumFlow_Tutorial`, which can be directly executed at Google Colab.

References

[1] Shaolun Ruan, Yong Wang, Weiwen Jiang, Ying Mao, and Qiang Guan. VACSEN: A Visualization Approach for Noise Awareness in Quantum Computing. *IEEE VIS 2022*, Under Review.

[2] Ronald Chrisley. Quantum learning. In *New directions in cognitive science: Proceedings of the international symposium, Saariselka*, volume 4. Citeseer, 1995.

[3] Yudong Cao, Gian Giacomo Guerreschi, and Alán Aspuru-Guzik. Quantum neuron: an elementary building block for machine learning on quantum computers. *arXiv preprint arXiv:1711.11240*, 2017.

[4] Francesco Tacchino, Panagiotis Barkoutsos, Chiara Macchiavello, Ivano Tavernelli, Dario Gerace, and Daniele Bajoni. Quantum implementation of an artificial feed-forward neural network. *Quantum Science and Technology*, 5(4):044010, 2020.

[5] Weiwen Jiang, Jinjun Xiong, and Yiyu Shi. A co-design framework of neural networks and quantum circuits towards quantum advantage. *Nature communications*, 12(1):1–13, 2021.

[6] Weiwen Jiang, Jinjun Xiong, and Yiyu Shi. When machine learning meets quantum computers: A case study. In *2021 26th Asia and South Pacific Design Automation Conference (ASP-DAC)*, pages 593–598. IEEE, 2021.