Quantum Computation and Machine Learning

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This seminar will cover the conceptual, mathematical, and programming background needed to implement machine learning techniques in quantum computing, including quantum noise, quantum error correction, and the quantum Boltzmann machine. Prerequisites: PHYS 33 and MATH 23 and/or MATH 53, or by the consent of the instructor.

By the end of the course, you will acquire skills of:

- knowing the difference between the classical and quantum computational treatments of information.
- processing the physical interpretation of the quantum information, a.k.a. "No information without representation."
- determining the limitations and the challenges of the quantum computability in the computational complexity and the computing power.
- Executing machine learning techniques on quantum computation phenomena such as circuit models and quantum algorithms.

Main Syllabus:

1. Limitations of classical computability theory and why to be replaced by quantum version. Foundations of quantum mechanics. Unitary operations on qubits and Bloch sphere. Quantum entanglement.
2. Reversibility, information loss, and classical/quantum gates. Quantum circuits and quantum gates: H-gate, S-gate, T-gate, U-gates.
3. Quantum Computing Algorithms: Deutsch's algorithm (main focus). Other algorithms (as black boxes): Grover's algorithm, Shor's factoring algorithm, Quantum Fourier transform, and phase estimation algorithm.
4. Quantum random access memory (QRAM), SWAP test, Qdist routine. Time evolution of quantum states and Hamiltonian simulation (quick visit).
5. *Classical* information/data clustering, partitioning, k-mean, and principal component analysis. Distance-based classifications, k-nearest neighbors, and support vector machine.
6. Machine learning and basics of *classical* neural networks: optimizing weights and loss functions using gradient descent, perceptrons, backpropagation, feedforward, autoencoder.
7. Basics of quantum neural networks (QNN): quantum perceptrons, quantum feedforward, and quantum autoencoder. Quantum classifiers, quantum pattern recognitions, associative memory with Grover's algorithm.
8. (Optional) Boltzmann Machine (BM) & its quantum version (QBM) [**2024 Nobel Prize in Physics**].

References:

- D. Pastorello, "Concise Guide to Quantum Machine Learning", Springer Nature, 2023, ISBN: 978-9811968976.
- Y. Du et al., "A Gentle Introduction to Quantum Machine Learning", Springer Nature, 2025, ISBN: 978-9819512843.
- T. Wong, "Introduction to Classical and Quantum Computing", World Scientific, 2022, ISBN: 979-8985593105.
- R. Hundt, "Quantum Computing for Programmers", 2nd Ed. Cambridge University Press, 2025, ISBN: 978-1009548533.
- M. Schuld, F. Petruccione, "Machine Learning with Quantum Computers", 2nd Ed., Springer Nature, 2021, ISBN: 978-3030830984.
- C. Conti, "Quantum Machine Learning", Springer Cham, 2024, ISBN: 978-3031442261.