Quantum Machine Learning

Machine Learning

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Quantum machine learning is an emerging interdisciplinary research area at the intersection of quantum physics and machine learning. The most common use of the term refers to machine learning algorithms for the analysis of classical data executed on a quantum computer, i.e. quantum-enhanced machine learning. While machine learning algorithms are used to compute immense quantities of data, quantum machine learning increases such capabilities intelligently, by creating opportunities to conduct analysis on quantum states and systems. This includes hybrid methods that involve both classical and quantum processing, where computationally difficult subroutines are outsourced to a quantum device. These routines can be more complex in nature and executed faster with the assistance of quantum devices Furthermore, quantum algorithms can be used to analyze quantum states instead of classical data. Beyond quantum computing, the term "quantum machine learning" is often associated with classical machine learning methods applied to data generated from quantum experiments (i.e. machine learning of quantum systems), such as learning quantum phase transitions or creating new quantum experiments. Quantum machine learning also extends to a branch of research that explores methodological and structural similarities between certain physical systems and learning systems, in particular neural networks. For example, some mathematical and numerical techniques from quantum physics are applicable to classical deep learning and vice versa. Finally, researchers investigate more abstract notions of learning theory with respect to quantum information, sometimes referred to as "quantum learning theory".

Machine learning with quantum computers

Quantum-enhanced machine learning refers to quantum algorithms that solve tasks in machine learning, thereby improving and often expediting classical machine learning techniques. Such algorithms typically require one to encode the given classical data set into a quantum computer to make it accessible for quantum information processing. Subsequently, quantum information processing routines are applied and the result of the quantum computation is read out by measuring the quantum system. For example, the outcome of the measurement of a qubit reveals the result of a binary classification task. While many proposals of quantum machine learning algorithms are still purely theoretical and require a full-scale universal quantum computer to be tested, others have been implemented on small-scale or special purpose quantum devices.

- Linear algebra simulation with quantum amplitudes
- Quantum machine learning algorithms based on Grover search
- Quantum-enhanced reinforcement learning
- Quantum annealing
- Quantum sampling techniques

- Quantum neural networks
- Hidden Quantum Markov Models
- Fully quantum machine learning

Why Quantum Computing?

Quantum computing (QC) is viewed by many as a possible future option for tackling these high complexity or seemingly-intractable problems by complementing classical computing with a fundamentally different compute paradigm. Classically-intractable problems include chemistry and molecular dynamics simulations to support the design of better ways to understand and design chemical reactions, ranging from nitrogen fixation1 as the basis for fertilizer production, to the design of pharmaceuticals. Materials science problems that can be tackled by QCs include finding compounds for better solar cells, more efficient batteries, and new kinds of power lines that can transmit energy losslessly. Finally, Shor's algorithm, which harnesses QC approaches to efficiently factor large numbers, raises the possibility of making vulnerable the current data encryption systems that rely on the intractability of this calculation; the existence of a QC sufficiently large and sufficiently reliable to run Shor's on full-length keys could make current cryptosystems vulnerable to attack and eavesdropping.

The Inflection Point

The intellectual roots of QC go back decades to pioneers such as Richard Feynman who considered the fundamental difficulty of simulating quantum systems and "turned the problem around" by proposing to use quantum mechanics itself as a basis for implementing a new kind of computer capable of solving such problems . Although the basic theoretical underpinning of QC has been around for some time, it took until the past 5 years to bring the field to an inflection point: now small and intermediate-scale machines are being built in various labs, in academia and industry. Preskill has coined the phrase Noisy Intermediate-Scale Quantum (NISQ) to refer to the class of machines we are building currently and for the foreseeable future, with 20-1000 qubits and insufficient resources to perform error correction10. Increasingly, substantial research and development investments at a global scale seek to bring large NISQ and beyond quantum computers to fruition, and to develop novel quantum applications to run on them.

Conclusions

Overall, QC is poised at a deeply fascinating inflection point. Large industry and government investments are pushing for breakthroughs in qubit counts and fidelities, with quantum advantage being a much-sought-after milestone. To reach long-term practicality, however, will require considerable innovation after quantum advantage has been reached. Practical QC algorithms that can make use of intermediate-scale hardware will likely be needed in order to motivate ongoing investment of time and resources into QC developments. Without a “killer app” or at least a useful app runnable in the first ten years, progress may stall. In addition, the workshop agreed that there is a general need for research regarding how best to implement and optimize programming, mapping, and resource management for QC systems through the functionality in between algorithms and devices. Attention to systems design and scalability

issues will be important as QC systems grow beyond small qubit counts and require modular large-scale designs. For near-term NISQ machines, we will need to create and refine languages and compilation techniques that give programmers the expressive power needed to articulate the needs of QC algorithms relative to tight resource constraints on current implementations. Longer term, the use of abstractions to enhance productivity once quantum resources are more plentiful. We must establish the sorts of modularity and layering commonly needed for scalable systems. Furthermore, real-world quantum systems will be hybrids of classical and quantum units, and research is needed on how to program and map efficiently to “both sides” of such machines. Opinions vary on the degree of architectural sophistication warranted on each side, as well as on issues of communication between them.