

The Advantage and Disadvantage of Development of Quantum Computing in Machine Learning

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Abstract: Quantum computing is an emergent technology with great promise to reshape machine learning. It enables computations intractable by any classical system. This paper discusses the basic concepts of quantum computing, its advantages, and their limitations regarding ML. It can be concluded that quantum computers leverage phenomena in quantum mechanics, such as superposition, entanglement, and interference execute those computations that are beyond the capability of classical systems. A few of the most important fancies in QSVM, QPCA, and QNN perform such tasks as computing kernel matrices, high-dimensional data processing, and solving optimization problems in some key points. In contrast, several formidable challenges persist, beginning with the scalability and coherence of qubits as hardware-related issues, and extending to software-centric problems such as data encoding and the efficiency of specific algorithmic applications. This paper also underscores potential future avenues for advancement, including the development of hybrid quantum-classical algorithms, quantum error correction techniques, and quantum-native machine learning models, aimed at surmounting these limitations. By addressing these challenges and directing focus towards prospective research, quantum computing holds the promise of unlocking transformative breakthroughs in various domains such as big data processing, drug development, financial modeling, and natural language processing. Such advancements could firmly establish quantum computing as the cornerstone of next-generation artificial intelligence technologies.

Keywords: quantum computing, machine learning, quantum machine learning, quantum algorithms

1. Introduction

Nowadays, AI technology is taking a more and more important place in our no matter lives or industry production. It means that artificial intelligence keeps making breakthroughs and is widely used, which leads to "Computational anxiety." As our demand for computing power continues to escalate [1], quantum computing, as an emerging technology, emerges as crucial for the future advancement of humanity. In the body section of this essay, the first part is going to introduce the principles of quantum computers and their advantages and disadvantages, as well as the achievements they achieved. Second would be, having the biggest share, of quantum computing with the use of machine learning, to present some examples and compare these with the usual methods, taking into

consideration its advantages and disadvantages, along with possible solutions for the shortage it may have on quantum computing. The final section will discuss potential future advancements in quantum computing and explore its possible applications. This paper adopts the research methods of theoretical analysis and case analysis. The importance of the research is therefore to analyze the strengths and weaknesses of quantum computing in machine learning and come up with some thickness for future development.

2. Introduction to quantum computing

Quantum computing has the potential to address significant global challenges, including those related to the environment, agriculture, health, energy, climate, material sciences, and numerous other domains. Actually, for most of these kinds of problems, classical computation ability is severely taxed when systems scale up in size. Capable of scaling, quantum systems might have capabilities well beyond today's most powerful supercomputers.

Since it is hard to simulate a quantum system using a classical computer, ideas came to develop a quantum computer. In the 1980s, Richard Feynman and Yuri Manin independently suggested that it may be more effective at simulating quantum systems than a conventional computer since it relies on hardware based on quantum phenomena. The second reason it can be learned that quantum mechanics are hard to simulate is to observe the many ways possible configurations at the quantum level, which describes matter in a word status: exponential growth of quantum states. So, it had to be a question by researchers whether the quantum system can be simulated by just the same physical laws of the computer, and can these machines investigate further into other tasks that are important to us. These problems gave birth to Quantum computing. Just as bits are the basic objects of information in classical computing, so qubits are fundamental objects of information in quantum computation. They have similar effects, but different behaviors.

Classically, bits are binary in nature and can only take positions of 0 or 1, while qubits can hold superpositions of all possible states. In other words, a qubit can be in a state of 0, 1, or any quantum superposition of the two. There are infinitely many possible superpositions of 0 and 1, each of which is a valid state of the qubit.

What can be done to make a quantum computer?

A quantum computer is a computer that employs the phenomenon of quantum mechanics. Quantum computers store and compute information by using quantum states of matter. The construction of a quantum computer is an engineering challenge that requires deep knowledge of quantum mechanics and the capability to control quantum systems on at least a minimal scale. Quantum thinking with a computer, right from the very outset, is to think of how one can build qubits and, subsequently, how to store them, manipulate them, and read out results of calculations. The most used qubit technologies are ion trap qubits, superconducting qubits, and topological qubits. For some of the methods of storing qubits, the device that holds the qubits is stored near absolute zero to maximize their coherence and reduce interference. Other types of qubit devices use vacuum chambers to help minimize vibration and keep the qubits stable. Qubits can be sent signals by various methods: microwaves, lasers, and voltage.

A well-conditioned quantum computer should be able to satisfy all of the following five functions:

Scalable: It can have many qubits.

Initializable: It can set the qubit to a specific state, usually the 0 state.

Recoverable: It can maintain qubits in a superposition state for a long time.

Universal: Quantum computers don't need to implement all possible operations, but a universal set of operations will suffice. A universal set of quantum operations enables any other operation to be decomposed into a sequence of quantum operations.

Reliable: It should be able to measure the qubits accurately.

These five criteria are commonly known as the Di Vincenzo[2] conditions for quantum computing.

Quantum computing vs traditional computing in machine learning

3. The advantages of quantum computing

In the realm of machine learning, a quantum computer offers several significant advantages over traditional implementations: it possesses parallel computing capabilities, can tackle complex problems, and leverages quantum parallelism to simultaneously explore multiple computational states, thereby facilitating exponential speedup for specific computational tasks. Furthermore, the entanglement relationships among qubits enable efficient encoding of high-dimensional information.

Quantum interference: Amplifies the right solution and dampens the wrong solution due to quantum interference effects.

Now, let's take the example of SVM. SVM is a generalized kind of linear classifier. It binary-classifies data by supervised learning, whose decision boundary is the maximum margin hyperplane to solve the learning sample [3]. Acceleration of a kernel matrix computation:

Traditional SVM: The computational complexity of the Kernel Matrix is $O(N^2)O(N^2)$, where "NN" is the amount of data points. When the dataset is large, this step will be very time-consuming.

Advantages of QSVM: QSVM uses the Quantum Kernel Estimation method in quantum computing, which can directly calculate the inner product of the kernel matrix on the quantum state. By using quantum parallelism, QSVM is able to exponentially accelerate the computation of the kernel matrix, and the theoretical complexity can be reduced to $O(\log N)O(\log N)$ or even lower.[4] Efficient processing of high-dimensional data:

Traditional SVM: During high-dimensional data processing, its computation complexity will explode in the high dimensions, especially for a nonlinear kernel function such as the RBF kernel.

QSVM advantages: High-dimension data can be expressed and operated on the quantum status effectively. With Quantum Feature Mapping, QSVM can map the classical data to the high-dimensional quantum status space and efficiently perform classifications in the high-dimensional space.

Accelerating optimization with quantum parallelism:

Traditional SVM: It is necessary to address Quadratic Programming Problems during the training phase, wherein the computational complexity is $O(N^3)$, rendering the process computationally intensive for large datasets.

Advantages of QSVM: it can use quantum optimization algorithms such as the quantum interior point method or quantum gradient descent to accelerate the solution of quadratic programming problems. Quantum parallelism enables the Quantum Support Vector Machine (QSVM) to concurrently explore multiple solution spaces, thereby facilitating the rapid identification of the optimal solution. In addition to this, the advantages of QSVM are numerous and include, but are not limited to, the following:

First, enhanced expressiveness of kernel functions: Quantum kernel functions possess the capability to capture more intricate patterns.

Second, direct processing of quantum data: Avoid loss of information of classic transformation.

Third, theoretical computational advantages: breaking through the lower bounds of classic computation.

Forth, resource efficiency: Reduce demands for memory and computing resources

4. Disadvantages of quantum computing

Besides the advantages, the disadvantages of quantum computing should also be taken into consideration. And it could be divided into two aspects: hardware and software.

Limitation of hardware:

Insufficient qubits remain a significant challenge: one of the most advanced quantum computers, such as IBM Quantum System Two, boasts only approximately 1000 qubits [5], whereas classical neural networks like GPT-3 possess around 175 billion parameters. Consequently, it is currently infeasible to construct a model of equivalent complexity on a device such as a Noisy Intermediate-Scale Quantum (NISQ) computer, even with the use of Quantum Neural Networks (QNNs) based on quantum parametric circuits.

Quantum state preparation incurs overhead: transitioning classical data into quantum states necessitates $O(N)$ time, particularly in extensive datasets such as ImageNet, wherein the duration required for data loading surpasses the forward propagation time of classical convolutional neural networks.

Software Limitation:

Limitation of HHL algorithm: The HHL algorithm[6], which theoretically accelerates the solution of linear equations, exhibits practical limitations in machine learning applications. Although the right vector b can efficiently prepare the quantum state solution vector to satisfy the matrix condition $\kappa = O(\text{polylog } N)$, certain measurement requirements for observables pose challenges. For instance, in the MNIST classification task, traditional Stochastic Gradient Descent (SGD) solves linear systems approximately three orders of magnitude faster than quantum methods.

5. Future Development and application scenarios

Although quantum computing is still in the early stage of development, the technology has shown its potential ability to have better performance than classical computing in some aspects. Here are some possible future directions on machine learning: Quantum Principal Component Analysis (QPCA):

Principle: Quantum algorithms shall be employed to efficiently compute principal components of data for data reduction and feature extraction.

Advantage: QPCA has a higher speed compared to classical methods for large datasets.

Quantum Neural Network (QNN):

Principle: Map classical neural network into the quantum circuit, and use the superposition and entanglement properties of quantum states to calculate.

Advantage: QNN can deal with more complex and non-linear relationships, and also has the possibility of implementing exponential acceleration in some tasks.

Quantum optimization algorithm:

Principle: Quantum Annealing or QAOA is applied to solve, in particular, some optimization problems in machine learning, such as parameter optimization and hyperparameter tuning.

Benefit: Quantum optimization algorithms may run faster than their classical counterparts when dealing with a combinatorial optimization problem.

Application scenarios of quantum computing in machine learning:

Large-scale data processing: Quantum computers can speed up large-scale data processing and analytics. For instance, it will find patterns or features in high-dimensional data.

Drug Discovery and molecular simulation: Quantum computing can simulate the behavior of molecules and chemical reactions for faster drug discovery and material design. This can be combined with machine learning to more efficiently screen drug candidates.

Financial Modeling: Quantum computing can accelerate analysis and prediction, including risk analysis, portfolio optimization, and market forecasting, using financial data.

Natural Language Processing: Quantum computing can potentially greatly improve the training and inference efficiency of language models when semantic spaces are high-dimensional.

Image and Video Processing: Quantum computing can facilitate the speeding up of feature extraction and classification processes in image and video data, for instance, in medical image analysis.

6. Conclusion

The paper discusses the potential of quantum computing in ML and analyzes the revolutionary importance compared to classical computing methods by comparing the principles, advantages, and limitations of the latter.

Quantum computing employs quantum mechanics principles like superposition, entanglement, and quantum interference in carrying out, with polynomial complexity, some computational tasks that are beyond the reach of classical computers. Key advances include QSVM, QPCA, and QNN; all these have shown the potential for exponential acceleration in tasks such as kernel matrix computation, high-dimensional data processing, and optimization problems. In spite of all these promising developments, quantum computing still faces severe challenges in both hardware, like scalability and coherence of qubits, and software, such as data coding and algorithmic applicability. Nevertheless, the significant potential applications of quantum computing in big data processing, drug discovery, financial modeling, and natural language processing position this field as transformative for the future. Despite the bright prospects of quantum computing, the following issues remain for its full expression in machine learning: Hardware: Current quantum computers, such as devices based on Noise-Intermediate Scale Quantum technology, are relatively small in the number of quantum bits and suffer from decoherence and noise problems; stability and the correction of quantum bits during the scaling of quantum systems is an enormous challenge. Avenues toward solution include the construction of more advanced quantum bits technologies, such as topological quantum bits, and error correction methods, like surface codes. Hybrid quantum-classical systems can be used as an intermediate stage until fully fault-tolerant quantum computers mature. Software and algorithmic challenges: many quantum algorithms, such as the HHL algorithm for linear systems, are theoretically very powerful but have limitations in real-world machine learning tasks. Another problem often related to many quantum algorithms is the overhead of data encoding and quantum state preparation. Avenues for advancement encompass the development of sophisticated quantum bit technologies, including topological quantum bits, alongside error correction techniques such as surface codes. Hybrid quantum-classical systems may serve as an interim step toward the realization of fully fault-tolerant quantum computers. Integrating quantum computing with classical machine learning frameworks, such as TensorFlow Quantum, can also improve the usability of the former. Resource and access issues: Currently, resources for quantum computing are very limited and costly, thus restricting their wide range of applications and experiments. Means for solutions include expansion in the use of quantum cloud platforms, such as IBM Quantum and Google Quantum AI, which may "grease" the wheels of academia-industry collaboration.

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