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Quantum Machine Learning: A review of Emerging Concepts

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Abstract

Machine learning is widely used in many scientific and technological fields as a component of artificial intelligence, such as "computer vision, natural language processing, data mining, biological analysis, and so on". One of the human race's most promising technologies for the near future is the quantum computer. Researchers are contemplating fusing machine learning with quantum computing to optimize the potential advantages of the former. This has led to the creation of a brand-new, interdisciplinary area called quantum machine learning. The current state of the field in "quantum machine learning techniques" is analyzed from a computer science viewpoint, and a research pathway from fundamental quantum data to these techniques is shown. It's possible to argue that QML will soon reach its full potential in resolving practical issues. It increases machine learning's capacity to handle, analyse, and mine massive amounts of data by using the high parallelism of quantum computing.

Keywords: Quantum Machine learning, Artificial intelligence, Noisy Intermediate-Scale Quantum (NISQ), Support Vector Machine, Quanvolutional Neural Networks.

1 Introduction

In the language of physics, a quantum is the smallest discrete representation of a physical quantity. Dualistic (wave-particle) quantum objects are associated with the field of quantum theory, which deals with the probability of a quantum particle at a given location in space. The field of "quantum machine learning (QML)" has been expanding and evolving in computer science in recent decades due to its

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connection to machine learning (ML), which uses a range of decision-making models to process and analyze data. Data volume is growing at a rate of around 20% annually, thus it must be managed effectively [1].

The development of quantum computers that can significantly outperform conventional computers for certain tasks is still a challenge in the scientific community. Alongside the device's development, automated tools and techniques to support the simulation and design of the relevant applications must be improved. If not, one might find themselves in a position where they have access to powerful quantum computers but very little suitable methods of using them. Conversely, we are now able to construct large-scale, more fault-tolerant quantum computers thanks to technical developments in the domains of error correction, compilation, hardware manufacturing, and materials research". A few of the primary goals are to shorten the time it takes to create drugs by significantly increasing the simulation times of chemical compounds. Sophisticated cryptography systems will also make it possible to build secure computers that guarantee internet security for every consumer and to create new artificial intelligence methods that are already present in most devices and can range from prediction and suggestions to better industrial support systems [2].

Recently, there has been a significant expansion in the application area of quantum algorithms, offering effective solutions in fields including machine learning, cybersecurity, chemistry, communications, physics simulations, solving systems of linear equations, and cybersecurity. The field of machine learning has been one of the most recent to emerge. While quantum procedures are being improved by the use of classical machine learning, certain classical processes have already been improved with the use of quantum algorithms and contemporary quantum devices. Recent work demonstrates the use of traditional machine learning methods to enhance the quantum world: it is possible to detect quantum entanglement in completely and partly entangled systems using informal training. Deep learning approaches also allow us to identify structural characteristics and molecular dynamics in the quantum scenario while reducing the noise generated in quantum systems. It has been suggested that hybrid deep learning algorithms be created and implemented using "hybrid graphical convolutional networks (QGCNN)". Compared to conventional convolutional networks, "quantum convolutional neural networks", and multilayer perceptrons (MLP), QGCNN may achieve superior performance in several applications, including high-energy physics (HEP). Financial applications have used hybrid neural networks to predict GDP growth. Boltzmann machines are used in the medical profession to categorise people with lung cancer [3].

2 Literature Review

(Peral-garcía et al., 2024) [4] This paper intends to give a summary of the body of work that has been done in this field in order to categorize, evaluate, and identify the many kinds of algorithms used in "quantum machine learning and their applications". The technique is compliant with the Comprehensive Literature Review criteria, which have been suggested by Kitchenham and other software engineering writers. "The k-nearest neighbor model and support vector machines” are two instances of quantum adaptations of traditional machine learning techniques, whereas traditional deep learning approaches such as quantum neural networks fall into the other major category of discovering algorithms. Image classification is one of the most useful uses of machine learning. Numerous studies, particularly in the classification area, attempt to use quantum devices and algorithms to address issues that conventional machine learning presently addresses. Even with encouraging outcomes, quantum machine learning is still a long way from reaching its full potential. Since the quality of present quantum computers is insufficient, improvements in quantum hardware are necessary to achieve this promise.

(Wang & Liu, 2024) [5] Within the business and academic worlds, there has been a lot of interest in quantum machine learning—the utilization of "machine learning method on quantum devices". In this study, we provide an exhaustive and impartial analysis of the many ideas that have surfaced in the area of quantum machine learning. This covers methods for algorithms inside "the Noisy Intermediate-Scale Quantum (NISQ) technology" as well as methods for working with fault-tolerant quantum computing hardware. We explore the statistical learning theory, techniques, and foundational ideas related to quantum machine learning.

(Chen et al., 2024) [6] The use of machine learning to real-world problem solving has shown enormous promise. However, as data volume grows exponentially and model complexity rises, machine learning processing efficiency rapidly declines. Meanwhile, the basis of quantum machine learning—which arose with quantum computing and shows exponential optimization over conventional machine learning—is super position and entanglement. In this research, therefore, we revisit the basic concepts, techniques, applications, and challenges of quantum machine learning. From a practical standpoint, we begin by reviewing the fundamental ideas of quantum computing, such as gates, qubits, and quantum entanglement. The five quantum machine learning algorithms—"quantum k-Means algorithm, quantum analysis of principal components, quantum neural network, quantum k-nearest neighbor, and quantum support vector machine"—are then covered in great depth. Thirdly, we go over how quantum machine learning is being used to cybersecurity, image identification, and predicting the efficacy of medications. Our last section provides an overview of the difficulties associated with quantum machine learning, such as algorithm development, hardware constraints, data encoding, noise, decoherence, and quantum landscapes.

(Jadhav et al., 2023) [7] One of the main applications for the capabilities of quantum computing is machine learning. Even if a number of machine learning methods have been developed successfully, quantum computing may still be used. Entanglement might hold the key to solving this issue, and in recent years, there has been a surge in the creation of "quantum machine learning methods". Classification and clustering are the two machine learning topics that have been the focus of the bulk of recent research. This research examines the potential applications of "quantum machine learning" for common issues and provides a concise overview of the most recent methods and algorithms in the field.

(Tychola et al., 2023) [8] In this paper, these issues are examined by comparing the accuracy of quantum and conventional methods, as well as by assessing the status of "quantum machine learning" today. Specifically, we investigated three datasets for binary classification using "the Support Vector Machine

(SVM) and Quantum SVM (QSVM) methods". Our results imply that the QSVM method performs better on complex datasets than the conventional SVM technique, and that the difference in performance between the quantum and classical models grows with the complexity of the dataset since simple models have a tendency to overfit. "Quantum machine learning" has great potential for applications such as generative models and learning without supervision, even if efficient quantum hardware is still a long way off. Finding special "quantum learning models" that take use of quantum physics will need further research in order to get beyond the constraints of traditional machine learning.

(Zeguendry et al., 2023) [3] It should come as no surprise that more and more machine learning specialists are looking at the potential benefits of quantum computing, given the likelihood that this trend will continue. Since a large amount of research has already been done on "quantum machine learning", it is critical to assess the field's current state in a manner that is accessible to non-physicists. This paper aims to provide an overview of "quantum machine learning" in comparison to traditional methods. This is not a computer scientist's view of a research path that goes from fundamental quantum principles to "Quantum Machine Learning methods. Provide a collection of foundational techniques for Quantum Machine Learning, which are the building blocks of "Quantum Machine Learning algorithms". We compare the performance of the quantum computer-implemented Quanvolutional Neural Networks (QNNs) with its conventional cousin, the Convolutional Neural Networks (CNNs), for handwritten digit recognition. Furthermore, we compare the results with the traditional SVM using "the QSVM on the breast cancer database". Finally, we use "the Variational Quantum Classifier (VQC)" on the Iris dataset to compare its accuracy with other traditional classifiers.

(Valdez & Melin, 2023) [9] In this talk, we provide an overview of the domains of deep learning (DL) and quantum computing (QC) and how they are used in computational intelligence (CI). Quantum algorithms (QAs) employ quantum information to solve problems based on the fundamentals of quantum physics. Quantum information relates to the state of a quantum system and may be changed via the application of quantum information techniques and other processing techniques. The basic conclusion of the numerous QAs that have been proposed lately is that an enormous speedup (polynomial, exponential, or super polynomial) may be achieved by using the effects of quantum physics over ordinary algorithms. This suggests that QA may be able to help solve certain difficult issues that are now unsolvable using conventional techniques. However, deep learning algorithms provide what are referred to as machine learning methods. DL aims to teach a computer how to anticipate and categorise data by filtering inputs across layers. Observations may be expressed verbally, visually, or sonically. Deep learning draws inspiration from the way the human mind processes information. So, we looked at these two subjects in our study to see what works and applications scholars throughout the globe have generated that are most relevant.

(O'Quinn & Mao, 2020) [10] Today, the intersection of engineering and science is quantum computing. Even while the noisy, little quantum computers of today are becoming more and more advanced, the pace of development is remarkable. Furthermore, a lot of the most recent developments have been made possible by machine learning. Combining these two domains to create Quantum Machine Learning is a relatively young but very exciting area with almost limitless potential. In addition to discussing current developments and unsolved issues, this book aims to provide an overview of this developing topic.

(Mishra et al., 2019) [2] Research on quantum machine learning, a highly sought-after field, revolves on the interface of quantum computing and conventional machine learning. Applying findings from the quantum environment to machine learning issues is the focus of quantum machine learning research. The volume of data required to consistently train a traditional computing model is too large for standard computer systems to process. In a situation like this, quantum computing would be useful for carrying out training with enormous volumes of data. The goal of quantum machine learning is to develop learning algorithms more quickly than those of regular machine learning. Classical machine learning seeks to identify patterns in data and then uses those patterns to forecast future occurrences. Contrarily, quantum systems generate unusual patterns that classical systems are unable to develop, raising the possibility that quantum computers might surpass conventional computers in machine learning tasks. In this article, we review and summarize the previous studies on "quantum machine learning".

3 Conclusion

These techniques are computationally demanding because they use the ideas of superposition datasets in quantum machine learning. A solution to this difficulty is promised by quantum machine learning, which makes use of the notions of superposition and entanglement. Even with encouraging outcomes, quantum machine learning is still a long way from reaching its full potential. To realise this potential, quantum hardware must be improved, since current quantum computers are not of enough quality. A thousand-bit quantum computer is definitely possible, and quantum hardware is becoming more and more capable every day. Constructing an appropriate quantum algorithm for the depth and complexity of circuits of current NISQ devices remains challenging, despite the rapid development of QML algorithms. Therefore, it's possible that QML's potential for resolving practical issues may soon be realised. It improves machine learning's ability to manage, comprehend, and mine huge volumes of data by using the tremendous parallelism of quantum computing. The ideas of quantum physics should serve as inspiration for the creation of new machine learning algorithms.

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