

# Quantum Neural Networks: Evolution of Artificial Neural Networks in Quantum Domain

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**Abstract**— Quantum Neural Networks (QNNs) represent a fascinating intersection of Quantum Computing and Artificial Neural Networks. Researchers explored combining quantum computing and neural networks in the 1990s and early 2000s. Quantum Neural Networks (QNNs) combine principles from quantum computing and artificial neural networks to potentially revolutionize machine learning. QNNs are neural networks that utilize quantum computing principles, such as superposition, entanglement, and quantum parallelism, to process and transform information. With Quantum Superposition QNNs can represent complex probability distributions, allowing for more nuanced modeling of uncertainty. While with Quantum Entanglement, QNNs can capture complex correlations between inputs, enabling more accurate modeling of complex relationships. Apart of that Quantum Parallelism facilitates QNN to process multiple inputs simultaneously, potentially speeding up certain computations.

QNNs can potentially solve certain problems faster than classical neural networks. QNNs can also capture complex relationships and patterns, potentially leading to improved accuracy and can provide new insights into complex systems and phenomena. QNNs hold promise for advancing machine learning and solving complex problems. Ongoing research aims to overcome challenges and unlock their full potential. Quantum-Classical hybrid approaches were introduced, combining the strengths of both paradigms. This research paper presents an exploratory and critical survey of the current status of Quantum Neural Networks, Quantum Computing, along with the potential applications of QNNs in Artificial Intelligence.

**Keywords**—Quantum Computing, Quantum Computers, Superposition, Entanglement, Quantum Parallelism, Quantum Machine Learning, Artificial Intelligence

## INTRODUCTION

Quantum Computing is a modern computing paradigm that makes use of quantum- mechanical phenomena like Superposition, Interference & Entanglement in order to perform computations which are extremely much faster than Classical Computing, and perform in a far better manner with respect to space and time complexities. Quantum Computing has proved it's superiority over all classical computing techniques in the sense that quantum mechanical phenomenon makes Quantum Computing robust and efficient in terms of: its enormous capability of processing huge combinations of

inputs at a single instant, searching a specific pattern among huge amount of unstructured database in  $O(\sqrt{N})$  order of time, factorization of a large integer in  $O((\log N)^3)$  order of time, data security via No-Cloning Principle, Teleportation of the quantum information to remote locations beyond the boundary of the planet earth at almost speed of light and many more [1,2].

A Quantum Neural Network (QNN), a type of ANN that can be built using the principles of Quantum Information Processing. QNN is a rapidly growing field which integrates Classical Neuron-Computing with Quantum Computation. It is argued that the study of QNN may give us both new understanding of brain function as well as unprecedented possibilities in creating new systems for information processing, including solving classically intractable problems, associative memory with exponential capacity and possibly overcoming the limitations posed by the classical computation (Church-Turing thesis).

There are two main reasons to discuss QNN. One has its origin in arguments for the essential role which quantum processes play in the living brain. A second motivation is the possibility that the field of Classical ANN can be generalized to the quantum domain by eclectic combination of that field with the promising new field of quantum computing. Both considerations suggest new understanding of mind and brain function as well as new unprecedented abilities in information processing. Here we consider QNN as the next natural step in the evolution of Neuron-Computing Systems, focusing our attention on artificial rather than biological systems [3].

Quantum Computing when used in the field of Machine Learning gives rise to Quantum Machine Learning (QML). Quantum Machine Learning is an amalgamation of two breakthroughs in the world of science & technology domain, namely Quantum Physics and Machine Learning / Artificial Intelligence. QML offers a new channel / dimension to- how to solve Machine Learning problems using the concept of Quantum Computing. This research paper advocates new techniques to implement a very popular sub domain of Machine Learning i.e. Artificial Neural Network based architectures / learning algorithms with the use of Quantum Computing in order to demonstrate the computational power of Quantum Neural Networks (QNN). Research in previous

two decades in the field QNN / QML have shown that Quantum Computing can tremendously change the way we know machine learning as of now, its basic functional blocks, how it achieves its high computational power and the applications of QNN / QML in a real-world scenario [4].

This research paper proposes an initiative towards the ‘Study and Implementations of Quantum Neural Networks for Pattern Recognition’ and also covers literature review and critical survey of the current status of Quantum Computing, Principles of Quantum Computing, Quantum Algorithms, Quantum Circuits, Quantum Computers, and Quantum Simulators along with the new possibilities and optimizations in the most emerging field of computing: Quantum Machine Learning (QML) and specially its sub domain i.e. Quantum Neural Networks (QNN) along with the potential applications of Quantum Computing can be used to implement and optimize Classical ANN based Models / Algorithms. An obvious advantage of QML / QNN is that- In future if there is a crises of new Pure Quantum Algorithms for solving certain problems, then we will not face compromising situations, because at that time we will have a variety of QML / QNN based Learning Models / Algorithms for solving those problems which are either computationally challenged or shows high complexities w.r.t. time & space. On the other hand the new ways will be open for taking advantage of both technologies- ‘Quantum Computing’ and ‘Artificial Neural Networks’.

#### MAJOR PROPERTIES OF QUANTUM SYSTEM

The most fundamental, remarkable and inherent properties on which any Quantum System works and obeys are the law / phenomenon of ‘Superposition’, ‘Interference’, and ‘Entanglement’. Quantum Computer System is a special case of a Quantum System. A Quantum System dedicated to perform information processing and computation is abbreviated as ‘Quantum Computer System’. These three properties make a Quantum Computer System absolutely unique and extremely more powerful than the classical computers. All these three laws / phenomenon are explained in subsequent sections.

Quantum mechanics, also known as quantum physics or quantum theory, is a fundamental branch of physics that describes the behavior of matter and energy at the smallest scales, such as atoms and subatomic particles. It provides a theoretical framework for understanding the often counterintuitive behavior of particles, where phenomena like wave-particle duality, uncertainty, and quantum states play a crucial role. Superposition and Entanglement and Interference are the three major fascinating phenomena in quantum mechanics, each with its distinct characteristics. The primary distinction lies in their nature. ‘Superposition’ concerns the coexistence of multiple states in a single particle. Superposition pertains to the measurement of a single particle. On the other hand ‘Entanglement’ involves the correlation of properties between particles and Entanglement is related to the measurement of multiple particles [5].

- **Superposition:**

Superposition allows particles to exist in multiple states simultaneously, a concept drastically different from classical physics and chemistry. In classical terms, objects typically occupy a single state, but quantum superposition enables particles to coexist in a blend of states, with each state carrying a specific probability of being observed upon

measurement. These states are described by a mathematical superposition of wave functions, each with its associated probability amplitude. Superposition is observed in experiments where particles, such as electrons, exhibit wave-like behavior.

Quantum superposition is the foundation of quantum computing, enabling the processing of vast amounts of information simultaneously. It also plays a role in quantum algorithms and quantum simulations, offering potential advancements in various fields, including cryptography and materials science. Properties of quantum superposition include the linearity of quantum states, where combinations of states result in new states, and the importance of phase information, which affects interference patterns.

- **Entanglement:**

Entanglement occurs when two or more particles become interconnected in such a way that the state of one particle is instantly dependent on the state of another, irrespective of the physical distance separating them. This remarkable interconnection can persist even if the particles are separated by vast distances. Quantum entanglement refers to the entwined state of two or more particles, where the measurement of one particle instantly determines the state of the others, regardless of the spatial separation. These particles become correlated in a way that their individual properties are no longer independent.

Entanglement can be created through various processes, such as particle interactions, where two particles are produced together in a way that their properties are interconnected. It can also be generated intentionally in laboratory settings through processes like entanglement swapping. Quantum entanglement has applications in quantum computing, quantum cryptography, and tests of fundamental physics principles. It plays a vital role in the development of quantum technologies.

- **Interference:**

Quantum Interference is a phenomenon in quantum mechanics where the wave-like behavior of quantum particles leads to the superposition of multiple states, causing their probability amplitudes to combine either constructively or destructively. This interference affects the likelihood of measuring specific outcomes when a quantum system is observed. For example, in the double-slit experiment, electrons simultaneously pass through both slits, creating an interference pattern.

When a quantum system can evolve along multiple paths, the probability amplitudes associated with each path can interact with each other. This interaction can lead to two types of interference:

**Constructive interference:** When the amplitudes add up, increasing the probability of certain outcomes.

**Destructive interference:** When the amplitudes cancel each other out, decreasing the probability of other outcomes.

#### MAJOR PROPERTIES OF QUANTUM COMPUTING

Most of the introductory parts of almost all literatures available on quantum computing are physics-centric in the sense that they deeply focus first on theoretical quantum physics and how quantum dynamical systems can be used to perform computations that cannot be performed efficiently on

a classical computer. Such a presentation may mirror the historical way in which quantum computing emerged from the evolving theory of quantum physics, but on the other hand it unnecessarily obscures the abstract computational model implied by quantum theory with the details of quantum mechanics as they apply to physical systems. This kind of approach is analogous to introducing Boolean Algebra in terms of transistors or Computer Programming in terms of the behavior of electrons in semiconductors.

In this section our objective is to introduce quantum computing as an abstract mathematical framework stripped of any connection to the physical world. Now we will highlight eight most fundamental properties that are necessary and sufficient in order to describe the quantum computational model. These properties are tightly coupled with each other, and thus these properties are not independent of each other, so they do not constitute an axiomatic set from which the quantum model is formally defined, but they each capture an aspect of the quantum computing model that distinguishes it from the classical computing [1, 2].

Property(1): The first property of Quantum Computing Model is actually a definition of “What is meant by information in the quantum world?” Specifically the ‘Qubit’ is defined as a generalization of the classical bit as the new unit of information.

Property(2): Quantum Computing Model is a Probabilistic Computational Model.

Property(3): Measurements (Read Operations) in the Quantum Computing Model are destructive in nature.

Property(4): Quantum Computing Computational Space is exponentially much larger than the Classical Computing Computational Space for a fixed size register. An  $n$  – qubit quantum register can simultaneously index  $2^n$ ,  $n$  – bit states, while its classical counterpart can only store the index of one  $n$  – bit state.

Property(5): Except for ‘measurements’, all operations on Qubits must be reversible, because an irreversible operation will cause collapse of a superposition. Virtually all classical logic gates can be efficiently replaced with functionally equivalent reversible quantum gates.

Property(6): Quantum Computing Model offers Intrinsic Parallelism. Because of this property quantum computing models are able to simultaneously transform all the states in a superposition permits some of the quantum computing operations to be performed more efficiently than the best known possible classical alternative.

Property(7): Quantum Information can not be copied, i.e. it is impossible to copy the superposition in one quantum register into another quantum register. In Quantum Computing context, this property is known as ‘No-Cloning Theorem’.

Property(8): Quantum Algorithms or Quantum Registers will always have to be initialized to the ‘0’ State. When the quantum computer is first booted, the quantum register may take an arbitrary quantum state, which is impossible to determine, because one can not determine the state of a register, if it is an unknown state. So to overcome from this side effect, it is desired that upon booting the quantum register has to be placed on a known, pre-determined state. i.e. The architecture of a quantum computer must be such that the initial state will always be the same.

## POSTULATES OF QUANTUM COMPUTING

Postulate (1): Associated to any isolated physical system is a complex vector space with inner product (that is, a Hilbert space) known as the *state space* of the system. The system is completely described by its *density operator*, which is a positive operator  $\rho$  with trace one, acting on the state space of the system. If a quantum system is in the state  $\rho_i$  with probability  $p_i$ , then the density operator for the system is

$$\sum_i p_i \rho_i .$$

Postulate (2): The evolution of a *closed* quantum system is described by a *unitary transformation*. That is, the state  $\rho$  of the system at time  $t_1$  is related to the state  $\rho'$  of the system at time  $t_2$  by a unitary operator  $U$  which depends only on the times  $t_1$  and  $t_2$ ,

$$\rho' = U \rho U^\dagger$$

Postulate (3): Quantum measurements are described by a collection  $\{M_m\}$  of *measurement operators*. These are operators acting on the state space of the system being measured. The index  $m$  refers to the measurement outcomes that may occur in the experiment. If the state of the quantum system is  $\rho$  immediately before the measurement then the probability that result  $m$  occurs is given by:

$$p(m) = \text{tr}(M_m^\dagger M_m \rho)$$

and the state of the system after the measurement is:

$$\frac{M_m \rho M_m^\dagger}{\text{tr}(M_m^\dagger M_m \rho)}$$

The measurement operators satisfy the *completeness equation*,

$$\sum_m M_m^\dagger M_m = I$$

Postulate (4): The state space of a composite physical system is the tensor product of the state spaces of the component physical systems. Moreover, if we have systems numbered 1 through  $n$ , and system number  $i$  is prepared in the state  $\rho_i$ , then the joint state of the total system is  $\rho_1 \otimes \rho_2 \otimes \dots \otimes \rho_n$ .

These reformulations of the fundamental postulates of quantum mechanics in terms of the density operator are, of course, mathematically equivalent to the description in terms of the state vector. Nevertheless, as a way of thinking about quantum mechanics, the density operator approach really shines for two applications: the description of quantum systems whose state is not known, and the description of subsystems of a composite quantum system [2].

## QNN: THE FUSION OF QC AND ANN

A quantum neural network (QNN), a type of artificial neural network, can be built using the principles of quantum information processing. It is somewhat remarkable that in 1982 just as Richard Feynman published his first paper on quantum computation, John Hopfield proposed his model of neural content-addressable memory, which attracted many physicists to the field of artificial neural networks [6].

There are two main reasons to discuss Quantum Neural Networks. One has its origin in arguments for the essential role which quantum processes play in the living brain. A second motivation is the possibility that the field of classical artificial neural networks can be generalized to the quantum domain by eclectic combination of that field with the promising new field of quantum computing.

Both considerations suggest new understanding of mind and brain function as well as new unprecedented abilities in information processing. Here we consider quantum neural networks as the next natural step in the evolution of neuron-computing systems, focusing our attention on artificial rather than biological systems [7].

### ANALOGY BETWEEN QUANTUM COMPUTING & ARTIFICIAL NEURAL NETWORKS

There are many different approaches to what we can call quantum neural networks. Many researchers use their own analogies in establishing a connection between quantum mechanics and neural networks.

The main concepts and a general analogy between these two fields can be summarized below in Table (1) [8, 9]:

**Table (1): Analogy between Quantum Mechanics and Neural Networks**

One should be careful not to consider corresponding concepts in the two columns as analogical – in the table above their order is arbitrary. Indeed, the establishment of such correspondences is a major challenge in the development of a model of quantum neural networks.

To date, quantum ideas have been proposed for the effective realization of classical – rather than neural – computation. The concept of quantum computation may arguably be traced back to the pioneering work of Richard Feynman [10], who examined the role quantum effects would play in the development of future hardware. As hardware speeds continue to increase, hardware scales correspondingly continue to decrease and at some point in the not too distant future, Feynman realized, gates and wires may consist of only a few atoms, and quantum effects will then play a major role in hardware implementation. Feynman concluded that such quantum devices can have significant advantages over classical computational mediums. In 1985 David Deutsch formalized the foundations of quantum computation.

### MERITS OF QNN OVER ANN

It is now known that quantum computing gives us unprecedented possibilities in solving problems beyond the abilities of classical computers. For example Shor’s algorithm gives a polynomial solution (on a quantum computer) for the problem of prime factorization, which is believed to be classically intractable [42]. Also, as previously mentioned, Grover’s algorithm provides super-classical performance in searching an unsorted database.

What of quantum neural networks? Will they give us some advantages unattainable by either traditional von Neumann computation or classical artificial neural networks? Compared to the latter, quantum neural networks will probably have the following advantages [11, 12, 13]:

- Exponential memory capacity
- Higher performance for lower number of hidden neurons
- Faster learning
- Elimination of catastrophic forgetting due to the absence of pattern interference
- Single layer network solution of linearly inseparable problems
- Absence of wires
- Processing speed ( $10^{10}$  bits/s)
- Small scale ( $10^{11}$  neurons/mm)

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- Higher stability and reliability

These potential advantages of quantum neural networks are indeed compelling motivation for their development. However, the more remote future possibilities of QNN may be even more exciting.

### QUANTUM MACHINE LEARNING

Quantum Machine Learning (QML) is the study of quantum algorithms which solve machine learning tasks. The most common use of the term refers to quantum algorithms for machine learning tasks which analyze classical data, sometimes called quantum-enhanced machine learning. QML algorithms use qubits and quantum operations to try to improve the space and time complexity of classical machine learning algorithms, which includes hybrid methods that involve both classical and quantum processing.

Quantum Mechanics	Neural Networks
Superposition (Coherence)	Interconnections (Weights)
Measurement (Decoherence)	Evolution to Attractor
Entanglement	Learning Rule
Unitary Transformations	Gain Function
Wave function	Neuron

The term "Quantum Machine Learning" is sometimes used to refer classical machine learning methods applied to data generated from quantum experiments (i.e. machine learning of quantum systems), such as learning the phase transitions of a quantum system or creating new quantum experiments. QML also extends to a branch of research that explores methodological and structural similarities between certain physical systems and learning systems, in particular neural networks. Furthermore, researchers investigate more abstract notions of learning theory with respect to quantum information, sometimes referred to as "Quantum Learning Theory".

Quantum Computing is the use of quantum- mechanical phenomena like superposition, interference and entanglement to perform computations which are faster and perform better with respect to space and time complexities. Proving themselves to be better than classical computing techniques, quantum computing when used in the field of machine learning gives rise to Quantum Machine Learning [4].

### WHERE CAN WE APPLY QUANTUM MACHINE LEARNING?

- Model classical data on quantum computers, or create novel quantum- inspired classical algorithms for faster computation and better results.
- As the feature space of the problem domain expands, the computations become really expensive for classical computers. Using superposition and other quantum properties, quantum machine learning helps extensively in kernel evaluation and optimization.
- Quantum machine learning also has the capability of mapping the trillions of neurons in our brain and decoding the genetic makeup.
- Supervised learning and adaptive layer-wise learning with the help of quantum classifiers and neural networks.

Although Quantum Machine Learning has proved to have the great computational power and an extremely high level of parallelism, it is still a relatively new concept. While significant progress and research have already been made in this direction, we are yet to tap the true potential of Quantum

Machine Learning to develop new algorithms and discover newer and better solutions to solve the real-world problems like never before.

#### RECENT RESEARCHES IN THE AREA OF QNN

- Analogies between ANN and QNN
- Pattern Classification using a Quantum System
- Role of Entanglement in QNN
- Role of QFT in QNN
- Role of Quantum Teleportation in QNN
- Entangled Neural Networks
- H-Gate Perceptron Model
- Simulation of a Perceptron Model on a Quantum Computer
- Optimizing QNN via Grover's Search
- Pattern Association using QNN
- Training a QNN

#### XI. ADVANTAGES OF QNNS

- An immediate advantage of quantum computing is its potential speed. Qubits can exist synchronously in superposition's of multiple states, so quantum computing can process data in parallel. In contrast, classical computing requires processing each state sequentially. In QNNs, this parallel processing capability is used to accelerate the training and reasoning process of neural networks.
- According to some studies, quantum computing could theoretically achieve an exponential speed increase when solving certain optimization problems. For example, the Shor's algorithm is several orders of magnitude faster than the best classical algorithms on prime factorization problems. This means that in the training of large data sets and complex models, QNNs can significantly reduce computation time and thus improve efficiency. Results show that the Quantum Variational Optimization Algorithm (VQA) is more efficient than the classical algorithm when dealing with complex optimization problems, particularly in image segmentation. This efficiency boost is important for deep learning tasks that require a lot of computing resources.
- Another significant advantage of quantum computing is its energy efficiency. The parallel processing capabilities of quantum computing make it consume much less energy than classical computing for the same computational task. For example, quantum circuits can perform complex matrix operations with low energy consumption, which is particularly important in large-scale neural network training. The high energy efficiency of quantum computing not only helps to reduce energy consumption but also can significantly reduce computing costs.
- High-dimensional data processing is a key challenge in modern machine learning and data science. When dealing with high-dimensional data, traditional neural networks often face the problem of dimensional disaster, that is, the computational complexity increases exponentially with the increase of data dimensions. Quantum computing can process data more efficiently in high-dimensional space.
- The superposition property of quantum states allows qubits to represent multiple states simultaneously, allowing for parallel computation in high-dimensional Spaces. For example, in quantum states, a system of  $n$  qubits can represent  $2^n$  states. This capability allows QNNs to significantly reduce computation time when working with high-dimensional data.
- Another advantage of quantum computing when dealing with high-dimensional data is its ability to perform dimensionality reduction and feature selection operations

efficiently. The optimal feature subset can be quickly found in the high-dimensional space, thus improving the efficiency and accuracy of data analysis. For example, techniques such as quantum state projection and quantum Fourier transform (QFT) are widely used in quantum feature selection.

- Quantum parallelism allows quantum neural networks to inspect multiple possible solutions simultaneously, resulting in significantly improved computational efficiency. Quantum parallelism is achieved through the superposition of qubits, allowing multiple computation paths to occur simultaneously. This property is particularly important when training and reasoning large neural networks.
- Specifically, quantum parallelism can improve the performance of QNNs at multiple levels. For example, during training, quantum gradient descent algorithms can compute multiple gradients simultaneously, thus speeding up the convergence process. In reasoning, quantum parallelism can speed up the prediction process and improve real-time processing power.
- Quantum parallelism also plays an important role in optimization algorithms. Algorithms such as quantum particle swarm optimization and quantum genetics, for example, greatly improve optimization efficiency and accuracy by exploring multiple parallel solution Spaces.

#### XII. BROAD OUTLINES OF SOME NOTABLE WORK IN THE AREA OF QNN

**Alexander A. Ezhov and Dan Ventura, et al. [3]**, This research paper provides a brief review of Quantum Neural Network's (QNN's). The authors raise the importance of QNN over the Classical Artificial Neural Network's (ANN's) on the basis of two reasons: First is that, It is a well known fact that quantum processes play the significant role in living brain. Second, it has been strongly believed that ANN's can be generalized to quantum domain by eclectic combination of it with the most promising and emerging computing paradigm i.e. Quantum Computing (QC).

Since it is a pure review paper the authors didn't propose any new kind of QNN developed by themselves, but many analogies, implementation issues, alternatives, and benefits regarding portability between ANN and QC in order to develop more efficient QNN have been discussed such as- Role of Superposition (Coherence), Measurement (Decoherence), Entanglement, and Unitary Operations etc. Information Storage and Recall are two of the main functions of brain, therefore authors have highlighted their own already published work on Quantum Associative Memory (QAM) which is also a Quantum inspired ANN and also showed analogy between Classical ANN and QAM.

Since ANN's are not only capable of processing local information in parallel and distributed manner but also capable of propagating information between layers via neurons so from this point of view there are two short comings of this review paper- First there is no discussion done on the use of Quantum Teleportation in QNN, which is one of the most powerful phenomenon of quantum systems for communicating unknown quantum state / information between source neuron & destination neuron. Second, No discussion is done on the use of Grover's Quantum Search Algorithm in the development of QNN's. So on the basis of above mentioned rich information, this review paper is informative and highlights the potential use of QNN over the Classical ANN.

**Dan Ventura, et al. [14]**, This research paper mainly highlights the vital use of the three fundamental approaches for learning the pattern classification of binary patterns through Quantum Neural Networks on the basis of representation of these patterns via three different quantum superposition techniques: Inclusion, Exclusion and Phase Inversion.

- **Inclusion** represents each of the labeled points in learning the set T as a basis state in the superposition with nonzero coefficient and Basis States corresponding to points not in the learning set T have zero coefficients.
- **Exclusion** is the opposite approach, including each point not in the learning set T with a non zero coefficient, while those points in the learning set T have zero coefficients.
- **Phase Inversion** includes all basis states in superposition with coefficients of equal amplitude but with differing phases based on membership in the learning set T.

Hence this research paper present empirical results comparing three distinct approaches to quantum pattern classification. These results favor the inclusion method based on the fact that the inclusion method appears to produce the best conditional probability of correct classification. It should be emphasized that, however these results are not yet conclusive and that they apply only to the case where Grover's Search is involved- Other less general approaches may be more useful in pattern classification. If probability of irrelevant classification is considered, the exclusion method appears to exhibit the best performance, and it may be interesting to consider an inclusive / exclusive hybrid approach.

**Dan Ventura, et al. [15]**, This research paper mainly highlights the utility of 'Entanglement' in Quantum Neural Computing. Entanglement is the most powerful feature / property of Quantum Systems, but unfortunately scientist community couldn't fully leverage the advantages of it because they believe that Entanglement is still very less understood. Although 'Entanglement' is a pure quantum phenomenon, but in spite of that its versatile features make its remarkable importance in the area of Quantum Information Processing and Quantum Neural Networks which is a sub domain of Quantum Machine Learning.

In this research paper a sufficient linear algebra based calculations shown in order to reveal the structure of the Quantum State and Density Matrix formulation for the design and analysis of Generalized Quantum Operators for solving Two Qubit Boolean Functions via QNN. Also a very state forward analogy discussed between classical and quantum versions of the neural networks. This research paper presents a fundamental level framework for migrating from Classical ANN to QNN on the basis of 'Entanglement'. The phenomenon of entanglement in Quantum Systems can be viewed as playing a role similar to that of weighted connections in a classical neural network, producing correlations between different parts of the system. So at last, this research paper suggests that quantum computational systems that make use of entangled states have the potential functionality of QNN. It follows that just as quantum computation is provably superior to classical computation for some problems, it is conceivable that if a suitable analogy is

chosen on the basis of the nature of problem / function, then QNN may outperform than their classical counterparts.

**Li Weigang, et al. [16]**, This research paper is mainly focused on the kind of Quantum Neural Network's that use the most powerful phenomenon of Quantum Systems – i.e. 'Entanglement', and hence known as Entangled Neural Network's. These Entangled Neural Network's also use Quantum Teleportation and Grover's Search in an intelligent manner in order to take conscious decisions along with exploiting the inherent quantum parallelism.

The research paper also highlight the fact that although the unknown quantum information can be teleported from neuron A to neuron B (with the price of destroying the original quantum information), but nothing is learned during this transmission. So in order to make this Quantum Teleportation useful from the point of view of neural networks and learning capability- ENN's have been proposed.

This research paper projects and frames a feasible and flexible approach in order to develop Entangled Neural Networks (ENN's) for solving the practical problems that processes the input instances in very large extent. At the end of the discussion the author also highlight some of the notable properties of ENN's whose efficient utilization may open new doors for future research in the area of Quantum Machine Learning (QML). These key properties are:

- Non-repeated learning manner- Since Quantum Computation takes place only within the ENN and after the measurement of the reconstructed state in Neuron B (Bob), the information is transmitted to the next unit (ENN). Hence this approach avoids the repeated learning strategy of classical ANN and reduces the Decoherence problem in significant manner.
- Learning and learning law in ENN- In an ENN, a Quantum State always collapses in an intelligent manner i.e. to get an intelligent decision. Learning in ENN is realized through the Decision Key and Measurement Key of every unit (ENN). More Quantum suitable learning laws will definitely raise the applicability of ENN.
- Possible state generation and combination- Efficient utilization of quantum parallelism requires methods that generate the quantum states in a large extent. The most important aspect is to follow 'Conscious Decision Hypothesis'
- Multi-party communication- Monogamy of Entanglement is a well known phenomenon in quantum computing and although this discussion is mainly concerned with teleportation case, i.e. two-party communication. But generic case for ENN's, multi-party communication should be considered.
- ENN's simulation- In order to develop new ENN's based models for Quantum Machine Learning, an efficient ENN's simulator should be developed.

**Bob Ricks and Dan Ventura, et al. [17]**, This research paper proposes a straightforward way of designing a prototype of Quantum Neural Network. Although a wide variety of prototypes for QNN's have already been proposed by other

authors. Several researchers over the development of QNN have shown that QNN's may be trained in many ways. The idea is simple as we have used in Classical ANN i.e. to minimize the error during each iteration by just updating weights and bias till the neural network becomes stable and performance becomes optimized. Quantum State in QNN depends on the type of QNN and of course on the one or several properties Quantum System that plays major role behind the development of a particular QNN. The purpose of the development of QNN may be either Simulation of Classical ANN into the Quantum Domain or it may be of taking advantages of Quantum Computation over the Classical Computation in order to develop a more efficient and powerful QNN rather than Classical ANN. For the development of an efficient QNN, there are many distinct features in which some features are desirable, mandatory, optional and restricted. Author used generalized version of Grover's Search through the possible weight vectors for one which is consistent with the training data because it gives a good polynomial speed-up to the exponential task of finding a solution to QNN.

Therefore this method of training a QNN entangles a minimum number of qubits to classify the entire training set. The algorithm is able to search for solutions that cover an arbitrary percentage of the training set. This could be very useful for problems which require a very accurate solution. The drawback is that it is an exponential algorithm, even with the significant quantum decrease in complexity, and resolution of these issues have already discussed in above section.

### XIII. APPLICATIONS

- Quantum Neural Networks (QNNs) represent a significant advancement in artificial intelligence by integrating quantum computing principles with classical neural network frameworks. This synthesis offers potential improvements across various domains, including image recognition, natural language processing (NLP), financial forecasting, and bioinformatics.
- Quantum Convolution Neural Networks (QCNNs) leverage quantum computing's parallelism to process image features simultaneously, enhancing accuracy and reducing computational demands. Study have shown QCNNs' superior performance in tasks like CT scan image classification, demonstrating higher accuracy than classical CNNs.
- In NLP, QNNs utilize quantum superposition and entanglement to manage complex linguistic relationships, benefiting tasks such as sentiment analysis and machine translation. QNNs improve processing speed and accuracy, especially with large datasets.
- QNNs' capability to handle extensive financial data enables more accurate market trend predictions and risk management and efficiency of QNNs in financial forecasting, with notable improvements over classical approaches.
- In bioinformatics, QNNs enhance the analysis of biological data, such as genetic sequences. The study by Tao et al. introduced Quantum Bound, a hybrid neural network that integrates classical and quantum elements, optimizing the analysis of complex biological datasets.

### XIV. CONCLUSION:

Quantum Neural Networks (QNNs) represent a significant leap in the fusion of quantum computing and artificial intelligence, offering unparalleled computational capabilities. By leveraging quantum superposition and entanglement,

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QNNs can execute complex calculations and data processing tasks more efficiently than classical neural networks. This integration enhances the accuracy and speed of large-scale data analysis, making QNNs valuable for applications in finance, healthcare, and other fields.

The development and implementation of QNNs require interdisciplinary collaboration across quantum physics, computer science, and domain-specific expertise. Educational programs and industry-academia partnerships are vital for advancing QNN research and ensuring practical application. Promoting open science and data sharing can further accelerate innovation and prevent redundant efforts.

Future directions for QNNs include the development of hybrid quantum-classical systems, improved quantum hardware, and new quantum algorithms. These efforts aim to maximize performance and reliability. Additionally, addressing the ethical and societal implications of QNNs, such as data privacy and job displacement, is crucial for their responsible deployment.

In summary, the potential of QNNs is immense, promising significant advancements in computing and various application domains. Overcoming technical challenges and fostering interdisciplinary cooperation are key to realizing their full potential [43].

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