2021 12th International Conference on Information, Intelligence, Systems & Applications (IISA) | 978-1-6654-0032-9/21/$31.00 ©2021 IEEE | DOI: 10.1109/IISA52424.2021.9555570

Quantum Information Processing Algorithms with Emphasis on Machine Learning

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***Abstract*— Quantum Computing (QC) promises to elevate computing speed by an estimated 100 million times. Several applications, including signal processing, machine learning, big data, communication, and cryptography, will benefit from quantum computing. This paper provides a brief survey of quantum information processing algorithms with an emphasis on machine learning. We begin first, covering with an introduction to quantum systems. Then we describe briefly the fundamental blocks and principles of quantum mechanics, and we present several related QC concepts such as qubits, correlation, and entanglement. We also present simulations and tools for the quantum implementation of select algorithms. We cover specifically Quantum Machine Learning (QML) and demonstrate simple implementations. The paper also describes current research and provides an extensive bibliography for further reading.**

Keywords—Quantum Computing, qubit, entanglement, machine learning, signal processing, deep learning.

I. Introduction

Quantum computing (QC) [1]–[10] promises to revolutionize information processing by providing efficient real-time solutions to computationally complex problems. For example, non-deterministic polynomial-time NP-hard problems [11] are believed to be well within the anticipated capabilities of quantum computers. The importance of QC is evidenced by the heavy global investments in quantum hardware and tools by government labs and private organizations [12]. This interest in QC stems from emerging opportunities and threats:

- Opportunities to invent and find solutions to problems beyond the reach of classical computing, which may catapult humanity into a sustainable and scalable future, with rich applications and robust markets; and
- Threats in that QC speed can be used to suppress rather than elevate humanity by breaking security protocols, hacking information systems, and realizing malevolent Artificial Intelligent systems.

QC will address needs in several application areas, including engineering, business, defense, health, and sustainability. More specifically, massive high-speed QC will impact several fields, including signal processing [9], [13], [14], machine learning [15]–[21], big data [22]–[26], communications [27], encryption [28], [29], sensors [30], [31], genomic analysis [32], the Internet of Things (IoT) [33], pattern matching [34], and solutions of massive linear and non-linear systems of equations [35]. We are already witnessing quantum-inspired applications benefiting from exponential speed over classical algorithms such as linear algebra with sublinear complexity [36], [37]. Despite projections on processing speed, the greatest challenge is that the technology is still in the infancy stages, and quantum computing suffers from sensitivities to vibration, noise, and temperature. Hardware size, errors, and incredible costs are huge challenges in QC. At this point, only a few computing facilities are available, and high precision quantum computing is a great challenge.

Unlike classical computing that relies on binary arithmetic and microprocessors that are fundamentally stable, QC (Fig. 1) relies on quantum bits or *qubits*, which are inherently fragile. , Qubit processing enables exponential growth in computing capabilities. For example, a two-qubit processor enables four simultaneous computations by leveraging *superposition* and *entanglement*. Similarly, a three-qubit processor facilitates eight calculations, etc.

Quantum computing is ultimately based on quantum mechanics [38]–[45], which is the theory that governs the interaction of quantum objects (electrons, photons, etc.). These interactions define the way that systems that consist of quantum objects evolve. In addition, they define how observable information may be extracted through measurement. While the theory of quantum mechanics (QM) is essential, it will not be the focus of this paper. Instead, we attempt to highlight the connections between QM and Quantum Information Processing (QIP). For example, entanglement is a QM correlation that allows qubits to exist in non-separable and non-local states. This in turn, enables qubits to be teleported (transferred) over distance and quantum gate operations to be performed at high speed.

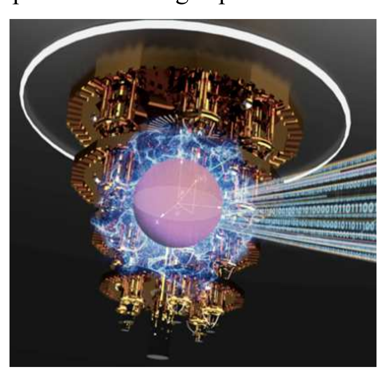

Fig. 1. Quantum Computing. (Image from SenSIP [46])

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Quantum information [47] is defined based on the state of the quantum system and qubits generally have two exclusive states, namely, state *0* and state *1*. However, based on the principles of quantum mechanics, qubit states are described in terms of probability. We can describe qubit processing and its relation to QC in terms of quantum gates and circuits. The quantum circuits are designed to realize quantum computations which are implemented on either a quantum simulator or an actual quantum computer.

Quantum Information theory describes the state of a quantum system and involves concepts such as entropy and probabilistic analysis [48]. The association of logical states with quantum systems was introduced by Von Neumann and Birkhoff [49]. In Fig. 2, we attempt to taxonomize quantum concepts and applications, including the systems and algorithms they enable.

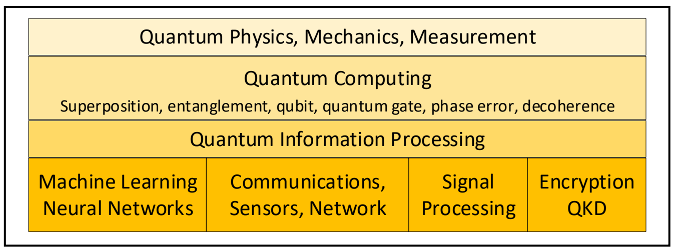

Fig. 2. Taxonomy and organization of quantum theory, process, algorithms, and applications with the focus on quantum information processing.

Research demonstrated that quantum algorithms are beneficial in the communication field [50]. The utility of QIP in communications typically involves superdense coding and quantum protocols. Research in quantum communication and networking has been reported in [51], [52]. The increase in speed and information rate is essential for future secure communications and encryption. The authors of [53], [54] described entanglement assisted communications and explored the potential for improved capacity of quantum relative to classical communications. In addition, the potential of distributed quantum sensing was explored with experiments in [55] and quantum sensing protocols were reported in [56].

We note, for example, that Quantum Key Distribution (QKD) [57] is a unique method to authenticate communications between two parties.

As mentioned before, QIP and QC will impact several areas, including machine learning [15]–[21], [58]–[62], signal processing [9], [13], [14], and big data [25], [63]. Descriptions of multidisciplinary QC applications are described in [64], [65] and several quantum hardware and simulation systems have been developed. Some of the implementation platforms that have emerged recently for quantum-based algorithms and applications include: the Noisy Intermediate Scale Quantum (NISQ) technology [6], [66], [67] that currently enables quantum implementations. Systems from Honeywell [68], IBMQ, IonQ [69], and Xanadu [70] are currently available NISQ-era quantum systems for QC.

We attempt in this paper to briefly survey the QIP field and provide extensive bibliography in various QC application fields with the focus on machine learning. We organize the paper as follows. Section II summarizes the basics of quantum mechanics, Section III presents quantum computing principles, and Section IV describes quantum information processing related research and bibliography. Section V presents applications in communications, and section VI describes machine learning implementations. Section VII provides additional references for further reading and VIII gives the conclusions.

II. Quantum Physics, Mechanics and Measurement

As mentioned earlier, quantum mechanics describe properties of nature at the scale of atoms and subatomic particles. At the quantum level, we can study the impact of QM on computing using *superposition*, *quantum measurement*, and *entanglement*. An introduction to quantum mechanics is given by Miller [42] and Dommelen [41]. We focus here first on quantum mechanics and highlight relations to QIP, and quantum enabled algorithms. We begin by introducing some of the necessary principles of quantum terminologies below.

A. Quantum state

In quantum information theory, qubits such as classical bits have two exclusive states. These are defined as state *0* and state *1*. The laws of quantum mechanics treat these differently; instead of looking at a discrete value, we describe these states in terms of probability because of uncertainties and noise in QC. We provide more information below.

B. Measurement

To determine the state of a qubit, we need to measure the system. The purpose of *quantum measurement* is to learn about the qubit's state. If we consider an atom or a photon, we can characterize its behavior in terms of its position and/or spin. The qubit's quantum state is in a superposition state until we take a *quantum measurement*. Once this measurement is made, it collapses the quantum state and transitions it to a component state. The component state is what is measured to get the new state. Quantum computing and qubit-based computations and error control require probabilistic analysis and matrix theory. Some of the mathematical., statistical, and geometric foundations are presented in the next section.

III. Quantum Computing

A. Mathematical Representation

The quantum system uses a finite-dimensional vector to represent its state. These vectors represent the *superposition* of the physical variable. We introduce the mathematical representation, a notation called the *bra-ket* or *braket,* to represent the vector and its matrix notation. The "*ket*" is the vector that represents the quantum state, described by the notation $|v\rangle$, i.e.

$$|v\rangle \rightarrow \begin{bmatrix} v_0 \\ v_1 \end{bmatrix}. \tag{1}$$

We note the following regarding the notation in (1). The "*bra*" is the conjugate transpose of the "*ket,*" described by the notation $\langle v|$. We define the combination of these notations as the inner product known as "*braket,*" $\langle v|w\rangle = |v\rangle . |w\rangle$.

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B. The Quantum Bit (qubit)

A qubit is the smallest unit for quantum information and the Bloch sphere can describe the qubit position. According to Lierta [71], the Bloch sphere can represent the position of the qubit, as shown in Fig. 3. The Bloch sphere allows the qubit to move using a sequence of rotations around the three principal axes (X, Y, Z) in the 3D space.

We present two states described using the *ket* vector notation $|0\rangle$ and $|1\rangle$. As shown in Fig. 3, they exist on the opposite side of the sphere. The state $|\psi\rangle$ is the *superposition* described in terms of the vectors $|0\rangle$ and $|1\rangle$. We define this as $|\psi\rangle = \alpha|0\rangle + \beta|1\rangle = \cos(\theta/2)|0\rangle + \sin(\theta/2)e^{i\varphi}|1\rangle$. This is a unit vector from the origin to the point on the unit sphere with spherical coordinates (θ, φ).

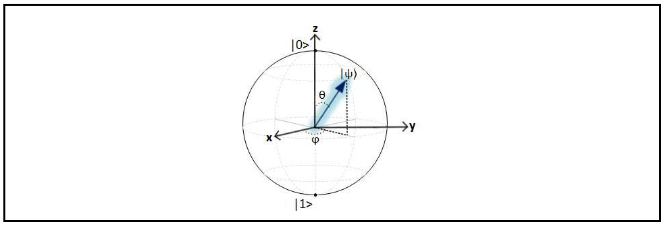

Fig. 3. Bloch sphere [71] representation of the vector, θ, φ on the sphere.

The quantum states determine the probability of measuring a *0* or a *1* when measuring the qubit. Using the *ket* notation, we write *0* and *1* as

$$|0\rangle = \begin{bmatrix}1\\0\end{bmatrix} \text{ and } |1\rangle = \begin{bmatrix}0\\1\end{bmatrix}. \tag{2}$$

We can also define a tensor product, denoted as $\otimes$, to combine the quantum states. This combination is a two-qubit system called a quantum register [72].

$$|\mathrm{ab}\rangle = |a\rangle \otimes |b\rangle \tag{3}$$

Now that we have a two-qubit system, we can see four possibilities $\{|00\rangle, |01\rangle, |10\rangle, |11\rangle\}$. First, consider $|00\rangle$; the first qubit is state *0*, the second is also state *0*. The equal value represents the correlation between the two qubits; when we measure the first state *0*, the other is state *0*. We can see that this applies to $|11\rangle$. This *correlation* allows for the first state to determine the other state [35], [36] ($|00\rangle$ and $|11\rangle$). The measurement of the first qubit provides knowledge of the second qubit because it is 100% correlated.

Further derivation defines the states of the *entangled* values as $\frac{1}{\sqrt{2}}(00\rangle + |11\rangle)$ and $\frac{1}{\sqrt{2}}(01\rangle + |10\rangle)$. This representation is called the Bell State [47], [73]. The capability to take one measurement and obtain two bits of information is the strength of QC. The other two states $|01\rangle$ and $|10\rangle$ still exist; therefore, the probability of obtaining the second entangled bit is 50%. These are the terms of probability mentioned earlier.

C. Quantum Gate

As we stated earlier, the qubits can be represented in terms of rotations around the Bloch sphere. To describe this movement, we introduce the term *quantum gate*. The quantum gate [8] is a complex square matrix which is also a unitary matrix. We express a single-qubit quantum gate $\mathfrak{U}$ operating on the qubit $|\psi_1\rangle$, it produces a rotated qubit $\mathfrak{U}|\psi_1\rangle = |\psi_2\rangle$. The new quantum state is $|\psi_2\rangle$. This is the vector movement of the qubit around the sphere to the new state. We can observe the Bloch sphere representation of the gate applied to the qubit in Fig. 4.

The different unitary matrices are defined as a *Pauli* Matrix [74]. As we add additional gates, we can move the qubits around the sphere and form what is called a *quantum circuit* [75], [76]. The gates associated with different *Pauli* matrices and their roots can help us understand how to build quantum circuits. These gates are also referred to as *Pauli* gates.

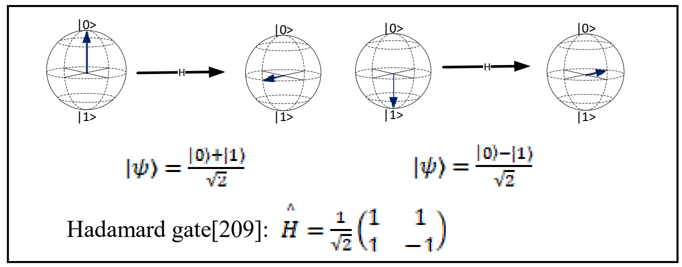

Fig. 4. The application of a Hadamard matrix to a qubit is shown in terms of a Bloch sphere.

D. Quantum Circuit

We describe a computation of *quantum gates* through a *quantum circuit*. As seen in Fig. 5, the circuit is a sequence of quantum gates and measurements. The symbols *H* and *Ry* are the representation of the quantum gates. The measurement shows that both qubits, q_0 and q_1, are measured.

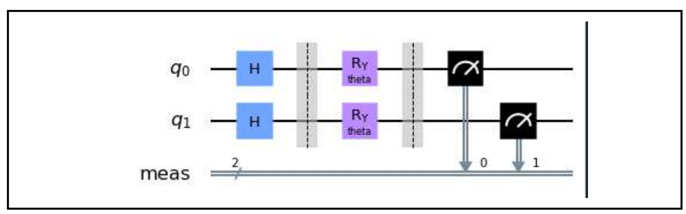

Fig. 5. The quantum circuit using Qiskit [77].

E. Quantum Error Correction

Quantum errors arise mainly because of uncertainties in coherence and noise [78]. Quantum error correction is based on a combination of quantum mechanics theory and error-correcting codes. As in the case of classical computing and communications error correction, redundancy [79] is often part of the error correction algorithm strategy.

Two types of errors can be described for qubits, namely phase errors and bit errors. Bit errors are similar to the classical definition, i.e., when the expected bit is not received correctly. Phase errors occur when the qubit state picks up a phase factor. These errors are significant because the state is no longer the same, and the angle φ (Fig. 3) can take on any value. Active research is devoted to increasing the probability of obtaining

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the correct bits using detection and estimation methods for correction [80]. We note that several studies have addressed quantum error correction [78]–[85] and parity checks [86], [87].

IV. Quantum Information Processing

The field of quantum information processing addresses information and computation aspects of quantum computing based on the laws of quantum mechanics. Research on applications of QIP includes Quantum Machine Learning (QML) [15]–[19], Quantum Neural Networks (QNNs) [18], [88]–[97], Quantum Signal Processing (QSP) [9], [14], [98], Quantum Cryptography (QCrypto) [28], [81], [99]–[103], Big Data Processing [63], Flexible Representation of Quantum Audio (FRQA) [104], [105] and Error Correction [78]–[85]. In the sections that follow, we discuss some of these applications and provide references.

A. Quantum Algorithms

The term quantum algorithms are used here to describe a collection of algorithms and their QC implementations. These algorithms are to solve unsolvable problems using classical algorithms. The quantum algorithms [106] improve efficiency on NP-hard problems, optimizing search algorithms and a more efficient transform. It has been demonstrated [107]–[109] that quantum benefits from various levels of computational speed improvement relative to equivalent classical algorithms [110], [111]. We describe next some of these algorithms and their potential for speed improvement.

Starting with a quantum oracle, we note that a significant speed-up of the oracle calls for a system. For example, a domain with a size N; a classical system will use N calls to describe all N bits. On the other hand, a quantum computer may perform with high probability using only $\frac{N}{2}+\sqrt{N}$ calls.

<ins>Quantum Fourier Transforms (QFT)</ins> is the linear transformation of qubits and its realization is based on a quantum circuit. QFT is used for factoring and computing the discrete logarithm. Additionally, QFT can be used to determine quantum phase estimation by determining the eigenvalue of qubits that were rotated using the previously mentioned Pauli matrices unitary operators [112]–[115].

<ins>Amplitude Amplification (AA)</ins> [116]–[119] is generally based on Grover's search algorithm [120] and was brought to the front by Brassard and Hoyer [121]. AA gave rise to several quantum algorithms and was shown to have quadratic speed benefits over classical algorithms.

<ins>Quantum Walk (QW)</ins> [122]–[124] is the counterpart of the classical random walk. Quantum walk has shown exponential or polynomial speed-up over classical algorithms [125]. Quantum walk can be used to analyze complex networks and may be used to solve problems in cryptography.

B. Quantum Systems

Earlier, we used the phrase *quantum system*. Here we define a quantum system as the environment where a quantum algorithm (for QIP) can be developed and tested. There are several descriptions of quantum computing systems [126]; however, we note here, specifically environments useful to quantum algorithm developers. Access to actual quantum computers with modest capabilities is available on a limited basis to academia [127] on a small or no-cost basis. High-resolution Qubit machines, though they are quite expensive to access at this time.

Regarding implementation, we note that quantum algorithms can also run on quantum annealing systems [128], [129]. These systems are essential for solving optimization problems, as they provide a more significant number of qubits than current NISQ-era systems. Similar to NISQ-era computers, these systems also require some cost to access.

Quantum simulators [130] can simulate a QC but on classical computing systems. For quantum algorithm research and development, the use of quantum simulators can provide insight into specific quantum implementations. Simulators enable algorithm developers to perform validation on their local machines.

V. Quantum Communications

We begin our discussion in communication by starting with Quantum Signal Processing (QSP) [14]. We present and cite some of the solutions in frame theory, quantization, and wireless communication systems. We also find current research for sampling methods to detect parameter estimation and covariance shaping [105]. When considering a QSP system, we also study the phase state as an essential means to carry the information for this system [131]. There is also a body of work in radio communication [132] and we note that these types of systems can also leverage quantum technology by using Rydberg atoms [133]–[135] for higher sensitivity [136]. In addition, phase estimation processes [131] are helpful in retrieving information at the quantum level. In terms of quantum communications [50] and networking, we note again security and cryptography [100] and quantum key distribution [57], [137].

VI. Quantum Machine Learning

As mentioned before, we focus on QML systems and begin with a brief introduction along with a simple implementation of a hybrid quantum-classical QML system.

A. Brief Introduction

As with traditional machine learning [138]–[140], QML algorithms studies cover supervised and unsupervised methods for classification and clustering [141]–[143]. Unsupervised QML has the potential for improved speed by performing tasks simultaneously and leveraging quantum superposition. The distances to all the centroids can then be computed simultaneously.

Some core QML algorithms appeared in the literature as follows: k-nearest neighbor [142], [144], k-means clustering [143], and decision tree [59]. To explore the speed improvement of one of the algorithms, we start with the standard method for solving k-means [145] (Lloyd's algorithm). The classical estimation of the distance to the centroids in the N-dimensional space takes $O(N)$ cycles. We also know that each step of the classical algorithm takes time $O(M^2N)$. However, when we examine the quantum

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implementation of Lloyd's algorithm, we find that this takes $O(M\log(MN))$ [142].

B. QML Example

We present below a method to build a quantum machine learning algorithm. We use Qiskit [77] as the quantum programming toolkit. We design our system using four steps described by Schuld [75], namely: State Preparation, Model Circuit, Measurement, and Post Processing.

The State Preparation step (Fig. 6) is used to apply various strategies to encode the input vectors into n-qubits. We follow the procedure in [75], where we use amplitude encoding on the input vector. The input map into higher dimensional space can apply a feature map by preparing copies of d to the state. The amplitude encoding with $N = 2$ and $d = 2$ without any preprocessing can be mapped with the feature vector $(x_1, x_2)^T$, where N is used to describe a binary classification task on an N-dimensional real input.

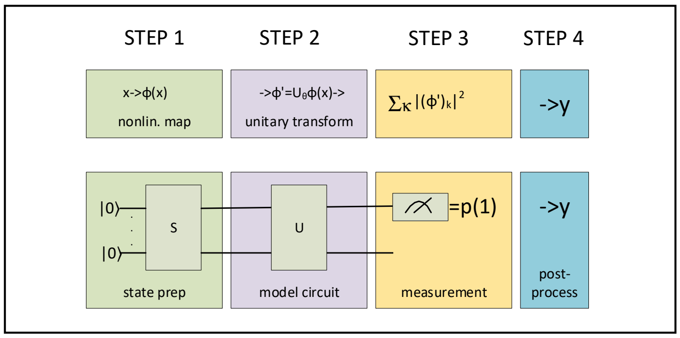

Fig. 6. Circuit-centric quantum classifier with four steps [75].

The Model Circuit step in Fig. 6 maps the vector to another vector $\varphi' = U_\theta \varphi(x)$ by a unitary operation U_θ. In this stage, the unitary U is decomposed into $U = U_L \ldots U_\ell \ldots U_1$, where each U_ℓ is a single or two-qubit quantum gate. The research in [75] further restricts and simplifies the gate by the "elementary parametrized gate set." We further create a new qubit gate G as a 2x2 unitary gate. This advantage is to using angles instead of parameterization with the Pauli matrix.

The measurement and post-processing steps shown in Fig. 6. allow us to determine the classification of the input data.

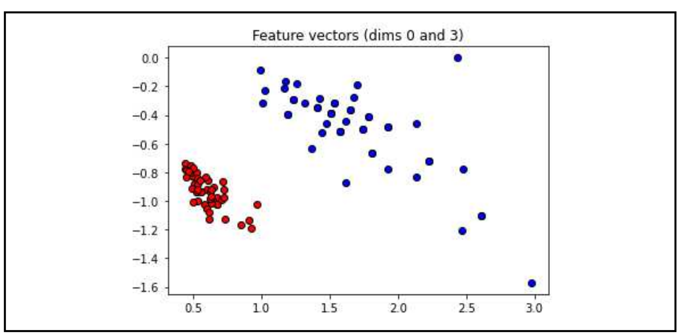

Fig. 7. Iris data set looking at only two classifier data (versicolor, virginica). Using the first two features for classification.

Taking an Iris dataset, we prepare the dataset. We begin by normalizing the data set and apply some padding. This transforms the data into feature vectors (Fig. 7). The feature vectors help with the state preparation of the data set. The quantum circuit used for this system is a 2-qubit system for only two feature sets. This allows for the quantum simulation to run in a more reasonable time.

Running the hybrid quantum-classical model on a quantum simulator, we see the following classification results.

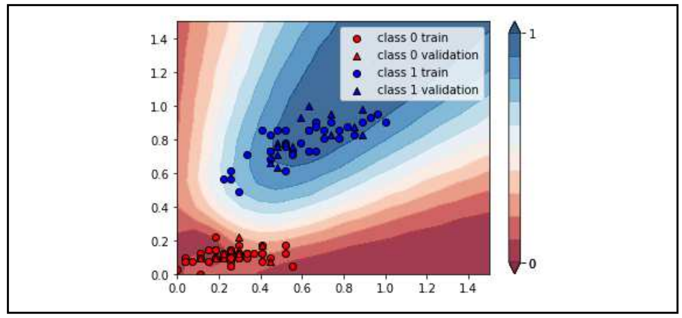

Fig. 8. Decision region plot generated from Qiskit Training and validation used to classify a simplified Iris dataset, using only two classes (versicolor, virginica).

The quantum circuit (software based on [146]) uses the qubits and attempts to run through the Hadamard gate. The dataset currently used is a modified Iris (class 1 & class 2) dataset. This allows for a reasonable simulation and computation time on a classical computer. We run the gradient descent algorithm to determine the weights needed for NN training. We then start with evaluating the cost of the parameter configuration θ and the bias b, for the least-squares minimization process. Begin with a training set $D = \{(x^1, y^1), \ldots, (x^M, y^M)\}$. We can look at the cost as

$$C(\theta, b, D) = \frac{1}{2}\sum_{m=1}^{M} |\pi(x^m; \theta, b) - y^m|^2 \quad (5)$$

where π in the model, $\pi(x; \theta, b) = p(q_0 = 1, x, \theta) + b$, is the continuous output. We then define

$$(q_0 = 1, x, \theta) = \sum_{k=2^{n-1}+1}^{2^n} |(U_\theta \varphi(x))_k|^2 \quad (6)$$

whereafter the execution of the quantum circuit $U_\theta \varphi(x)$, we have the probability of "state 1".

C. Example Result

We run through gradient descent updates with step size μ. We demonstrate the detection results in Fig. 8, which shows that the hybrid quantum-classical can run with quantum simulators on a classical computer. The results of this QNN model used a smaller feature set but demonstrated the implementation/simulation approach for a classification problem.

D. Additional Examples

In [147], we presented preliminary work with QNN parameter estimation. Due to limited access to an actual quantum

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computer, we developed and ran the algorithm on a quantum simulator. The design was tested with actual data and validated using different number of qubits (2, 3, 4) and different epoch (5, 10, 100) lengths. At this time, the accuracy of the QNN is 93%, with the confusion matrix shown in Fig. 9.

VII. Furher Reading

The following table has a collection of citations for different methods and applications for further reading.

TABLE I. Additional References For Quantum Systems

Description	Reference
Quantum Mechanics	[38]–[45]
Quantum Circuit Development	[75], [76]
Quantum Computing	[1], [2], [148], [3]–[10]
NISQ/Quantum Processors	[6], [66], [67], [149]
Quantum Information Processing	[150]–[155]
Quantum Signal Processing	[9], [14], [98]
Quantum Audio and Language Processing	[104], [105], [156]–[160]
Quantum Cyrptography/ Encrption	[28], [81], [99], [102], [103], [161]
Quantum Machine Learning	[15]–[21], [51], [162]
Quantum Neural Networks	[18], [88], [163], [164], [89]–[94], [96], [97]
Quantum Big Data/Finance	[22]–[26]
Quantum Communication, Network and Internet	[17], [27], [50], [165]–[171]
Quantum Estimation, Detection, and Control	[117], [172]–[175]
Quantum Error Control	[82]–[85], [176]
Quantum Radar	[177], [178]
Quantum Solar Energy Applications	[147], [179]
Quantum Sensor Networks	[55], [180]–[182]
Quantum Chemistry & Biology	[183], [184]
Quantum Principal Components and Eigenanalysis	[56], [185]
Quantum Imaging	[186]–[189]
Quantum Parity Check Codes	[86], [87]
Quantum Medical Applications	[190], [191]
Quantum Information Theory	[192], [193]
Quantum Information Hardware	[194]–[196]
Denoising & Decoherence	[45], [81], [98], [197]
SDK OpenQasm	[198]
SDK Microsoft's Q#	[199], [200]
SDK IBM's Qiskit	[73], [77], [200]–[204]
SDK Google's Cirq	[205]
Amazon's Braket	[206]
Quantum scalability	[207], [208]

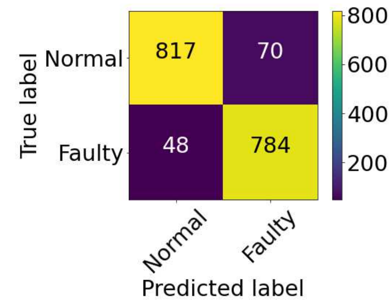

Fig. 9. Confusion matrix of the hybrid QNN [147].

VIII. Conclusion

This survey provided a brief introduction to quantum information processing technologies, emphasizing quantum machine learning implementations. The paper started with an introduction to the basics of quantum systems. It then continued with descriptions of qubit representations along with the relevant mathematics. Certain aspects of algorithm implementation of quantum computers were presented. Machine learning simulations were presented along with citations of work published by several industry government and academic research laboratories. In that context, we examined and provided a simple example of using a quantum circuit for an ML classification problem.

Regardless of the enormous opportunities in this area, open problems remain. The sensitivity of computation to quantum-related error is a major challenge. In addition, there are tradeoffs between qubit precision and quantum noise that need to be addressed and experts call for building systems with qubit "redundancy " – often 10s or 100s of thousands of qubits which are highly complex to design and control.

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