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Understanding Basic Principles of Qubits in Quantum Computing

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Abstract: Normal computer tends to use binary bits which are representable with 0 and 1 which 0 indicates low and 1 represents high. 0 and 1 cannot simultaneously exist in single gate in normal digital computer. But in quantum computer its different, in a quantum computer, 0 and 1 can indeed coexist at the same time within a single quantum bit or qubit, thanks to the principle of superposition in quantum mechanics. quantum computing has attracted attention as a core technology for the future generation. But as its under consistent development process it's not fully error corrected. To achieve perfectly error-corrected quantum computers, creating a logical qubit from multiple physical qubits is essential. Here, the basic principles of qubits, as well as the status of the field.
Keywords: Qubits, Quantum computing

I. INTRODUCTION

Quantum computing is emerging as an innovative technology introduced by Paul Benioff in 1980. It was a technology that attracted the widespread attention of the next generation. The growing complexity of current technological difficulties, particularly in science, finance, and humanities, has surpassed classic computers' capabilities. To solve these challenges, quantum computing aims to address complexities in stated areas previously considered impossible to solve.[1]

Additionally, many countries and organizations actively explore and invest in transformative technology. The result of this situation is that quantum computing has made significant innovations over the past few decades, introducing quantum advantages to the world.[7] If physical quantum computers were impossible, the theory and its algorithms would not have attracted so much attention despite their potential. Recently, the rapid development of quantum computing hardware achieved a stage where simple algorithms and various proof-of-concept implementations are feasible, which has expanded to multiple fields.[4] Practically, a more successful implementation of quantum computing requires more computing resources and demands breakthroughs.

In quantum computing lies the qubit, the quantum analog of the classical bit. Unlike a classical bit, which can exist in a state of either 0 or 1,[6] a qubit leverages the principles of quantum mechanics, allowing it to exist in both. The qubit, the quantum counterpart of the classical bit, is used in quantum computing. Unlike a classical bit[4], which can only exist in one of these states, a qubit can exist in both 0 and 1 simultaneously by using the laws of quantum physics. [1] This feature dramatically increases the potential of quantum computers, allowing them to complete specific tasks 10 times more quickly than classical ones.

Entanglement is a quantum computer phenomenon in which the states of two qubits are inextricably linked regardless of their distance. The computational capacity of quantum systems is based on this interconnection, which enables highly parallel operations and effective handling of challenging issues. Algorithms for quantum computing use qubits' unique properties to do tasks impossible for traditional computers. For instance, Shor's algorithm[12] shows that it can factor big numbers exponentially more quickly, which presents problems for conventional cryptography systems[8]. In contrast, Grover's approach[11] provides a quadratic speed-up for unstructured search tasks.

In addition to these well-known algorithms, scientists are creating quantum chemical simulations, quantum machine learning methods, and optimization algorithms specifically for quantum systems. These methods show how quantum computing can drastically change domains like encryption and material science. Although quantum computing's theoretical underpinnings are sound, its real-world applications are still complex. The main obstacles are building and keeping stable qubits, reducing noise, and expanding quantum computers to perform more extensive computations. Notwithstanding these challenges, advancements in hardware and software are advancing the field and helping to bring quantum computing to fruition.

II. REVIEW OF QUANTUM MECHANICS WITH A COMPARISON WITH CLASSICAL COMPUTING

This section will briefly overview quantum computers, their essential characteristics, and how they differ from traditional computers. (Fig. 1). Quantum computers differ from standard computers by the principles of "**superposition**" and "**entanglement.**" In quantum computing, superposition is crucial because it allows qubits to represent a combination of 0 and 1 with different probabilities. It has an error rate of approximately $10^{-4,}$ providing potential quantum computing power when it becomes fully functional and applicable. Quantum computers use superposition probabilities and the entanglement of qubits to perform operations.[14] Temperature fluctuations, environmental electromagnetic field errors, etc., are where the error originated. These errors should be reduced in quantum computations to bring out the sizeable hidden potential of quantum computers. To minimize these errors, it is essential to entangle multiple physical qubits and form logical qubits because, in a quantum state, they cannot be copied, unlike in classic computers.[15] Entanglement is also one of the quantum advantages that makes quantum computers and operations valuable. Entanglement is a correlation between quantum systems that allows quantum computers to perform multiple calculations simultaneously,[13] boosting the speed of complex calculations compared to regular computers and finding the most straightforward and quickest answer.[16]

A. Quantum States and Superpositions

In this section, we will deeply understand quantum states, superpositions, and the benefits of using superpositions in quantum computing. The state of a physical system is described by its quantum state in quantum mechanics. Qubit states should be defined to build a quantum computer. For example, you need a physical system with two energy levels to create one qubit.[18] Two quantum states of the qubit are usually noted with $|0\rangle$ and $|1\rangle$. Quantum mechanics allows the system to exist in multiple states simultaneously. This is called quantum superposition and can be expressed as a combination of two states $\alpha|0\rangle + \beta|1\rangle$, where the alpha and beta signs represent complex numbers and are coefficients that measure the probability of each state. Superposition causes interference effect. Utilized to modify quantum computing probability amplitudes)[19]. Because it enables the manipulation of various probabilities to accomplish predetermined results, this interference phenomenon is crucial for algorithms used in quantum computing.

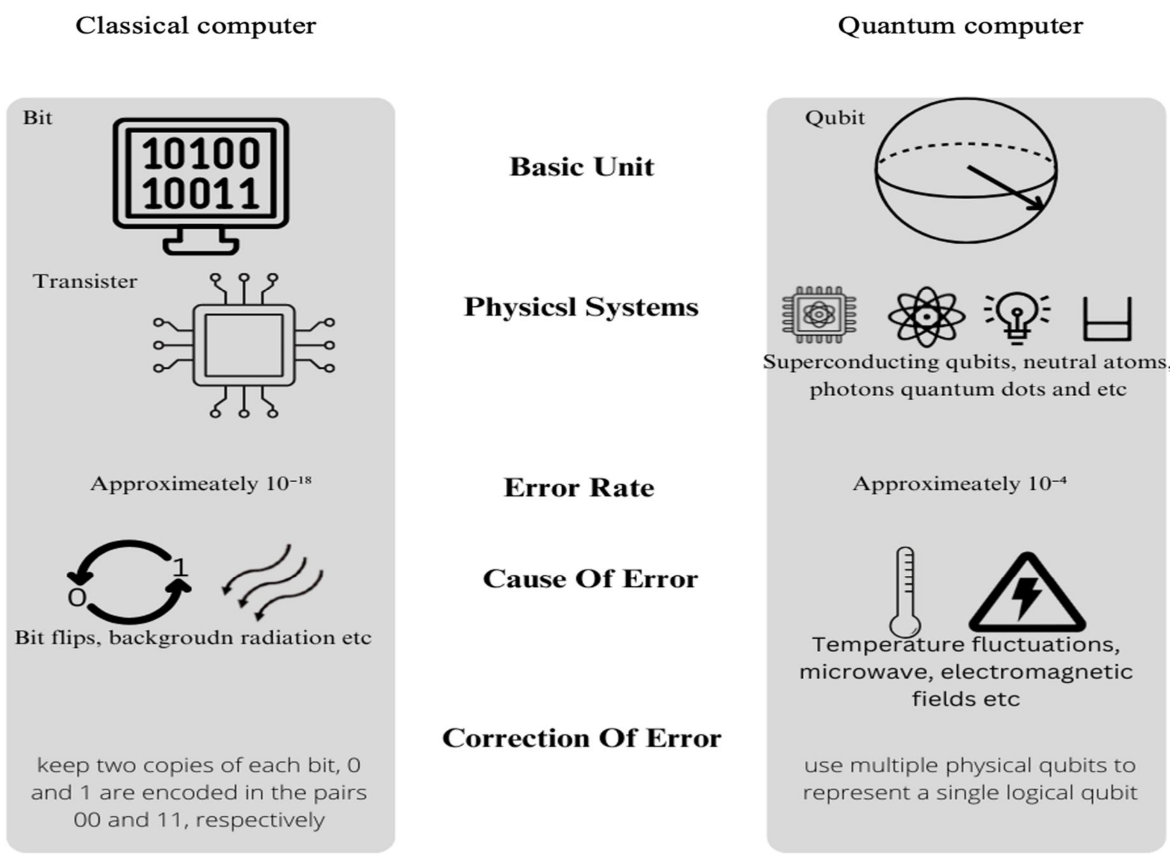

Fig. 1: Diagram of differentiating classic computer and quantum computer.[13] It's an introductory overview of comparing several differences between classical and quantum computers based on different bits, physical systems, the error rate of both computers, its cause, and the correction method.

B. Entanglement

Entanglement is when two particles link together in a certain way, no matter how far apart they are in space, and[15] their state remains the same. [20] The base of the quantum states of a computer with two qubits denoted with A and B, consisting of |00⟩, |01⟩, |10⟩, |11⟩, where the first number indicates the quantum state of A and the second number states for B. when the quantum beat is measured and if quantum state A doesn't affect the quantum state of B then we call those two qubits are independent of each other. Well-known examples of entangled states in quantum computing are Greenberger-Horne-Zeilinger states (GHZ). A Greenberger–Horne–Zeilinger (**GHZ**) state is an entangled quantum state that involves at least three subsystems (particle states, qubits, or qudits). The states are max of 4, which are entangled in a two-particle system with two states, which are |0⟩ and |1⟩, and there are a total of 4 cases that can be entangled with positive and negative cases. Bell states(a specific type of entangled quantum state involving two qubits) are the simplest building blocks in quantum computing. GHZ expands the concept of Bell states, in which there can be more than two particles.

C. Coherence Time

Superposition and entanglement are highly brittle. Coherence time refers to how long a quantum state can hold superposition and entanglement state. [21] "Coherence" also determines the quality of the quantum computer. The method of measuring coherence is also used to determine and evaluate how the quantum computer and state are good. There are two types of time: qubit relaxation time and decoherence time. They can be denoted as T_1 and T_2. They are the time scale for quantum computing, which measures if a system relaxes from one quantum state to another and presents a classical lifetime. [22] The relaxation time T_1 is calculated by applying a π-pulse signal to prepare the qubit in the excited state and reading the qubit state after a delay time. For each T_1 measurement, 1500 repetitions are used to obtain the mean decay plot. The graph is shown in **Fig. 2(a)** below.

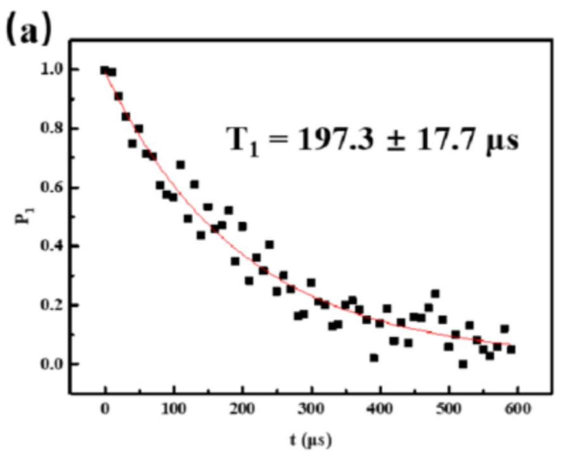

Fig. 2(a): Figure Taken from[Reference 24, 110] A typical decay curve of the qubit with T1 approximately 198μs. A qubit is excited state population P_1 is recorded as a delay time t**(μs)** function, and the relaxation time T1 is acquired by fitting the result to an exponential decay function.

T_2 is also known as decoherence time and dephasing time. It is the duration of a quantum system before it loses its coherence due to interaction with the environment, and T_1 can reveal its upper limit.[25]

III. ESTABLISHMENT OF QUBIT

Qubits are the fundamental unit in quantum information.[59] Also, qubits are the basic building blocks essential for quantum computing algorithms. All quantum computers start with the implementation of physical qubits in the system. DiVincenzo developed and proposed five criteria in the form of an essay for constructing a quantum computer. Guide progress towards using the power of quantum computing and communication. The requirements are: i) A scalable physical system with a well-characterized qubit. ii) The ability to initialize the state of the qubits to a simple fiducial state. iii) Long relevant decoherence times.[16] iv) A "universal" set of quantum gates. v) A qubit-specific measurement capability. [26] This section introduces qubits in different physical systems. Further, we will provide requirements to satisfy universal quantum computing algorithms. The upcoming section focuses on providing methods for constructing qubits on multiple systems.

A. Qubit States

Qubit is the basic unit as well as essential for constructing quantum computing algorithms. Quantum computers manipulate quantum states to operate information and store data. It harnesses quantum computer properties as well, which are entanglement and superposition. Implementing qubits is commonly categorized according to the physical systems used; its several examples are superconducting circuits, trapped ions, neutral atoms, nuclear magnetic resonance (NMR), etc. However, it is also essential to consider the choice of quantum states as basis states within these systems. The chosen physical system understands the properties of the physical qubits, and the qubits are encoded within the specific system. Quantum states outside of defined qubit space can be used as resources of quantum operations. [29] Superconducting Circuits: Superconducting qubits typically fabricated using thin-film deposition techniques leverage Josephson junctions to create anharmonic oscillators. The nonlinearity provided by the Josephson effect ensures that the energy difference between the ground state $|0\rangle$ and the first excited state $|1\rangle$ is distinct from higher energy levels, effectively isolating a two-level system.[39] Ion Trapping and Qubit Encoding: In trapped ion systems, ions such as $^{40}Ca^{+}$ or $^{171}Yb^{+}$ are confined using electromagnetic fields in Penning or Paul traps. Qubits provide exceptional stability because they are encoded in long-lived hyperfine or Zeeman states. [47]

Control by Laser: Laser pulses manipulate states by causing stimulated Raman transitions between qubit levels. Laser control precision is crucial, and high-fidelity operations are ensured using phase stabilization and pulse shaping techniques.

[44] Measurement and Scalability Issues: While trapped ions exhibit exceptional coherence times and high gate fidelities, the physical complexity of ion traps poses scalability challenges. Efforts to scale include segmented trap arrays and shuttling ions between interaction zones.[45] Nuclear Magnetic Resonance (NMR): Ensemble-Based Qubit Implementation NMR leverages the nuclear spins of atoms in a molecule, where each spin can be considered a qubit. The ensemble nature of NMR experiments means that measurements yield averaged signals over many identical quantum systems. Radio-frequency control and Readout Control are exerted through radiofrequency (RF) pulses that manipulate the nuclear spins, similar in principle to magnetic resonance imaging (MRI). The resultant signal, often detected as a free induction decay, is Fourier-transformed to infer the quantum state of the ensemble.[47] Natural qubits can be categorized into intrinsic two-level systems and two-level subset systems. In contrast, the system is an engineered two-level system for synthetic qubits. **[Refer to Fig.3]**

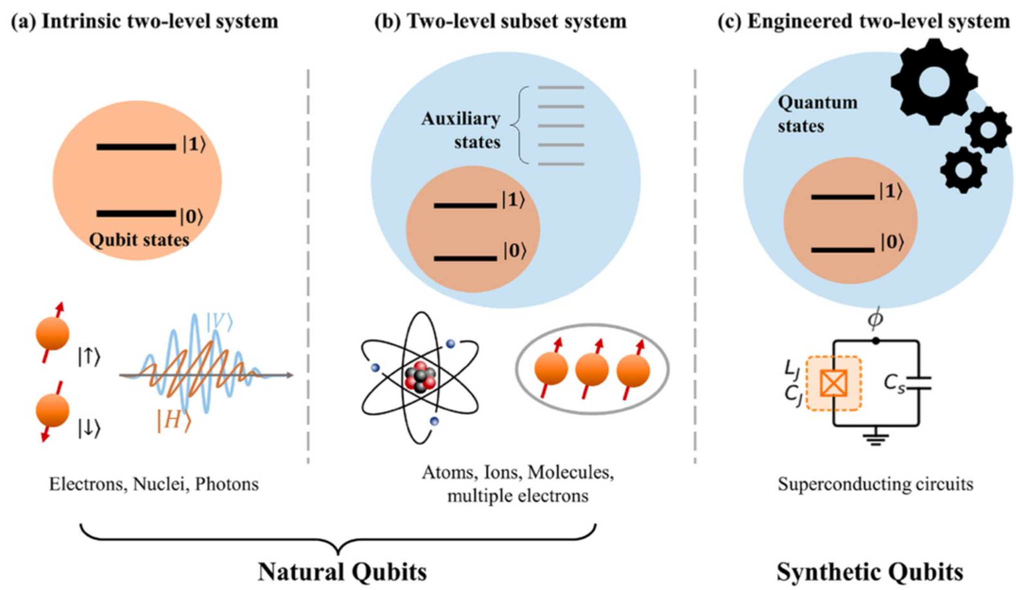

Fig.3, taken from Reference 48, shows the different qubit states segregated into natural and synthetic qubits, depending on physical systems, such as nuclei, superconducting circuits, multiple electrons, etc.

Specific systems inherently have multiple possible quantum states, making them natural for a qubit. For example, electrons and nuclei possess a spin of. This results in two possible spin states: up or down. When it is sufficiently large and has a stable magnetic field, these two spins degenerate and show a long coherence time, which is a good qubit status. Various physical configurations, such as floating on liquid helium[51] and electron Paul trap, can be used.[54] semiconductor quantum dots[56], nuclear magnetic resonance(NMR) molecules[45], and polarization of photons[57, 58] are several examples of intrinsic two-level systems.

The central nucleus and multiple electrons form more complicated systems than single-atom systems, and these composite systems have more complex energy levels. A qubit space can be defined as a two-dimensional subset, which is called a Hilbert space, and a complex vector space. The term "Hilbert space" is often reserved for an infinite-dimensional inner product space that has the property of being closed. However, as in these notes, the term is frequently used nowadays to include finite-dimensional spaces, which automatically satisfy the completeness condition.[50], which is classified as a two-level subset system. In this system, quantum states may propagate outside the qubit space, resulting in errors. Caused errors are highly problematic because they cannot be modified using the general quantum error correction method.[23], but auxiliary states can provide certain benefits, as they can serve intermediate states during the process. Many qubit-controlling protocols use their states to implement single and two-qubit gates [32] and qubit state discrimination and initialization.[46] In quantum computing, qubit state discrimination and initialization are essential processes that play crucial roles in quantum algorithms, error correction, etc. Qubit state discrimination is determining the state of a qubit after measurement. Several approaches for qubit state discrimination are orthogonal and non-orthogonal states. If the qubit is on an orthogonal basis (e.g., $|0\rangle$ and $|1\rangle$), measurement on that basis ideally determines the state. Suppose qubits are in non-orthogonal states (e.g., superpositions like $|+\rangle = \frac{1}{\sqrt{2}} + (|0\rangle + |1\rangle)$). In that case, measurement on a computational basis cannot fully determine the state without loss of information. Qubit initialization is preparing a qubit in a known starting state before computation. This is essential for reliable quantum computing. An example of this method is Measurement-Based Reset, which measures the qubit; if it's in $|1\rangle$, apply a corrective operation (e.g., an X gate) to ensure it's in $|0\rangle$. Thermal Relaxation (Passive Reset) uses natural relaxation to the ground state $|0\rangle$ via energy dissipation.[11] In contrast to natural qubits, synthetic qubits make use of the designed Hilbert space of artificial quantum systems. [39] For example, the quantum properties of superconducting circuits highly depend on circuit design. [38] The new creative design of the Hilbert space may enhance qubit performance in systems.

B. Operation of a single qubit

Qubit's operation heavily depends on Qubit's states and platform being utilized because all of Qubit's principles are different.[45] Mathematically, a qubit's state $|\psi\rangle$ can be expressed as a linear combination of two orthonormal basis states, $|0\rangle$ and $|1\rangle$:

$|\psi\rangle = \alpha|0\rangle + \beta|1\rangle$

Here, α and β are complex probability amplitudes satisfying the normalization condition $|\alpha|^2 + |\beta|^2 = 1$. This ensures that the total probability of the qubit being in either state is unity. The relative magnitudes and phases of α and β determine the qubit's state, which can be visualized on the Bloch sphere—a unit sphere where any point represents a possible pure state of the qubit.

1) Manipulating Single Qubits

Operations on single qubits are achieved through quantum gates, unitary transformations that alter the qubit's state. Standard single-qubit gates include: [59]

Pauli-X Gate: Flips the qubit's state, analogous to the classical NOT gate.

Pauli-Y and Pauli-Z Gates: Rotate the qubit's state around the Y and Z axes of the Bloch sphere, respectively.

Hadamard Gate: Creates an equal superposition of $|0\rangle$ and $|1\rangle$ from either basis state, effectively rotating the qubit's state to lie on the equator of the Bloch sphere.

These gates are represented by 2x2 unitary matrices that yield a new state vector when applied to the qubit's state vector. For example, the Hadamard gate (H) is represented as:

$H = (1/\sqrt{2}) * [[1, 1], [1, -1]]$

Applying H to $|0\rangle$ results in:

$H|0\rangle = (1/\sqrt{2})(|0\rangle + |1\rangle)$

This operation places the qubit into a superposition state, a crucial aspect of quantum parallelism.[41]

2) Physical Realizations and Control

The physical implementation of qubits varies across different quantum computing platforms, each utilizing distinct physical phenomena:

Superconducting Qubits: Using Josephson junctions and microwave pulses to make and control qubits. Utilize ions in electromagnetic traps and alter their qubit states by laser pulses to create trapped ion qubits. Using optical components such as beam splitters and phase shifters, photonic qubits use the polarization states of photons.[44]

The platform selection affects the qubit manipulation techniques. For example, different quantum gates can be implemented in superconducting qubits by using precise microwave pulses to effectuate rotations along the axes of the Bloch sphere. On the other hand, trapped ion qubits use laser-induced changes in internal energy levels to carry out gate operations.

3) Challenges in Single-Qubit Operations

There are various obstacles to precise control of single qubits: Decoherence: When a qubit interacts with its surroundings, it may lose its quantum characteristics and collapse superposition states. Gate Fidelity: Computational accuracy may be impacted by imprecise operations that result in errors in quantum gate implementations. Initialization and Readout: Preparing qubits in a specific beginning state and precisely measuring the final state are challenging tasks requiring sophisticated techniques. [27] Creating trustworthy quantum computers requires overcoming these obstacles. [24] To address these issues, research is being done on control precision, qubit isolation, and error correction.[23]

C. Entanglement Between Qubits

Creating entanglement between qubits is the most essential process and a component in quantum computing algorithms. However, in its current status, creating reliable quantum entanglement is difficult. Till now, many systems have successfully performed manipulation of a single qubit but not entanglement. The main challenge that has been addressed till now is that qubits should only react with other qubits, not the environment nearby them. [43] Specific qubit systems have a qubit-qubit reacting system, which generates entanglement between them.

NMR qubits (Nuclear magnetic resonance) react with each other by direct dipolar coupling and bond interaction.[46] Using these interaction methods, numerous gates for entanglement and algorithms were operated for NMR qubits.[40] Generally, it is preferable to have a system that can be controllable during the process. There are more existing methods, but qubit isolation remains. Auxiliary quantum states or auxiliary quantum systems are introduced to mediate these interactions.

In many quantum architectures, auxiliary quantum states are deliberately introduced to mediate and enhance interactions between primary qubit systems.

For example, one can effectively control and implement high-fidelity entangling operations by coupling qubits to intermediate auxiliary states with engineered properties (such as long coherence times or tunable couplings). This approach has been beneficial in Rydberg-based systems, where the strong, long-range dipole-dipole interactions among highly excited Rydberg states are exploited to realize fast quantum gates via the mechanism of Rydberg blockage. The constraints imposed by direct qubit–qubit coupling can be overcome in these systems by using auxiliary quantum states (or even specialized auxiliary atoms) to mediate interactions between distant qubits or shuttle quantum information. Such schemes have been demonstrated theoretically and experimentally, where, for instance, auxiliary "wire" atoms are employed in Rydberg arrays to couple remote qubits while maintaining a rapid control of the quantum state[29]. These innovations enhance the adequate interaction strength and help suppress decoherence channels, offering a promising route toward scalable quantum computation.

IV. CURRENT STATUS AND FUTURE DEVELOPMENT OF QUANTUM COMPUTERS AND ALGORITHMS.

Satya Nadella, CEO of Microsoft, called quantum computing a transformative technology, citing the Majorana 1 chip as a breakthrough for more stable qubits.[39] Also, **Scott Aaronson**, a quantum computing expert, highlighted its potential for breakthroughs in cryptography, drug discovery, and understanding reality.[33]

Many world leaders and computer scientists believe that the quantum computer's power, hidden potential, and algorithm are not measurable because whenever the testing occurs, it shows dramatic achievements—**Google's demonstration of quantum supremacy in 2019**. The company announced that its 53-qubit quantum processor, Sycamore, completed a specific computational task in approximately 200 seconds—a task they estimated would take the world's most influential classical supercomputer, Summit, around 10,000 years to perform. This milestone showcased the potential of quantum computers to[50] solve specific problems much faster than classical computers.[41] Examples of quantum computer power include Shor's algorithm[51] and Grover's searching algorithm[58]. For cryptography capabilities [52] and different research in multiple fields.[55] even though the advancement of quantum computing created remarkable change over decades. But still, there are universal experimental challenging tasks. In the following, there is brief information about the current status of the quantum computer and its algorithm in multiple fields, as well as error correction for fault-tolerant computing for quantum computing.

A. Current Status Of A Quantum Computer And Its Algorithm

We can look at two sections to understand its current situation through the hardware part and algorithm part. In both, there were noticeable innovations and changes. For the hardware part, Microsoft's Majorana 1 Chip: Microsoft unveiled the Majorana 1 chip, utilizing a topological superconductor—a new state of matter—to enhance qubit stability. This breakthrough aims to facilitate the development of large-scale, reliable quantum computers capable of addressing complex problems and strengthening the reach of classical systems[36]. The second point for hardware is quantum teleportation. Researchers at the University of Oxford achieved transmitting a quantum algorithm between two separate quantum processors using quantum teleportation. This method leverages quantum entanglement to enable processors to operate in parallel ways, effectively combining their power[37]. In contrast, it looks at innovation for quantum computing algorithms. Algorithms for quantum computing. In 2024, significant improvements in error-correcting techniques were created. Google's Willow quantum processor demonstrated how error-corrected qubits improved exponentially with scale. This semiconductor effectively reduces error rates by combining many qubits and carrying out real-time error correction, making considerable progress toward practical, large-scale quantum computing. [42] Color Code Implementation: A novel quantum error correction method, color coding, has been successfully applied to superconducting qubits by researchers. Given that it demonstrated high-fidelity operations and decreased logical error rates by 1.56, this approach might offer more efficient error repair than traditional methods. [43] All these developments are critical to the stabilization of qubits. And reducing computational errors. Improved error correction codes and the development of more stable qubits, such as topological qubits, have advanced the reliability of quantum computations.

B. Future Development Of Quantum System

A quantum computer has several advantages that are still underdeveloped and cannot be implemented with current technology. But when we look forward to several decades, we cannot predict what kind of technological innovation and development will be there. Several organizations interviewed scientists and experts in the quantum field, asking about the future of quantum computing technology.” In a special interview with CERN, John Preskill responded and went into further detail on the state of quantum computing today and its potential. He highlighted the rapid advancement of the field, its potential applications across multiple industries, and the challenges of introducing quantum computing to the general public. [49] Similar to this interview, practical issues still need to be addressed before we can fully utilize quantum computers and realize their promise. Several predictions have been made regarding the implementation of fully functional quantum computers. According to Google CEO Sundar Pichai, usable quantum computers could be developed in the next five to ten years. Additionally, NVIDIA CEO Jensen Huang has a more conservative outlook on the maturity of the technology, estimating that usable quantum computing may still be 15 to 30 years away. [52]. When we look at significant achievements of quantum computers these days and several past years, they are: Quantum Supremacy Demonstration: In 2019, Google showcased a quantum computer performing a specific task faster than the best classical supercomputers, marking a pivotal moment in computational history. Developments in Error Correction: To improve the stability and dependability of quantum calculations, researchers have created surface code schemes that can be adjusted to the necessary error rates in quantum processors. Extension of Qubit Arrays: A significant breakthrough toward large-scale quantum computing occurred in 2023 when TU Darmstadt researchers displayed a qubit array with more than 1,000 qubits. Development of Modular Quantum Architectures: Scalable and adaptable architectures have been made possible by the advent of quantum modularization, which has enhanced system accessibility and enabled more affordable updates. When we look at these remarkable achievements of quantum computers, we should know that these are done when they have not opened their full potential, which is hidden and waiting for technological advancement.

According to Michio Kaku on Quantum Computing's Impact interview, theoretical physicist Michio Kaku suggests that advanced quantum computers could revolutionize various fields by solving complex problems, such as decoding nuclear codes and discovering cures for diseases like cancer and heart disease. The basic takeaway from this interview is that when quantum computers are successfully ready to be operated with full potential, there will be significant changes in our science world. For example, Artificial Intelligence Enhancement: Integrating quantum computing with AI will accelerate machine learning, leading to more advanced and efficient AI systems. The synergy of these two(fully potential quantum computer and AI) could enhance data analysis, pattern recognition, and decision-making processes across various industries.[58] Data Security and Cryptography: While quantum computing offers numerous benefits, it challenges current encryption methods. The immense processing power of quantum computers could render traditional cryptographic techniques obsolete, necessitating the development of quantum-resistant encryption to protect sensitive information.[43]

V. CONCLUSION

Basic principles of a qubit, quantum computers' current status, and future possibilities were reviewed. Quantum systems still show dramatic improvements day by day. Still, we all know that in the future, there will be a moment when all quantum computer systems and algorithms will be applicable and bring a significant and remarkable change to us. Still, there are several challenges to overcome, such as more precise control of the qubit, the noise of the qubit, etc. Developing a fully fault-tolerant quantum computer requires considerable effort, but it will be a sensational achievement in the computer science field.

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