RESEARCH & INNOVATION DIVISION
IJIST

Qubits - Shaping the Future of Information Processing

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Citation | Hussain. M, Arfeen. M. Z, Orakzai. A. K, Zafar. T, “Qubits - Shaping the Future of Information Processing”, IJIST, Vol. 8 Issue. 1 pp 11-21, January 2026
Received | November 26, 2025 Revised | December 25, 2025 Accepted | December 29, 2025 Published | January 03, 2026.

In the endless striving to push the boundaries of information processing capabilities, the competition that rages today between Quantum Bits and Classical Bits has become the central area of interest in modern research. The research elucidates and analyzes the distinct characteristics of these two fundamental units of information. It also critically examines their prospective futures in computing. In this article, a comprehensive comparison between Classical Bits - the binary entities that constituted classical computing for decades - and quantum bits - quantum mechanical counterparts that realize the principles of superposition and entanglement - is given. The research is based on the fundamental principles of classical and quantum computers, information units, logic circuits, time scaling dissimilarities, and complexity of algorithms. This article fills this gap by providing a comprehensive and structured comparative analysis of Classical Bits and quantum bits, examining their foundational principles, logic circuit realizations, algorithmic complexity, and computational scalability. The study offers a consolidated perspective that helps clarify the fundamental differences and practical implications of classical versus quantum computation, thereby supporting researchers and practitioners in understanding the computational advantages and limitations of both paradigms. Key observations include: The world has witnessed that classical computers have emerged vastly over the decades, in terms of memory sizes and computing speeds. For this reason, classical computers are used in nearly all fields. Nevertheless, in many fields, classical computers are less effective in solving complex problems in terms of accuracy, speed, and efficiency. Therefore, research exploring the exceptional features - entanglement and superposition - of qubits or Quantum Bits explores how quantum phenomena give rise to new modalities in computing.

Keywords: Quantum Bits, Superposition and Entanglement, Quantum circuits, Performance of Quantum Computers.

Introduction:

The classical computer is based on binary logic for processing information, and the information is saved as bits. Currently, nearly all modern computers are based on binary logic, where the fundamental unit of information is a bit. However, many complex problems require classical computers to spend a huge amount of time to solve, and some problems remain intractable. This situation creates a demand to implement a new computing paradigm, namely quantum computing, which utilizes the fundamentals of quantum physics and resolves the complex problem using a qubit, which is the basic unit of quantum computing. It is observed that Quantum computers are speedier in solving complex problems than binary logic-based classical computers. This paper gives a demonstration of a comparative study of quantum and classical computers with some exceptional details [1].

This competition of classical bits Cbits with quantum bits Qbits marked a turning point or paradigm shift in information processing. Classical bits are mapped out simply as 0s and 1s for traditional computing systems and have shaped the digital age. In contrast, qubits introduce a novel dimension to information representation by exploiting quantum fundamentals such as entanglement and superposition. Classical computing has reached remarkable levels of performance, enabling expanded applications from data processing to artificial intelligence. However, as computational demands grow exponentially, classical computers are encountering inherent limitations, particularly in tackling problems of exponential complexity, for example, factoring huge numbers for encryption or simulating quantum processing. Quantum computing, in contrast, offers tantalizing promises of exponential speedup for specific classes of problems. Quantum algorithms, including Shor's algorithm for factoring and Grover's algorithm for searching, have demonstrated the potential to disrupt classical cryptographic systems and optimize search operations exponentially faster than classical counterparts. These advancements stem from the inherent properties of qubits that exist in various states simultaneously through superposition and exhibit instantaneous correlations between entangled particles. The race to build practical quantum computers has garnered significant attention from both academia and industry [2].

The significant strides made by companies such as IBM, Google, and several startups, including Rigetti and IonQ, are very evident in the advancement of quantum hardware and software. Great milestones such as quantum supremacy claims add to the intensity of progress these days in this field [3]. This represents a critical point where classical bits and quantum bits converge, highlighting the evolving landscape of information processing. This endeavor is aimed at explaining how this competition works and how classical bits will eventually coexist with quantum computing technology [4].

Research Gap:

Although numerous studies discuss classical and quantum computing separately, there is a lack of a systematic, unified comparative analysis that simultaneously examines information units (bits vs. qubits), logic circuit realization, algorithmic complexity, and time-scaling behavior within a single coherent framework. Existing works often emphasize theoretical quantum advantages without explicitly contrasting them against classical computing across these multiple dimensions.

Novelty:

The novelty of this study lies in presenting a unified and structured comparative framework that analyzes classical and quantum computing across multiple dimensions—information representation (bits vs. qubits), logic circuit realization, algorithmic complexity, and time-scaling behavior—within a single study. Unlike existing works that treat these aspects separately or focus predominantly on theoretical quantum advantages, this work integrates them into a cohesive comparison, emphasizing both conceptual and practical implications.

Objectives:

The main objectives of this study are:

To analyze and compare classical bits and quantum bits based on their fundamental operating principles.

To examine differences in logic circuit implementations in classical and quantum computing.

To evaluate algorithmic complexity and time-scaling behavior in both paradigms.

To provide a clear understanding of the strengths, limitations, and applicability of classical and quantum computing models.

Contribution of this Work:

This study addresses the identified gap by providing a structured and comprehensive comparison between classical and quantum computing. The main contributions include:

A unified analytical framework for comparing bits and qubits.

A detailed comparison of classical and quantum logic circuits.

An analysis of algorithmic complexity and time-scaling differences between the two paradigms.

Clear insights into the practical implications and limitations of both classical and quantum computation.

Furthermore, the rest of the article is planned as follows: Section 2 is a summary of the fundamentals of quantum mechanics. Section 3 explains and investigates quantum circuits with their principle of implementation. A discussion of the performance of quantum computers is presented in Section 4, and in Section 5, the conclusion is made.

Background:

Fundamentals of Quantum Mechanics:

Superposition:

A classical bit is a unit of information in classical computing that can take two states: 0 or 1. In formal mathematics, a classical bit can be represented by a binary variable:

$$\text{Cbit} = 0 \text{ or } 1 (1)$$

This expression is included to define the classical bit, the fundamental unit of information in classical computing, which exists only in one of two discrete states: 0 or 1. It establishes the deterministic and binary nature of classical information representation, serving as a direct contrast to the probabilistic superposition of qubits. Logical operations in classical computing are applied to these binary variables by means of logic gates, for instance, AND, OR, and NOT, to manipulate and process information. A quantum bit, however, is a more complicated and versatile unit of quantum information. Mathematically, a qubit is expressed as the basis states of superposition $|0\rangle$ and $|1\rangle$, as shown in Fig. 1. This superposition can be expressed by Dirac notation as follows:

$$|\text{Qbit}\rangle = |\psi\rangle = \alpha|0\rangle + \beta|1\rangle \ (2)$$

This equation is included to formally represent the quantum bit (qubit) state, which is the fundamental unit of quantum information used in the comparative analysis between classical and quantum computing. It provides the mathematical basis required to understand subsequent examples, circuit analysis, and comparative results presented in this research. $|\alpha|^2$ & $|\beta|^2$ are the probabilities of the qubit being in states $|0\rangle$ & $|1\rangle$, here, α & β are complex numbers. The condition that $|\alpha|^2+|\beta|^2 = 1$ ensures the sum of probabilities is equal to one. A classical bit has a definite state at any time, either 1 or 0, but a qubit can exist in a linear combination of both states until it is measured. This property enables parallel computation, which contributes to the speedup of quantum algorithms. [5][6].

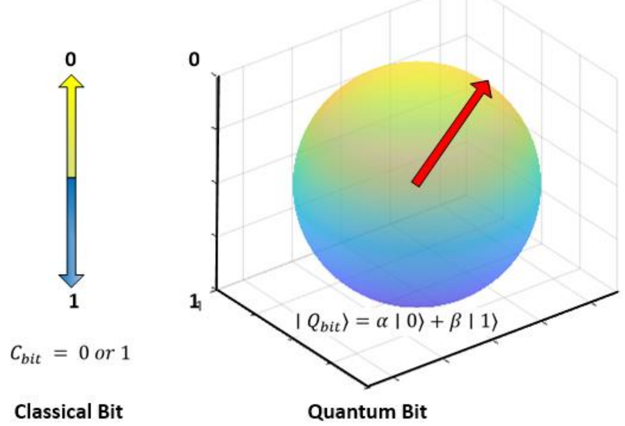

Figure 1. Quantum bit vs Classical bit.

Let's examine an easy case of a quantum computer with two qubits, q0 and q1. In classical computation, one needs to perform two different calculations, one after the other, to compute different cases. However, in quantum computing, these qubits can be put into a superposition state, which allows representing both calculations as performed in parallel. Mathematically, the state of these two qubits in superposition is as follows:

$$|\psi\rangle = a|00\rangle + \beta|01\rangle + \gamma|10\rangle + \delta|11\rangle \, (3)$$

This equation represents a two-qubit quantum state, expressed as a linear superposition of four computational basis states. It is included to extend the discussion from a single qubit to multi-qubit systems, which are essential for understanding quantum circuits and algorithmic scalability. Basis states corresponding to two qubits are $|00\rangle$, $|01\rangle$, $|10\rangle$, and $|11\rangle$, representing every possible outcome. Thus, α, β, γ, and δ are nothing but magnitudes of complex likelihood, squares of which provide probabilities for measuring the corresponding basis states. When you operate a quantum operation on this superposition, it operates on all possible states at once, thereby leading to parallelism. For instance, applying a quantum gate to $|q0\rangle$ performs the corresponding operation on all terms of the superposition simultaneously., and as a result, all four terms in the superposition will be influenced at once. This parallelism becomes increasingly powerful as the number of qubits grows and complex quantum algorithms are implemented. Quantum algorithms involve parallelism, for example, Grover's algorithm and Shor's algorithm, which can perform certain complex computations faster than classical methods. Grover's algorithm can search an unsorted database of N items in roughly √N steps, representing a significant speedup over the O(N) complexity of classical algorithms [7].

In a quantum computer, describing a 3-qubit system requires an 8-dimensional space because all qubits can exist in the superposition of two states (0 and 1), leading to $2^{3} = 8$ possible combinations as shown in Fig. 2. In contrast, in a traditional (classical) computer, adding 1 bit increases the required memory size by just 1 binary cell. This means that each additional bit in a classical computer doubles the number of possible states it can represent. In quantum computing, adding qubits exponentially increases the system's complexity due to the superposition property, allowing it to represent many states simultaneously, making it potentially more powerful for certain tasks.

Parallelism in quantum computing arises from the superposition of qubits, allowing quantum operations to affect multiple states at the same time, which can lead to exponential speedups for solving certain problems [8][9].

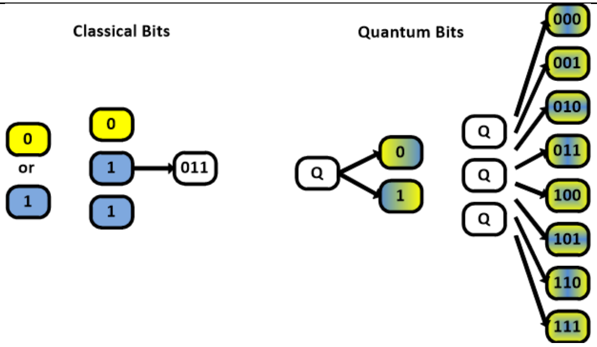

Figure 2. The number of bits required to match the computing power of qubits is n-qubits = 2^n bits.

Entanglement:

Additionally, qubits can exhibit another unique quantum property called entanglement. This property is not present in classical bits and is a powerful resource for quantum information processing. The quantum state of one qubit depends on the state of another, even when separated by large distances. This phenomenon is quantum entanglement, in which two or more qubits become correlated in a non-classical manner. The entangled qubits exhibit correlations that are stronger and more intricate than what can be explained by classical physics. Mathematically, entangled qubits are represented as a combined quantum state and cannot be written as independent qubit states.

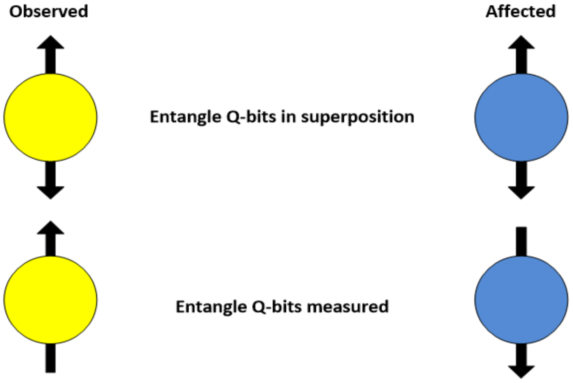

Figure 3. Quantum Superposition and measurements

Consider two entangled bits which can be measured as “0” (often denoted as $|\uparrow\rangle$) or “1” (denoted as $|\downarrow\rangle$). However, quantum bits exist in the superposition of both states simultaneously, as shown in Fig. 3. Now, let us create an entangled pair of bits:

$$|\psi\rangle = \frac{1}{\sqrt{2}}\left(|\uparrow\downarrow\rangle - |\downarrow\uparrow\rangle\right)(4)$$

The $|\downarrow\uparrow\rangle$ term represents the opposite, where the first one is in a “1” state while the second one is in a “0” state. Shown in Fig. 4.

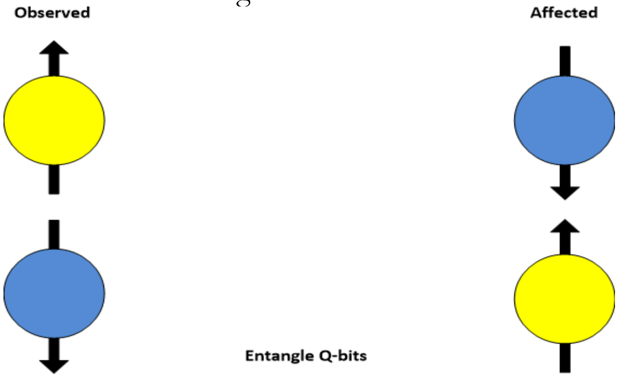

Figure 4. Entangle Q-bits.

This entangled state cannot be described as a combination of two separate qubit states. When two entangled qubits are measured, their measurement outcomes are correlated in a way that cannot be explained classically. For example, if one qubit is measured and found to be in state 0, the other qubit will be in state 1 as well, irrespective of the space between them. Therefore, entanglement involves a correlation between qubits, such that measuring one qubit immediately determines the state of the other, even if they are spatially separated.

Quantum entanglement has profound implications in quantum computing, quantum cryptography (such as quantum key distribution), and tests of the fundamental principles of quantum mechanics, challenging classical intuitions about the nature of physical reality [10].

Quantum Circuit:

A quantum circuit is a model for quantum computation, similar to how a logic circuit works in classical computing. It's called a "circuit" because it visually and structurally resembles classical circuits.

Single-Qubit Gates:

The Pauli gates are basic single-qubit gates that change the state of a quantum bit (qubit) in special ways, as described in Table I.

Pauli-XBit-flip (like classical NOT)

Pauli-Y Bit and phase flip

Pauli-Z Phase-flip

Hadamard creates a superposition (H gate)

Table 1. Pauli Gates With Description and Matrices

Gate Name	Description	Matrix
Pauli-X	Rotation of π radians around the X-axis.	$\begin{bmatrix} 0 & 1 \\ 1 & 0 \end{bmatrix}$
Pauli-Y	Rotation of π radians around the Y-axis.	$\begin{bmatrix} 0 & -i \\ i & 0 \end{bmatrix}$
Pauli-Z	Rotation of π radians around the Z-axis.	$\begin{bmatrix} 1 & 0 \\ 0 & -1 \end{bmatrix}$
Hadamard	Creates superposition.	$\frac{1}{\sqrt{2}}\begin{bmatrix} 1 & 1 \\ 1 & -1 \end{bmatrix}$

The Pauli-X gate is usually equated with the NOT gate of a classical computer. It changes the state of a qubit: altering $|0\rangle$ to $|1\rangle$ and vice versa. This shape is advantageous when a bit flip is required during a quantum task.

The Pauli-Y gate executes a more composite operation. The Pauli-Y gate combines both a phase-flip and a bit-flip. It changes $|1\rangle$ to $-i\ |0\rangle$ and $|0\rangle$ to $i\ |1\rangle$, where i is the imaginary unit. This gate is crucial in conditions where both the phase and the value of a qubit need to be changed concurrently.

The Pauli-Z gate, conversely, allows $|0\rangle$ unchanged but includes a negative phase to $|1\rangle$, successfully reversing the sign of its amplitude. This is termed a phase flip, and it plays an essential role in quantum algorithms where the outcome is affected by phase information.

The Hadamard gate (H gate) is also a basic single-qubit quantum gate that makes qubits in a superposition. When implemented on a qubit in the $|0\rangle$ or $|1\rangle$ state, it transforms it into an equal superposition of $|0\rangle$ and $|1\rangle$.

Each of these gates can be denoted by a 2×2 matrix and performs an essential role in making more complex quantum circuits. They are mainly important in quantum data processing and error correction [11].

Multi-Qubit Gates:

Multi-qubit gates are quantum logic gates that work on two or more qubits at once. Contrasting single-qubit gates, which operate on single qubits, multi-qubit gates permit qubits to become entangled, qualifying the exceptional benefits of quantum computing.

CNOT Gate (Controlled NOT)
Toffoli Gate (CCNOT)
Controlled-Z (CZ) Gate
SWAP Gate
Fredkin Gate (CSWAP)

Multi-qubit gates are quantum logic gates that work on two or more qubits at once. Contrasting single-qubit gates, which operate on single qubits, multi-qubit gates permit qubits to become entangled, qualifying the exceptional benefits of quantum computing.

The Controlled-NOT gate or CNOT gate is a two-qubit gate where the second qubit (target) is flipped if the first qubit (control) is in the 1 state. It's important for making entanglement of qubits, a key characteristic in quantum algorithms.

The Toffoli gate or Controlled-Controlled-NOT gate expands this operation with two control qubits and one target qubit. It reverses the target qubit only when both control qubits are 1. Meanwhile, it's reversible and universal for classical logic; the Toffoli gate is vital in quantum error correction and reversible computing.

The Controlled-Z gate, or CZ gate, is one more two-qubit gate. It stays both qubits unaffected unless both are in the 1 state, in which case it adds a phase shift of -1 to the system. This gate is frequently utilized in quantum circuits to include conditional phase flips, beneficial in many quantum algorithms.

The Fredkin gate, also identified as the Controlled-SWAP gate or CSWAP gate, is a three-qubit quantum gate. It consists of two target qubits and controls a qubit. The gate exchanges the states of the two target qubits only if the control qubit is in the 1 state. If the control qubit is 0, the target qubits stay unaffected. The Fredkin gate is reversible and preserves information, making it useful in both quantum and reversible classical computing. It is utilized in error correction and certain algorithms in quantum machines where conditional data exchange is required [12].

Methodology:

The results presented in this study are based on a comparative analytical evaluation rather than experimental or empirical data. The analysis draws upon established theoretical models, standard computational complexity theory, and widely accepted classical and quantum computing algorithms reported in the literature. Authoritative sources, including foundational textbooks and peer-reviewed research articles in classical and quantum computation, were systematically reviewed and synthesized. The study flow diagram illustrating the research process from literature review to comparative analysis and conclusions, improving structural clarity and readability in Figure 5.

The comparison metrics—such as information representation, logic gate implementation, algorithmic complexity, and time-scaling behavior—were defined before analysis and applied consistently across both paradigms. The results, therefore, reflect analytical insights derived from theoretical performance bounds and architectural characteristics, not from simulated or hardware-based experimentation.

This study follows a comparative analytical methodology based on an extensive review of existing literature in classical and quantum computing. The methodology involves:

Identifying core computational components of both paradigms.
Analyzing information units, logic gates, and circuit structures.
Comparing algorithmic complexity and computational scaling behavior.
Synthesizing results into a structured comparative framework.

This study does not involve experimental hardware; rather, it focuses on a theoretical and architectural comparison supported by established models and prior literature.

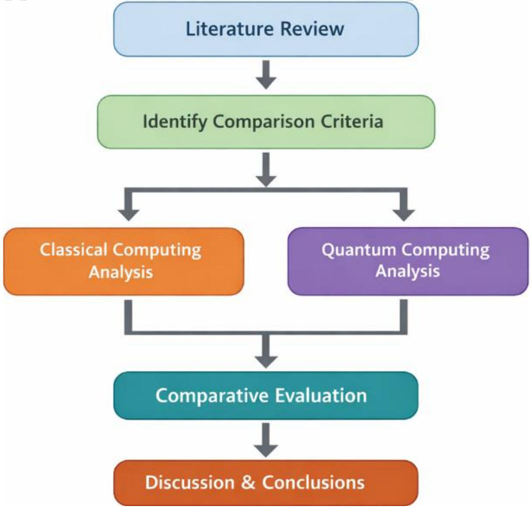
Literature Review
Identify Comparison Criteria
Classical Computing Analysis
Quantum Computing Analysis
Comparative Evaluation
Discussion & Conclusions

Figure 5. Study flow diagram

Result:

For quantum gates and errors in measurement, Quantum Volume is used as a metric. Quantum Volume is a metric that takes into account connectivity, device crosstalk, and circuit software compiler efficiency. IBM uses Quantum Volume as a metric to define and track Quantum Advantage in achieving its goals for the 2020s. In comparison with current- era classical computers, IBM describes Quantum Advantage as a significant performance improvement. The term 'significant' refers to performance improvements that can be hundreds or thousands of times greater than classical computations. A 5-qubit quantum machine, IBM Q 5 Tenerife, has a Quantum Volume of 4, while a 20-qubit quantum machine, IBM Q 20 Tokyo, has a Quantum Volume of 8. In early 2017, results from the IBM Q System quantum machine indicate its Quantum Volume has just reached 16. Consequently, IBM has been able to double the Quantum Volume annually. since 2017, as shown in Figure 5. As a single number standard, IBM accepts that Although Quantum Volume provides a useful benchmark, additional metrics, such as qubit entanglement quality, are needed to fully evaluate system performance. [13].

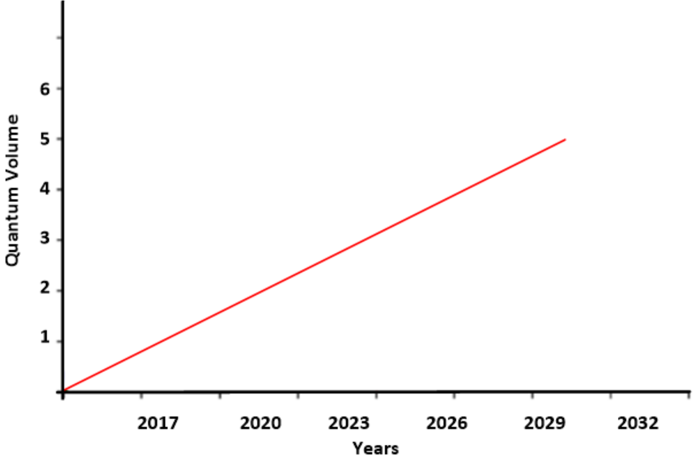

Figure 6. Exponential forecast for growth of quantum processing power [13]

Quantum entanglement can exponentially increase computing power. Two classical bits can be either 0 or 1; both can have one of the following values: {(0, 0), (0, 1), (1, 0), (1, 1)}. Conversely, two qubits can have all values at once, due to entanglement.; therefore, in this scenario, 2 qubits can represent all 4 possible classical states simultaneously. Table II shows the above logic for increasing the number of bits/qubits [14].

Table 2. Qubits Equivalent Performance [14]

Qubits	Required Bits	Classical RAM	Classical Time
10	1024	128 Bytes	2.6 μs
20	1,048,576	131 KB	0.26 ms
30	1.1×10^{9}	134 MB	0.27 s
40	1.1×10^{12}	137 GB	4.6 min
53	9×10^{15}	1 TB	625 h
63	9×10^{18}	1 PB	73 years
100	9×10^{30}	1 EB	10^{13} years
1000	9×10^{301}	1.3×10^{232} EB	8.5×10^{283} years

Quantum computers are not advantageous for all the problems to be solved. In general, quantum computers are advantageous in computing problems where a quantum algorithm exhibits slower growth in computational time compared to the corresponding classical algorithm., as shown in Fig. 6. for problems that involve highly complex or multifaceted relationships among data features. [15].

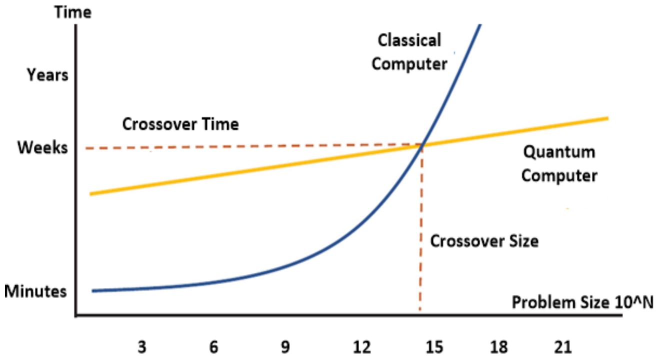

Figure 7. Time scaling dissimilarities between quantum and classical computing [15].

In classical computer systems, new algorithms must determine the number of computational steps required. These steps are usually expressed as a function of N, where N is the size of the problem. The number of steps in the computation rises linearly with N. In comparison, the quantum algorithm rises as the square root of the step size. This indicates that if a sequence of 100 steps (N=100) is performed, then the classical algorithm needs 10x times more steps. As the step size gets larger, this trade-off changes in favor of a more quantum algorithm and quantum computing becomes faster, as shown in Figure 7.

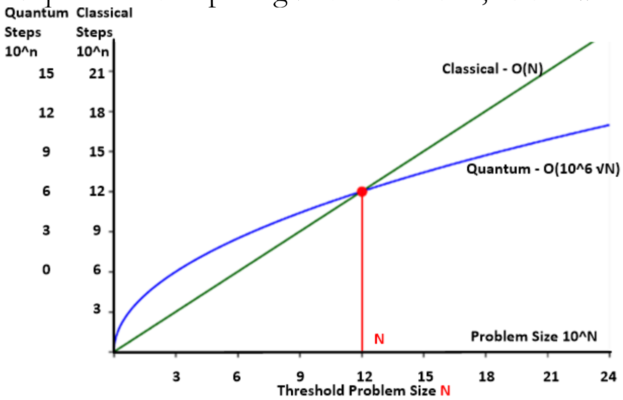

Figure 8. Comparing classical and quantum algorithms [16]

Fig. 8 illustrates an important property: if the problem is bigger, then the greater the potential benefit from a quantum algorithm. This graph shows a threshold point N. At this point, the problem becomes so huge that the advantage of the quantum algorithm becomes more apparent as problem size increases. N=1 trillion (i.e., 1012) is the cutoff point; Grover's algorithm is beneficial for problems only bigger than this N.

Discussion:

The prospects of quantum computing are boundless; however, there are challenges, some of which include error correction, qubit coherence, and hardware scalability. Even with exponential improvements, attaining 40,000 error-free qubits would require considerable work. For quantum computing to fully take advantage of its abilities, further development in quantum software is needed. For businesses and researchers, the main issue is that quantum computing is not a one-size-fits-all replacement for classical computing. Instead, it is a specialized tool for certain problems where quantum algorithms promise exponential speedup. The most obvious ones are cryptography, optimization, and material simulation, for which the real impacts of quantum computing will be felt. One example of a complex problem is the occurrence of impulse noise that is statistically random and very difficult to predict. The high computation capability and probabilistic nature of quantum computing can help in predicting the occurrence of impulse noise [11]. Quantum Volume on the part of IBM represents a more holistic view of quantum performance. While the number of qubits is an important indicator, involving all metrics, from error rates to algorithmic efficiency, will ultimately be the deciding factor when quantum computers become useful in real-world applications. If that rate of progress continues, the decade after next may see the emergence of large-scale quantum breakthroughs, transforming industries that depend on computation-laden tasks.

Recommendations:

Based on the comparative analysis of classical and quantum computing paradigms, it is recommended that classical computing continue to be employed for tasks requiring deterministic execution, scalability, and well-established hardware support. Quantum computing should be explored for computational problems involving high complexity, such as optimization, cryptography, and large-scale simulations, particularly within the constraints of the NISQ era. Hybrid classical–quantum approaches are recommended as a practical near-term solution, allowing classical systems to handle control and preprocessing while quantum processors address problem components where quantum advantage is expected. Future research should focus on experimental validation and noise-aware algorithm design to improve real-world applicability.

Conclusion:

The fundamental and mathematical dissimilarity between classical bits and quantum bits lies in the representation of information. Classical bits are binary and deterministically either 1 or 0, while qubits remain in the superposition of these states. Quantum superposition permits single qubits to exist in various states at the same time, whereas quantum entanglement involves a strong and non-classical correlation between two or more qubits, where the measurement of one qubit affects the state of another, even at a distance. Both phenomena are essential in quantum computing and are harnessed in various computer algorithms and technologies. Therefore, quantum algorithms that execute multiple options simultaneously require many fewer steps compared to classical algorithms and perform faster.

The comparative analysis between classical bits and quantum bits has direct relevance to emerging computational challenges in optimization, cryptography, machine learning, and large-scale simulations. With potential emphasis on the future of quantum computing, hardware shortages, tune-up of quantum algorithms, and realization of quantum advantage, research will concentrate on scalable and error-free qubit systems. Hybrid quantum-classical computing and new quantum algorithm designs for optimization, artificial intelligence, and cryptography will get the focus. With the augmentation of quantum volume will come disruption in industries like finance, materials science, and cybersecurity; the quantum cloud will further allow for widespread use. By 2040, quantum computing might transform problem-solving entirely, overtaking classical systems in certain domains. Yet quantum computers will face some more challenges before they can be put to significant use for error correction and scalability. The research will keep defining the path.

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