

“A REVIEW ON QUANTUM COMPUTING: CONCEPTS, WORKING PRINCIPLES, ADVANTAGES, LIMITATIONS, AND RECENT ADVANCEMENTS”

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ABSTRACT

Quantum computing harnesses quantum mechanics to process information in fundamentally new ways. This review systematically examines the core concepts of quantum computing, contrasting them with classical computing, and surveying recent developments. Our methodology is a comprehensive literature review of high-impact sources (IEEE, Springer, Nature, and Google Scholar) from 2019–2024. We outline how qubits, superposition, entanglement, and quantum gates form the basis of quantum computers, and we compare classical and quantum architectures. Key insights include the theoretical speed-ups of quantum algorithms (e.g. Shor’s and Grover’s) and the broad applications in cryptography, optimization, artificial intelligence, and drug discovery^{[1][2]}. At the same time, we discuss practical limitations: current devices are small, noisy, and require complex error correction^{[3][4]}. Recent breakthroughs such as Google’s Sycamore supremacy experiment and IBM’s 433-qubit Osprey highlight rapid hardware scaling^{[5][6]}. We conclude that while quantum computing is not yet ready for general-purpose tasks, ongoing advances in qubit count, coherence, and error correction promise transformative impacts.

KEYWORDS: Quantum Computing, Qubit, Superposition, Entanglement, Quantum Gate, Quantum Algorithm.

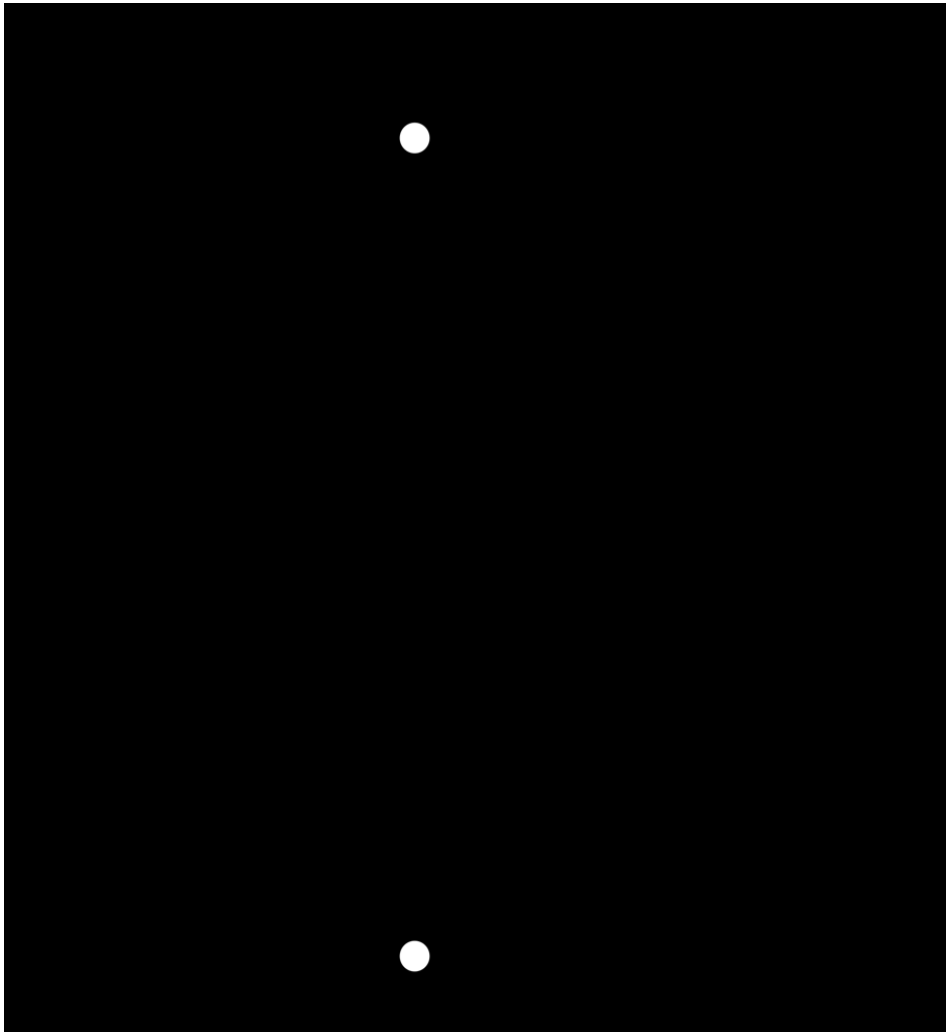
INTRODUCTION

Quantum computing is an emerging paradigm of computation that uses the principles of quantum mechanics to process information. Unlike classical bits, which can only be 0 or 1, a quantum bit (or *qubit*) can exist in a superposition of both states simultaneously[7]. This enables quantum computers to potentially handle certain problems much faster than classical machines. For example, Gill and Buyya (2026) note that quantum computing “uses the principles of quantum mechanics to handle highly challenging situations in a very short amount of time,” with the potential to revolutionize industries from communications to materials science[8]. Traditional computers are based on Boolean logic, whereas quantum computers exploit phenomena such as superposition and entanglement that have no classical analog. This difference is crucial because many important problems in cryptography, optimization, and simulation are believed to be intractable for classical devices but solvable by quantum ones[9][10]. The importance of quantum computing has grown today due to these theoretical advantages and the increasing investment in quantum technology worldwide. Governments and corporations are developing quantum hardware and software, aiming to demonstrate practical use-cases. Given this rapid progress, a comprehensive review is motivated to clarify the fundamentals and survey the latest advances. This paper’s scope is to present an in-depth review of the concepts and working principles of quantum computing, compare it with classical computing, and discuss recent advancements such as quantum supremacy experiments and error correction research.

MATERIALS AND METHODS

This work is structured as a systematic literature review. We searched major academic databases including IEEE Xplore, SpringerLink, Nature Journals, and Google Scholar for publications between 2019 and 2024 on quantum computing. Keywords such as “quantum computing,” “qubit,” “quantum algorithms,” and “quantum hardware” were used to filter relevant articles. Our analysis focuses on conceptual comparison and qualitative synthesis. We examined the fundamental building blocks of both classical and quantum systems, and constructed comparative tables and narrative summaries to highlight differences in information encoding, operations, and performance. The methodology emphasizes conceptual and comparative analysis: for example, we compare classical logic gates to quantum gates, and classical bits to qubits. Insights are drawn by cross-referencing multiple review articles, technical surveys, and experimental reports to ensure a balanced and comprehensive overview.

RESULTS AND DISCUSSION



The qubit is the fundamental unit of quantum information. A qubit can be represented as a state vector on the Bloch sphere, a geometrical model of a two-level quantum system. In the Bloch sphere figure above, the north and south poles represent the classical basis states $|0\rangle$ and $|1\rangle$, while any point on the sphere's surface represents a superposition of these states. Mathematically, a qubit's state $|\psi\rangle$ is given by $\alpha|0\rangle + \beta|1\rangle$, where α and β are complex amplitudes satisfying $|\alpha|^2 + |\beta|^2 = 1$ ^{[7][11]}. Superposition means the qubit holds both 0 and 1 simultaneously (in a probabilistic sense) until measured. This allows a quantum computer to explore many states in parallel. Upon measurement, the qubit collapses to 0 or 1 with probabilities $|\alpha|^2$ and $|\beta|^2$.

Entanglement is another uniquely quantum phenomenon that links qubits. When qubits become entangled, the state of one qubit instantaneously affects the state of another, regardless of distance^[12]. This correlation has no classical analogue and is a key resource for

quantum computing. For instance, entangled qubits can encode joint information efficiently and enable quantum teleportation and error correction protocols. Modern experiments have even captured images of entangled photons (as in an experiment by Glasgow University, shown below), illustrating that entangled particles behave as a unified system^[12].



Figure: A captured image of two entangled photons (Bell-state entanglement). Each bright ring corresponds to correlated photon events; such entanglement underpins quantum computation and quantum cryptography^[12].

Quantum gates operate on qubits in ways that generalize classical logic gates. A quantum gate is a reversible unitary transformation on one or more qubits^[13]. Common gates include the Hadamard gate (which creates superposition), Pauli gates (which flip or phase-flip qubits), and the controlled-NOT (CNOT) gate (which entangles qubits). Unlike classical

gates, quantum gates can manipulate the amplitudes of superposed states without measuring them, allowing interference effects. For example, a Hadamard gate transforms $|0\rangle$ into $(|0\rangle+|1\rangle)/\sqrt{2}$, creating equal superposition^[7]. Building sequences of quantum gates creates quantum circuits that implement algorithms.

Comparing quantum and classical computers highlights their fundamental differences. The table below contrasts key aspects:

Aspect	Classical Computer	Quantum Computer
Basic unit	Bit (0 or 1)	Qubit (can be in superposition of 0 and 1) ^[7]
State representation	Single definite state at any time	Superposition of basis states ^[7]
Information processing	Deterministic logical operations	Reversible unitary operations (quantum gates) ^[13]
Parallelism	Limited (one state per computation path)	Inherent quantum parallelism via superposition ^[13]
Algorithmic nature	Sequential or parallel on classical cores	Exploits interference of amplitudes (e.g., Grover's interference) ^[1]
Error & noise sensitivity	Relatively robust, mature error correction	Highly susceptible to decoherence ^[4] , needs quantum error correction
Practical status	Widely available, scalable (Moore's Law)	Prototype NISQ devices (tens to hundreds of qubits) ^[14]
Example tasks	Binary arithmetic, Boolean search	Factoring large numbers (Shor's), database search (Grover's) ^[10]

Advantages: Quantum computers offer theoretical speed-ups for certain problems. In cryptography, for instance, Shor's algorithm can factor large integers exponentially faster than the best known classical algorithms^[10], threatening RSA encryption. Grover's algorithm offers a quadratic speedup for unstructured search^[1], which could accelerate database search and optimization. Quantum computers also excel at simulating quantum systems. They can model molecular interactions and materials properties natively, enabling advances in drug discovery and materials science^{[2][15]}. For example, NISQ (Noisy Intermediate-Scale Quantum) devices have been used to compute the ground-state energies of small molecules more efficiently than classical simulation^[2]. Other advantages include exploring high-dimensional optimization spaces (via algorithms like QAOA)^[16] and enhancing machine learning (quantum neural networks and support vector machines can process large datasets in novel ways)^[15]. Overall, quantum parallelism and entanglement provide capabilities beyond classical reach for specific problem classes.

Disadvantages and Limitations: Current quantum computers face serious challenges. The main limitation is hardware fragility: qubits are prone to errors due to decoherence and noise, and quantum gates have limited fidelity^{[4][3]}. As Kumar and Pinheiro note, “current quantum devices possess significant limitations. Among major problems are short qubit coherence time, low gate fidelity, and limited qubit systems,” making large-scale computation extremely difficult^[4]. Moreover, quantum error correction requires many physical qubits per logical qubit, which is not yet achievable. NISQ devices have only tens to a few hundred qubits and lack full error correction^[14]. As a result, practical quantum algorithms (like full Shor’s algorithm) remain out of reach, and many advantages exist only “on paper.” Scalability, fabrication of qubit systems, and maintenance of quantum coherence are all active research challenges. Also, quantum computation is probabilistic, requiring repeated runs to get reliable results. These issues limit current applications to mostly specialized tasks and simulations.

Applications: Potential applications of quantum computing span many domains. In **cryptography**, quantum computers could break current public-key systems; Shor’s algorithm could crack RSA keys in realistic time^[10]. Conversely, quantum technology enables new secure communication methods (e.g. quantum key distribution) that classical systems cannot match. In **artificial intelligence and machine learning**, quantum algorithms (quantum-enhanced neural networks, clustering, support-vector machines) promise to improve pattern recognition and optimization^[15]. In **drug discovery and chemistry**, quantum simulation can model molecular structures exactly, which is currently intractable classically^[2]. Companies are already exploring quantum-assisted material design and reaction simulations. In **optimization**, many combinatorial problems (logistics, finance) could see speedups via quantum approximate optimization algorithms (QAOA)^[16]. Quantum computing also impacts **sensing and metrology** through entanglement-enhanced measurements, and could revolutionize areas like climate modeling, traffic routing, and beyond. These applications remain largely experimental today, but research indicates substantial future gains if technological hurdles are overcome^{[9][2]}.

Recent Inventions and Advancements: Major milestones have been achieved in recent years. In 2019, Google’s 53-qubit “Sycamore” processor performed a random circuit sampling task that took ~200 seconds, which Google claimed would take classical supercomputers thousands of years – a demonstration of “quantum supremacy”^[5]. (This claim was contested by IBM researchers but remains a watershed moment.) Since then, hardware

scale has grown rapidly. For example, IBM introduced the Osprey processor with 433 qubits in 2022, and plans a 1,121-qubit “Condor” by 2023^[6].



IBM’s new 433-qubit **Osprey** processor significantly advances superconducting qubit technology^[6]. Osprey’s layered design (shown above) isolates and controls hundreds of qubits. This tripled the qubit count of IBM’s 127-qubit Eagle chip, and sets a path toward the 1121-qubit Condor system^{[6][17]}. Such hardware scaling is accompanied by improved control electronics and cryogenic designs that boost coherence. Other companies and platforms have also progressed: IonQ, Rigetti, and others have reached dozens of high-quality qubits, and topological qubit prototypes are being explored.

In parallel, researchers are advancing **quantum error correction and fault tolerance**. For instance, Google Quantum AI (2024) demonstrated a distance-7 surface code on 105 qubits with error rates below the fault-tolerance threshold^[18]. This landmark experiment showed logical qubit error decreasing exponentially with code distance, indicating a path toward truly fault-tolerant quantum memory. Ongoing work in codes and qubit design aims to achieve ‘below-threshold’ error rates, which are essential for running large-scale algorithms^{[18][3]}.

These developments illustrate that while practical general-purpose quantum computers are not here yet, the field is rapidly moving forward. Several quantum cloud services are available today for experimentation, and ecosystems of software tools (Qiskit, Cirq, PennyLane) are maturing. The synergy of theoretical algorithms with emerging hardware

drives optimism. However, it remains a critical challenge to demonstrate clear “quantum advantage” on real-world tasks; current devices are still in the NISQ era^[14], meaning that they can perform useful but noise-prone quantum behavior. Looking ahead, many experts expect **hybrid quantum-classical architectures**, where quantum processors act as accelerators for specific subroutines while classical computers handle coordination, will be the norm^[19]. This approach may yield early practical gains as hardware continues to improve.

CONCLUSION

This review has summarized that quantum computing leverages qubits, superposition, entanglement, and quantum gates to pursue computational advantages beyond classical methods^{[7][1]}. We contrasted quantum systems with classical ones and identified key strengths: notably, quantum algorithms can in principle accelerate search and factorization, and quantum devices excel at simulating quantum phenomena. We also highlighted significant limitations: current machines have few qubits, short coherence times, and require complex error correction^{[4][3]}. In practice, most quantum applications today remain experimental or hybrid. Nevertheless, rapid progress — exemplified by Google’s supremacy experiment and IBM’s 433-qubit Osprey — indicates an accelerating trajectory. As hardware, error correction, and algorithms mature, quantum computers are expected to complement classical supercomputers in solving specialized problems. The future scope of quantum computing includes achieving fault-tolerant devices, integrating quantum accelerators into hybrid computing stacks, and unlocking new applications in cryptography, materials, optimization, and AI. While still nascent, the field’s advances suggest a transformative potential akin to past shifts like the rise of classical computing or modern AI. Continued research across theory, engineering, and application domains will determine when and how quantum computing realizes its promise.

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