

# A Comprehensive Survey on Quantum Computing Systems

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**Abstract:** Quantum computing represents a groundbreaking technological advancement that can tackle problems beyond traditional computers' reach. This innovative approach leverages quantum mechanical principles to execute computations in ways that surpass the capabilities of conventional computing systems. In theory, certain computation tasks can be completed exponentially quicker on quantum machines compared to their classical counterparts. This article provides a comprehensive examination of the rapidly advancing quantum computing approaches, encompassing recent developments in quantum hardware, programming languages, algorithmic methods, error mitigation techniques, and practical applications across various fields, including cryptography, sensing, and simulation. The study examines how quantum computers may potentially drive breakthroughs in various fields, including medicine, materials science, and artificial intelligence. Additionally, it addresses the obstacles that must be overcome to fully realise the transformative potential of this cutting-edge computing paradigm.

**Keywords:** Quantum computing, quantum algorithms, quantum error correction, quantum applications, quantum tools.

## 1. INTRODUCTION

The field of quantum computing is an advanced technology that uses quantum mechanical principles to perform calculations beyond the capabilities of traditional computers. Unlike conventional computers that use bits for processing information, quantum computers utilise quantum bits, or qubits, which can exist in a superposition, representing both 0 and 1 simultaneously [1]. (Quantum Computing Explained, n.d.) This unique trait allows quantum computers to manage large amounts of data at once, potentially solving complex problems faster than their classical counterparts. To illustrate, imagine navigating a busy city with countless routes. A classical computer might evaluate each route one by one to find the shortest. In contrast, a quantum computer can assess multiple routes at the same time, thanks to qubit superposition, quickly identifying the most efficient path. The development of quantum computing offers the potential to transform various sectors, including cryptography, materials science, artificial intelligence [2], optimisation and simulation, and data management, by delivering unparalleled computational power. (The Impact of Quantum Computing on Present Cryptography, 2025)

The development of a quantum computing system involves multiple aspects, including quantum algorithms, hardware architectures, error correction methods, and practical applications. Quantum algorithms are used for integer factorisation and database search, demonstrating theoretical speedups over classical algorithms, showcasing the potential of quantum computing. These algorithms require robust quantum hardware capable of maintaining coherence and minimising error. To create scalable and dependable quantum processors, a variety of physical implementations are being investigated, including system qubits, trapped ions, and superconducting qubits.

Quantum technologies are highly sensitive to error due to DE coherence and environmental noise, necessitating advanced error correction techniques and fault-tolerant architectures. The scaling of quantum computers to a large number of qubits while maintaining coherence and minimising error rates is a major

technical hurdle. The exchange between hardware and software development is crucial in overcoming these challenges, as advancements in quantum error correction, quantum algorithms, and materials science contribute to building more robust quantum systems.

In binary representation, a bit, the fundamental unit of classical computing, can have two possible values: '0' and '1'. In contrast, the basic unit of information in quantum computing is a quantum bit, or qubits can be "0", "1" or both "0" and "1" simultaneously due to quantum mechanics. A qubit can be expressed mathematically as  $a|0\rangle + b|1\rangle$ , where  $a$  and  $b$  are coefficients that permit the superposition or mixing of "0" and "1" states. Many problems with high computational complexity can be resolved by leveraging qubits' superposition, allowing access to a vast computational space. A 3-bit number can have one value at any given time from the following set of eight potential values: {000,001,010,011,100,101,110,111}. All eight values can be superposed to form a 3-qubit state:  $a|000\rangle + b|001\rangle + c|010\rangle + d|011\rangle + e|100\rangle + f|101\rangle + g|110\rangle + h|111\rangle$ . This means that increasing the number of bits in a conventional computing machine by two will only double the computational space, but the same result can be obtained by increasing the number of qubits from three to four by just one, or from 23 to 24.

This survey's goal is to offer an in-depth look at the present status of quantum computing technology, with a focus on advancements in quantum algorithms, hardware, error correction, and real-world applications. This paper aims to provide insights into the future of quantum computing research and its potential impact on different fields by analysing the advancements and difficulties in each of these areas. Understanding the technological foundations of quantum computing is crucial for both researchers and practitioners as it transitions from theoretical exploration to experimental realisation.

## 2. Related Works

In the literature, many review papers have been devoted to the realm of quantum computation and information. Several surveys address Quantum computing technologies and their applications.

Sterne et al. [1] reviewed the intersection of quantum computing, classical information theory, and quantum physics. It outlines the significance of quantum information theory, highlighting concepts like quantum cryptography, quantum error correction, and quantum computation. The review emphasises the role of quantum entanglement as a computational resource and explores the principles of quantum error correction to preserve quantum coherence during computation. Additionally, it touches on experimental advancements in quantum computing and the challenges of correcting errors in quantum systems. Singh [4] presented an overview of quantum computing tools and technologies for groundbreaking research and addressed challenges, advancements, and prospects in the quantum computing field.

F.F. Flusher [8] and R. U. Racoon et al [12] gave an overview of Quantum technologies in medicine and healthcare [7]. Quantum algorithms enhance genomics, diagnostics, and treatments in medicine. Quantum computing's potential in health and medicine applications. Halbouniet et al. [16] reviewed intrusion detection systems that use machine learning and deep learning [10]. Their work discusses learning algorithms, network implementations, and operational systems, with a focus on datasets, algorithms, and applications for effective cybersecurity measures [2]. F. Acute et al. reported [20] Quantum supremacy achieved using a 53-qubit processor with high-fidelity gates. Quantum processor outperforms classical supercomputers, marking a significant advancement. Quantum computing is transitioning from research to practical technology with new capabilities. The remaining articles gave a concise overview of the main directions that have been taken to develop quantum computing technologies.

### 3. Fundamentals of Quantum Computing

The principles of quantum mechanics [6], a branch of physics that describes how particles behave at the atomic and subatomic scales, are the foundation of quantum computing. Unlike classical computing, qubits utilised in quantum computing can exist in multiple states at once rather than being limited to values of 0 or 1.

#### 3.1 Qubits:

The basic unit of information in quantum computing is the quantum bit, or qubit. A qubit differs from a classical bit in that it can represent a superposition of both 0 and 1 concurrently.

#### 3.2 Quantum Superposition:

A cubit can exist in a state that is a linear combination of the  $|0\rangle$  and  $|1\rangle$  states [21]. Mathematically, this is represented.

Where  $a$  and  $b$  are complex numbers that represent the probability amplitudes of the qubit being in the  $|0\rangle$  or  $|1\rangle$  state, respectively. The probabilities are given by, and the condition  $|a|^2 + |b|^2 = 1$  must be fulfilled.

#### 3.3 Quantum Entanglement:

Quantum entanglement is an uncommon correlation involving qubits that is not classically explainable. When two or more cubits become entangled, the state of one cubit is linked to the state of the others, regardless of the distance between them.

## 4. Classical Physics and Quantum Physics

Classical physics is useful for understanding the large-scale world, whereas quantum physics is Quantum physics and classical physics are distinct method for comprehending the universe, necessary for explaining the behaviours of tiny particles and basic forces. The study of quantum mechanics has not only transformed physics, but it has also led to significant technological advancements that continue to impact our everyday activities.

### 4.1 Classical Physics

Explains the principles that dictate the behaviour of large-scale phenomena, like the movement of objects, orbits of planets, and characteristics of gases and liquids. It covers Newton's mechanics and wave theory. Accurate for large objects where quantum effects can be ignored in comparison to the speed of light.

### 4.2 Quantum Physics

Focuses on how atomic and subatomic particles, such as electrons, photons, and other fundamental particles, behave. The Heisenberg uncertainty principle, quantum entanglement, wave-particle duality, and quantum field theory are all included the need to explain phenomena that are outside the scope of classical physics, like semiconductor physics, laser and superconductor operation, and the behaviour of electrons in atoms.

## 5. Classical Computing and Quantum Computing

Classical and quantum computing represent two very different approaches to computing. Classical computers will always be necessary for most everyday tasks. Nevertheless, quantum computers could transform various sectors [4] by offering answers to currently unsolvable problems. Understanding the differences between these two paradigms is crucial as we approach a time when quantum computing may complement classical computing for furthering advancements in science, technology, and other fields.

### 5.1 Classical Computing

The bit, the basic building block of information, can be in either of two states: 0 or 1. This binary architecture, on which all classical computers run, uses logical gates to manipulate bits to carry out operations.

### 5.2 Quantum Computing

The fundamental unit of information in quantum computing is the cubit. Unlike bits, cubits can exist in a state of 0, 1, or any quantum superposition of these states. This ability to be in multiple states simultaneously allows quantum computers to process a vast amount of information more efficiently than classical computers.

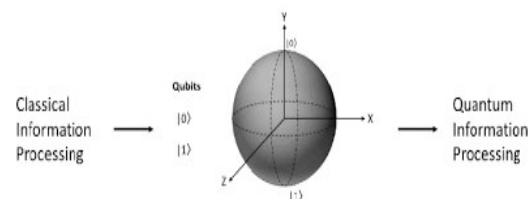


Figure 1 : Information processing of quantum computing

## 6. Types of Quantum Computing

- **Gate-Based Quantum Computing:** Gate-based quantum computing, also known as the circuit model, is the most common approach to quantum computing. The logical operations are performed using quantum gates on qubits.
- **Quantum Annealing:** Quantum annealing is a specialised type of quantum computing designed to solve optimisation problems by finding the lowest energy state of a system.
- **Topological Quantum Computing:** Topological quantum computing is a theoretical model that aims to use quantum mechanics for computation. It is designed to be more resistant to errors and coherent than other forms of quantum computing.
- **Photonic Quantum Computing:** Photons, or light particles, are used as qubits in photonic quantum computing. This kind makes use of the entanglement and superposition that are inherent to light.
- **Adiabatic Quantum Computing:** Adiabatic quantum computing (AQC) is similar to quantum annealing. It relies on the adiabatic theorem of quantum mechanics, which ensures that a system remains in its ground state if changes to the Hamiltonian are slow enough.

## 7. Quantum Hardware

Developments in quantum hardware [20] are critical to the implementation of quantum computing. To create scalable and dependable quantum computers, several technologies are being investigated, including:

- **Superconducting Cubits:** Superconducting circuits are one of the most mature technologies for building quantum computers. Companies like IBM and Google have developed quantum processors with superconducting qubits that demonstrate high-fidelity operations and scalability.
- **Trapped ions:** Ions held inside electromagnetic traps are used as qubits in trapped ion quantum computers. This technology is a good contender for quantum computing because it provides lengthy coherence durations and high-fidelity quantum gates.
- **Topological Cubits:** A theoretical technique known as topological quantum computing seeks to create cubits that are intrinsically immune to external noise by utilizing anyons, which are particles existing in two-dimensional environments. Although this technology is still in its early stages, it has the potential to produce scalable and reliable quantum computers.

## 8. Quantum Gates

In a quantum computer, quantum gates operate unitarily on quantum states. Since each quantum circuit may be broken down into a sequence of Feynman or Fredkin gates, which can also mimic NOT or CNOT (Controlled Not) gates, three-bit Toffoli and Fredkin quantum gates are crucial. In other words, universal quantum calculations can be made possible by any gate. Only significant outputs are retained after clearing the ancilla states because quantum gates are reversible.


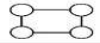
Gate	Equation	Matrix	Transform
Identity (I)	$I =  0\rangle\langle 0  +  1\rangle\langle 1 $	$\begin{pmatrix} 1 & 0 \\ 0 & 1 \end{pmatrix}$	$I 0\rangle =  0\rangle$ $I 1\rangle =  1\rangle$
Pauli-X (X or NOT)	$X =  0\rangle\langle 1  +  1\rangle\langle 0 $	$\begin{pmatrix} 0 & 1 \\ 1 & 0 \end{pmatrix}$	$X 0\rangle = \frac{1}{\sqrt{2}} 1\rangle$ $X 1\rangle = \frac{1}{\sqrt{2}} 0\rangle$
Hadamard (H)	$H = \frac{1}{\sqrt{2}}( 0\rangle +  1\rangle)$	$\frac{1}{\sqrt{2}}\begin{pmatrix} 1 & 1 \\ 1 & -1 \end{pmatrix}$	$H 0\rangle = \frac{1}{\sqrt{2}}( 0\rangle +  1\rangle)$ $H 1\rangle = \frac{1}{\sqrt{2}}( 0\rangle -  1\rangle)$
Controlled- NOT (C)	$CNO =  0\rangle\langle 0  \otimes I +  1\rangle\langle 1  \otimes X$	$\begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 1 \\ 0 & 0 & 1 & 0 \end{pmatrix}$	$CNOT 00\rangle =  00\rangle$ $CNOT 01\rangle =  01\rangle$ $CNOT 10\rangle =  11\rangle$ $CNOT 11\rangle =  10\rangle$
Toffoli T or CCNOT	$T =  0\rangle\langle 0  \otimes I \otimes I +  1\rangle\langle 1  \otimes X$	$\begin{pmatrix} 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 \end{pmatrix}$	$T 000\rangle =  000\rangle$ $T 001\rangle =  001\rangle$ $T 010\rangle =  010\rangle$ $T 011\rangle =  011\rangle$ $T 100\rangle =  100\rangle$
			

Figure 2 : Details of Quantum Gates

## 9. Quantum Software

The architecture of quantum software (4) can be represented through components and connectors, where Qubits and Qugates are mapped to these architectural elements. This representation serves as a blueprint for implementing Quantum software. Qiskit, Cirq, and Qe are the most common quantum programming languages.

### 9.1 Quantum Software Tools and Technologies

- **Ocean SDK:** Developed by D-Wave Systems, this SDK focuses on quantum annealing algorithms and provides tools [4] for problem formulation, execution of quantum annealing experiments, and data analysis
- **Forest SDK:** Created by Rigetti, this quantum software platform allows users to explore quantum programming and research. It includes access to Rigetti's quantum processors, simulators, and quantum cloud services, facilitating the development of quantum and hybrid algorithms.
- **Qiskit:** An open-source software development kit from IBM. Working with quantum computers at the circuit, pulse, and algorithm levels is possible with Qiskit. It integrates with Python and supports various quantum hardware architectures.
- **Microsoft Quantum Development Kit:** This comprehensive toolkit from Microsoft is aimed at empowering quantum programming and research endeavours, providing a range of tools for developing quantum applications

## 10. Quantum Cryptography

Quantum cryptography [2], a form of encryption, utilises principles of quantum physics to enhance the security of communication systems. Unlike standard encryption, which depends on mathematical difficulty, quantum cryptography uses the special properties of particles, such as superposition and entanglement, to guarantee safe key exchange and protect data from eavesdropping. The most widely used application of quantum cryptography is called Quantum Key Distribution (QKD), which uses the no-cloning theorem and the Heisenberg uncertainty principle to allow safe key exchange between two parties while detecting eavesdropping attempts.

As quantum computing advances, the importance of quantum cryptography is increasing to safeguard data from potential threats posed by quantum computers that may be able to break traditional encryption methods.

### 11. Quantum Computing in Machine Learning and Deep Learning

Quantum entanglement enhances input processing and feature extraction in quantum neural networks, leading to heightened accuracy and robustness of deep learning models [7]. Due to its ability to perform parallel computations and utilise quantum parallelism, quantum computing can enhance machine learning methods by efficiently handling large datasets and optimising complicated models. The remarkable capacity of quantum computing to handle and compute vast volumes of data. Quantum neural networks can utilise quantum entanglement to enhance information processing and feature extraction. This could lead to more robust learning models capable of handling complex patterns and data representations.

### 12. Quantum Algorithms

Quantum algorithms [23] outperform their classical counterparts in problem-solving by taking advantage of quantum superposition, entanglement, and interference. The following are some of the most popular quantum algorithms:

- **Shor's Algorithm:** Developed by Peter Shor, this algorithm can factorise large integers exponentially faster than the best-known classical algorithms, posing a significant threat to classical cryptography
- **Grover's Algorithm:** Lov Grover developed this method, providing a quadratic improvement for unstructured search issues. For tasks like these, it is much faster than any traditional method. Grover's algorithm offers a quadratic speed increase compared to searching each item individually, by locating the target element in  $\sqrt{N}$  steps instead. In order to find the target element quickly, it uses Grover diffusion operators and Oracle diffusion operators repeatedly after placing the system in a uniform superposition across all states.
- **Quantum Approximate Optimisation Algorithm (QAOA):** QAOA is designed for solving combinatorial optimisation problems and has shown promise in outperforming classical optimisation algorithms under certain conditions
- **Factorised Quantum Search Algorithm:** The factorised quantum search algorithm efficiently locates objects in unordered databases with a querying complexity of  $O(\log^4 N)$ , utilising sorting to facilitate searches and factorisation to enhance search performance.
- **Quantum-Inspired Ant Colony Algorithm:** The quantum-inspired ant colony algorithm aims to identify the most efficient join order in distributed databases by minimising the overall query plan cost, utilising a sum of IO and data transfer costs as the total cost metric.
- **Quantum Approximate Optimisation Algorithm (QAOA):** QAOA is a layered quantum circuit that uses shallow quantum circuits and a variational nature to solve a

variety of combinatorial optimisation problems on Noisy Intermediate-Scale Quantum (NISQ) devices.

### 13. Quantum Error Correction

Quantum error correction is essential for making quantum computers a reality since qubits are classically prone to errors caused by decoherence [11] and imperfections in operations. Error-correcting codes such as the Surface Code and Steane Code are created to identify and fix errors while preserving the quantum state. The surface code, for example, has been commonly embraced because of its relatively minimal resource usage and ability to tolerate faults. Efficient error correction methods are crucial for quantum computers to reliably handle complex computations when scaling.

### 14. Practical Applications of Quantum Computing

Quantum computing holds promise for various applications that are currently infeasible for classical computers:

- **Cryptography:** Quantum computers have the potential to break widely used cryptographic protocols, such as RSA and ECC, through algorithms like Shor's. Conversely, quantum cryptography, based on principles like quantum key distribution, offers secure communication.
- **Optimisation Problems:** Quantum algorithms like QAOA and the Quantum Annealing technique, used by D-Wave systems, show potential in solving complex optimisation problems.
- **Material Science and Drug Discovery:** Quantum simulations can model molecular and chemical interactions at a quantum level, enabling breakthroughs in material science and drug discovery that traditional computers cannot handle.

### 15. Challenges and Future Directions

Lowering error rates, preserving qubit coherence, and achieving scalability are a few hurdles in quantum computing. Creating usable quantum software and algorithms that fully utilise quantum hardware's capabilities is still an ongoing area of research. Future studies should centre on:

- Enhancing the durability of qubit coherence and the accuracy of gate operations.
- Creating strong quantum error correction techniques
- Expanding quantum systems to a greater quantity of qubits.
- Developing effective quantum algorithms for practical use cases

### 16. CONCLUSION

In this study, we looked into the literature and current research directions on quantum computing. We outlined the components of quantum computing, the milestones leading to the advancement of large-scale quantum systems, and the most recent breakthroughs in studies on the practical applications of quantum devices, computers, and algorithms. Additionally, we addressed several incoming challenges in the field. The paper's conclusion is deemed satisfactory, and the findings are encouraging. By leveraging the fundamental properties of information, quantum

information processing creates new avenues for networking, communication, and computation. The technologies associated with quantum computing have the potential to significantly improve future computational and communication capabilities.

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