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A Review Study of Quantum Computing

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Abstract : A new paradigm of computation has appeared recently that is known as quantum computing and which is able to solve difficult problems that cannot be solved using classical computing. It provides a comprehensive overview of the basic concepts, computational models, architectures, tools, applications and implications of quantum computing. The paper is based on the latest research, and it's used to evaluate the state of quantum computing, from theory to practical, application-oriented implementations. Fundamental concepts such as qubits, superposition, entanglement and hybrid quantum-classical computation are explained, along with major models and frameworks of quantum computing, including Cirq, TensorFlow Quantum and ProjectQ. Furthermore, various significant application areas, such as cryptography, optimization, AI, drug discovery, and industrial computing, are explored, highlighting the applications' potential and their technological development. Although great strides have been made, scalability, noise, error correction, interoperability and hardware challenges are major problems in the NISQ era. It also examines new trends, future research directions and the societal, security and ethical considerations of the advancement of quantum technology. But the bigger picture indicates that quantum computing is progressing from theory to reality, and there are many technical and institutional challenges to be resolved along the way. Interdisciplinary studies and responsible innovation will be key to unlocking the potential of quantum computing as the next generation of computational technology.

Keywords : Quantum Computing, Quantum Algorithms, Qubits, Quantum Machine Learning, Quantum Optimization, Noisy Intermediate-Scale Quantum (NISQ).

1. INTRODUCTION

The development of computational technologies has been a key enabler in advancing science and industry [1]. While classical computing, working with binary logic and deterministic operations, has been a great success, it is facing fundamental limitations in applications like cryptography, optimization and material science in solving computationally intractable problems [2]. With the complexity of the problems has grown the interest in alternative paradigms of computation, notably quantum computing. The basis of quantum computing is that information is processed in a different manner than at present, based on the principles of quantum mechanics, most notably superposition, entanglement and quantum interference. Unlike classical bits, a qubit can be in several states at once, which allows for parallel computation and potentially exponential speedups for certain areas of problem-solving [3], [4]. Such properties make quantum computing a game-changing technology with potentially wide-ranging applications in areas ranging from secure communication and drug discovery to artificial intelligence.

The development of practical quantum systems has been progressed in recent years by developments in quantum hardware, algorithms, and software frameworks [5]. With the development of quantum programming tools as well as cloud-based platforms, the accessibility and experiment have been further extended. However, there are still many hurdles to be overcome, such as the problem of decoherence, error correction, and the scalability of the system [6]. This paper reviews the fundamentals, architectures, tools, applications, and compares the various approaches to quantum computing in a structured manner. It also reviews some of the major problems and recent developments and provides insight into the state of the art and future developments in quantum computing research.

2. LITERATURE REVIEW

In the last few years, significant advancements have been shown in quantum computing in various aspects ranging from fundamental research to application-oriented fields. Takook and Mohammad-Djafari (2024) highlighted the significance of quantum states and quantum field theory in underpinning the theoretical foundation of quantum computing, and Alabi (2024) and Bawa (2024) discussed the potential of quantum computing in various fields including optimization, artificial intelligence, cryptography and molecular simulation [7], [8], [9]. Upama et al. (2022) surveyed the tools and platforms available in the field of quantum computing, such as Cirq, TensorFlow Quantum and ProjectQ, in the context of computational frameworks and system development, while Gultom et al. (2024) emphasized the significance of hybrid quantum-classical computing [10], [11]. The security and cryptographic implications were investigated by Seiler (2024), especially with regard to the insecurity of traditional encryption methods and the necessity of post-quantum cryptography [12]. Moreover, these studies provide insights into the prospects of scalable architectures, virtualization technologies,

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industrial applications, and the remaining challenges, such as scalability, interoperability, noise, and practical deployments, discussed by Kumar (2024), Zheng et al. (2026), and Rajčević et al. (2024), respectively [13], [14], [15]. Together, these studies suggest that quantum computing is emerging from theoretical investigations to application-oriented and technically-informed systems, albeit with current technical and infrastructural challenges. The objectives and research gaps from the selected literature related to quantum computing are summarized in Table 1.

Table 1 : Literature review table

Serial No.	Title	Author(s) and Year	Objective	Research gap(s)
1.	Evolution of Quantum Computing : A Systematic Survey on the Use of Quantum Computing Tools [11]	Paramita Basak Upama et al.(2022)	Review quantum computing tools, frameworks, platforms, and development ecosystems.	Insufficient interoperability and standardization across quantum frameworks.
2.	Exploring Quantum Computing : Principles and Applications [9]	Sidak Bawa(2024)	Analyze the core principles and practical applications of quantum computing.	Limited discussion on scalability and real-world implementation challenges.
3.	Quantum Computing Advancements : Unraveling the Potential for Revolutionary Computing Paradigms [13]	Pawan Kumar(2024)	Examine recent advancements, applications, and societal implications of quantum computing.	Limited analysis of interoperability and practical large-scale deployment.
4.	Quantum Computing and the Future of Encryption [12]	Gavin Seiler(2024)	Investigate the impact of quantum computing on encryption and cybersecurity systems.	Limited practical transition strategies for post-quantum cryptography adoption.
5.	A Revolution in Processing Capabilities and its Possible Uses : Quantum Compuitng [7]	Moses Alabi (2024)	Explore the principles, applications, and challenges of quantum computing across multiple domains.	Lack of scalable fault-tolerant architectures and practical deployment strategies.
6.	Quantum States and Quantum Computing [8]	Mohammad Vahid Takook & Ali Mohammad-Djafari(2024)	Explain the relationship between quantum states, quantum field theory, and quantum computing fundamentals.	Limited focus on practical large-scale implementation and hardware integration.
7.	VirtualQPU : A Novel Implementation of Quantum Computing [15]	Danyang Zheng et al.(2026)	Propose virtualization and resource allocation strategies for cloud-based quantum computing.	Limited validation in large-scale real-world quantum environments.
8.	Bits in Modern Technology : From Quantum Computing to Classical Computation [10]	Alma Murael Gultom et al.(2024)	Examine the evolution of bits and qubits in classical and quantum computation,	Limited solutions for coherence, error correction and hardware efficiency.

			including hybrid models.	
9.	Quantum Computing : The Next Frontier in Technology [14]	Dušan Rajčević, Ivona Brajević & Francine Niedo(2024)	Explore the principles, industrial applications, and future potential of quantum computing.	Practical adoption remains constrained by hardware and infrastructure limitations.

3. FUNDAMENTAL PRINCIPLES OF QUANTUM COMPUTING

Quantum computing offers a completely new paradigm for information representation and processing, trying to overcome the limitations of classical computing in solving certain problems that are considered “computationally intractable” [16]. While classical systems are based on deterministic binary states, quantum systems are based on probabilistic access to states that are governed by quantum mechanics and provide new opportunities to achieve computational advantages [17]. The subsequent concepts are the theoretical basis for quantum computing that are fundamental to grasp the architectures, tools, and applications of quantum computing.

3.1 Classical Bits vs Quantum Bits(Qubits)

In classical computing, the information is represented by bits which are in one definite state or another, either 0 or 1. They are the states in which a deterministic logic operation and predictable computation result. But this binary restriction is limiting for classical systems when solving problems with large combinatorial spaces or exponential complexity [18]. However, quantum computing relies on quantum bits, or qubits, which can be in both states at the same time. A qubit can be mathematically represented as:

$$|\psi\rangle=\alpha|0\rangle+\beta|1\rangle \qquad [19]$$

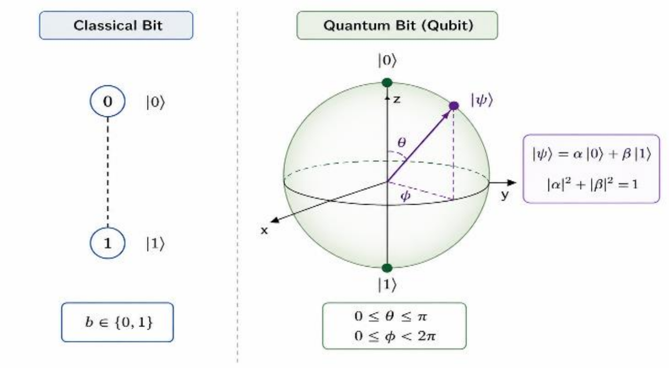

Figure 1. *Comparison of classical bits and quantum bits(qubits), illustrating discrete binary states versus superposition represented on the Bloch sphere, where* $|\psi\rangle=\alpha|0\rangle+\beta|1\rangle$.

α and β are complex probability amplitude satisfying the normalization condition $|\alpha|^2 + |\beta|^2 = 1$. This representation enables a system of n qubits to represent 2^n different states at the same time, vastly increasing the amount of states that a system of qubits can represent in comparison to classical computers. This exponential representation is the foundation for quantum parallelism, and directly inspires the design of quantum architectures and programming languages covered in the following sections. **Figure 1** is depicting this concept.

3.2 Superposition

A characteristic of quantum systems is superposition, which means that qubits can be in more than one state at once until they are measured. This property allows quantum computers to work out many possible solutions, at the same time, instead of sequentially as in classical computers [20]. Superposition is therefore the fundamental mechanism that can be used to gain computational speedups in certain problem areas, such as search and optimization. Computationally, superposition is a way for quantum algorithms to explore a large space of solutions efficiently [21]. This interplay will be especially important in the context of quantum circuits and algorithms, which are realized via tools and frameworks described in later sections.

3.3 Entanglement

Entanglement is a purely quantum phenomenon that is defined by the intrinsic correlation between the state of several qubits: the state of one qubit depends on the states of the other qubits. This correlation is maintained even when the qubits are not physically near, allowing for synchronization of operations throughout the quantum system [22]. Entanglement is one of the key factors which makes computation more efficient than classical computation, as it allows for interesting relationships between qubits which cannot be reproduced in classical systems. It plays a crucial role in various quantum algorithms and protocols such as quantum teleportation and secure communication.

$$|\Phi^+\rangle = \frac{1}{\sqrt{2}}(|00\rangle+|11\rangle) \qquad [23]$$

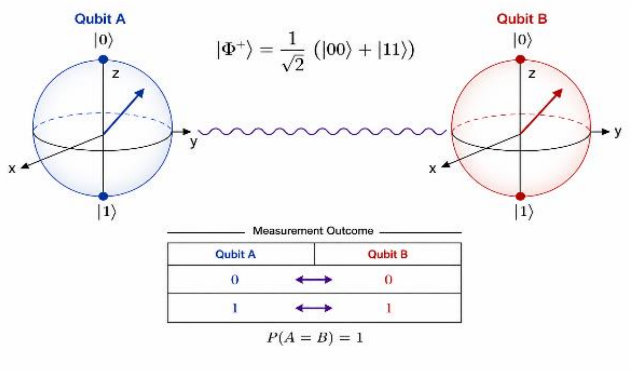

Figure 2. *Simplified representation of a maximally entangled Bell state* $|\Phi^+\rangle$*, illustrating perfect correlation between qubits A and B, where P(A=B)=1*

When entangled qubits are measured, the results are perfectly correlated, as shown in **Figure 2**; that is, the state of one qubit completely determines the state of the other. This non-classical correlation is essential for a number of quantum algorithms and communication protocols [24]. In real-life applications, a major issue is the generation and preservation of entanglement, which impacts the design of quantum hardware and architectures, as will be discussed in the next sections.

3.4 Quantum Interference

In the computation, the probability amplitude of quantum states interfere according to the rules of quantum interference. But quantum probabilities are not probabilities at all: they are amplitudes, which can interfere constructively or destructively to increase or decrease the chances of getting a right answer [25]. This is important to the viability of quantum computations. In other algorithms, such as Grover's search algorithm, interference is used to increase the likelihood of finding the correct solution from a large number of data [26]. Therefore, with superposition, interference makes it possible to combine parallelism with a computational gain. It is particularly useful in the design and optimization of quantum circuits and algorithms.

3.5 Quantum States and Hilbert Space Representation

The state vector of a quantum system is a vector in a complex vector space called Hilbert space that completely describes the system. Every configuration of a quantum system lies at a point in this space and the evolution of a system is a trajectory in this space [27-28]. It also introduces the formalism of quantum gates and circuits and connects theory to the implementation in quantum programming environments.

3.6 Quantum Gates and Circuits

Quantum computation is done using unitary operations called quantum gates, which act on the states of a qubit. These gates are the building blocks of quantum algorithms that are similar to logic gates in classical computing [29]. These include the Hadamard gate, which makes the superposition, and the controlled-NOT (CNOT) gate, which makes the entanglement between the qubits. A sequence of quantum gates are called quantum circuits, which specifies the computational workflow [30].

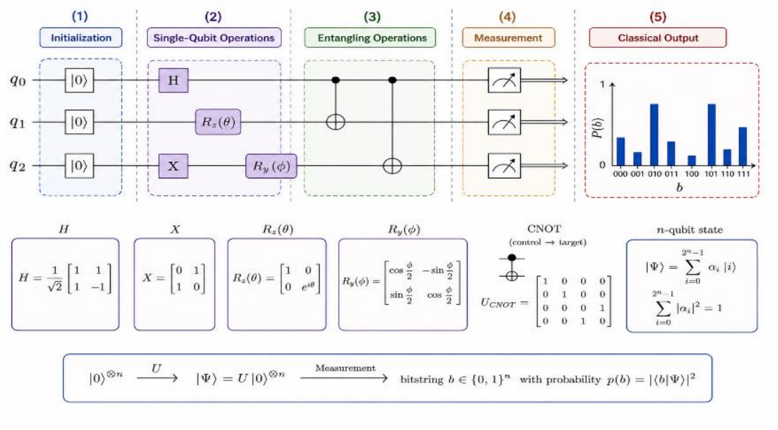

Figure 3. *Quantum circuit representation illustrating initialization, single-qubit gates, entangling operations(CNOT), measurement and probabilistic classical output, with corresponding unitary transformations.*

The process of a quantum circuit is a sequence of operations: initialization, single qubit operations, multi qubit operations, entanglement generation, and measurement, all leading to probabilistic classical outputs as shown in **Figure 3**. They play a key role in modern quantum computing frameworks like Cirq and TensorFlow Quantum for implementing and running algorithms. It is therefore crucial to have an understanding of quantum gates and circuits to analyze the tools and platforms discussed in later sections and for comparing different computational approaches.

3.7 Measurement and Probabilistic Nature

Measurement is the action of observing a quantum system, which causes the quantum state to collapse into one of its basis states (0 or 1). The result of a measurement is a matter of chance, and depends upon the squares of the probability amplitudes [31]. This probabilistic nature makes quantum computation different from classical deterministic computation and it poses special problems in designing quantum algorithms. The quantum computation may have to be repeated many times and statistical analysis applied to get reliable results [32]. This feature is also important in the assessment of quantum algorithms and the interpretation of their results in real applications.

3.8 Decoherence and Noise

However, quantum systems are extremely fragile against interactions with their environment. Such interactions are called decoherence and cause the system to lose its quantum coherence, behaving more classically, which leads to errors in computation [33]. Moreover, the noise in quantum operations also impacts the accuracy and reliability of the results.

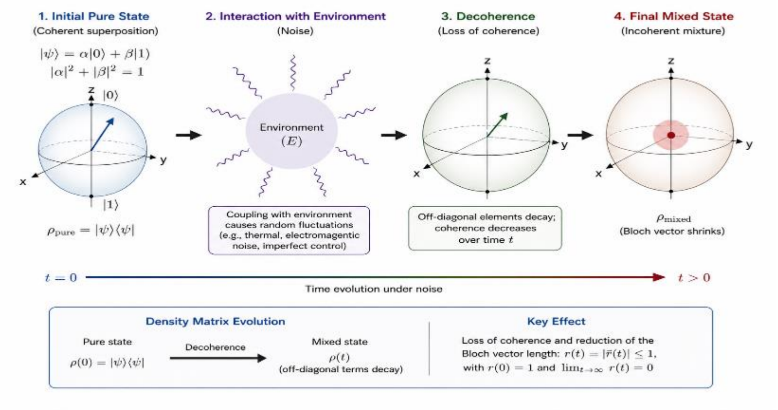

***Figure 4**. Decoherence in a quantum system, showing the transition from a pure state to a mixed state due to environmental interactions, resulting in loss of coherence.*

As shown in **Figure 4**, the interaction with the environment leads to the loss of coherence of the quantum state with time, turning a pure state into a mixed state and computational reliability becomes less. These are some of the challenges that limit the scalability of quantum systems and lie at the heart of current efforts in quantum error correction and fault-tolerant quantum computing [34], [35]. Decoherence and noise have a direct impact on the design of quantum hardware, the development of robust algorithm and the limitations that are discussed later in this review. The concepts presented in this section--qubits, superposition, entanglement, interference and quantum circuits--are all part of the operational structure of quantum computing.

4. QUANTUM COMPUTING ARCHITECTURE AND MODELS

4.1 Overview of Quantum Computing Architectures

After introducing the basic concepts of quantum computation, including qubits, superposition, and quantum circuits, a physical realization of quantum computation will necessitate a structured combination of physical devices and logical control. Quantum computing architecture involves the multi-layered design of preparing, manipulating and measuring quantum states while minimizing decoherence and noise [36].

In contrast to classical systems, quantum systems are subject to many physical parameters, such as the coherence time, error rates, and connectivity between qubits. A typical architecture can be broken down into four interacting layers: (i) physical qubit realization, (ii) control and gate operation layer, (iii) measurement and readout interface, and (iv) classical control and feedback system [37].

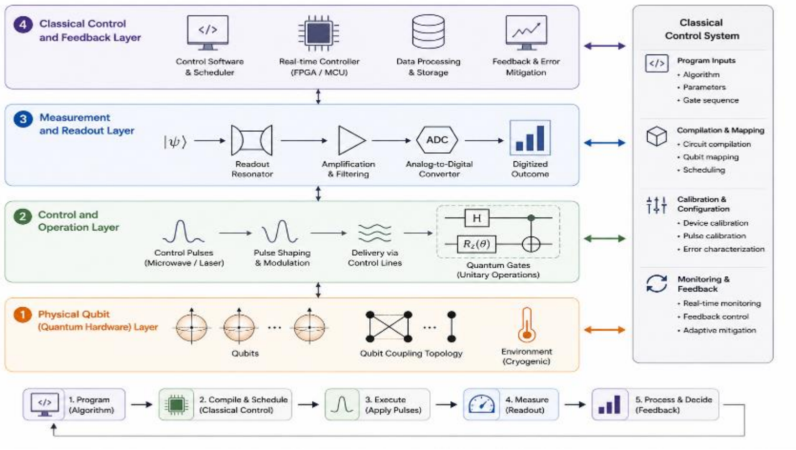

***Figure 5.** Layered architecture of a quantum computing system illustrating the interaction between physical qubits, control operations, measurement, and classical feedback.*

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Figure 5 shows that, as in other quantum computing systems, quantum operations occur at the hardware level and are coordinated and optimized by classical control and feedback. It is this layered view which makes it useful when analyzing quantum computing platforms and tools, as will be discussed in later sections.

4.2 Physical Realizations of Qubits

One of the most active research fields is the implementation of qubits: there are several different technologies which offer different compromises between scalability, coherence and operational fidelity.

- Superconducting qubits are an established technology used by IBM and Google, and offer very fast gate operations but require cryogenic environments and have relatively short coherence times.
- Trapped ion systems offer high fidelity operation, long coherence times, but scalability and gate speed are still limiting factors.
- Photonic qubits are ideal for communication and have a low decoherence time, but were a problem for two-qubit interactions.
- Spin-based qubits, such as quantum dots and nitrogen-vacancy centers, offer compatibility with semiconductor technologies, but rely on precise control mechanisms [38].

4.3 Quantum Computing Models

Apart from the hardware aspects, there are several different models of quantum computation, each offering a different abstraction for the design of algorithms and implementation of the system.

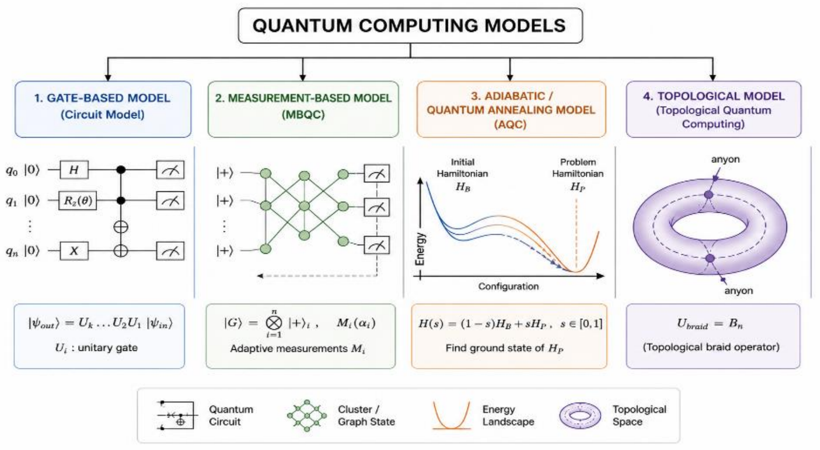

__Figure 6.__ Overview of major quantum computing models, including gate-based, measurement-based, adiabatic, and topological approaches, with their core operational principles.

Quantum computation can be achieved by several models, which vary in ways of manipulation, measurement and use of quantum states for problem solving, as shown in **Figure 6**.

4.3.1 Gate-Based (Circuit) Model

The most common model is the gate-based model, which is a collection of unitary operations on qubits [39]. This model is directly related to the quantum circuits described in Section 3.6 and is the underlying model of most existing quantum programming languages like Cirq and TensorFlow Quantum. It is the predominant paradigm in research and industry because of its compatibility with the current hardware architectures [40].

4.3.2 Measurement-Based Quantum Computing (MBQC)

The one-way model of quantum computing is based on highly entangled resource states and adaptive measurements.

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This model distinguishes the entanglement generation from computation and offers an alternative that could be helpful in certain architectures, especially those that focus on distributed quantum systems [41], [42].

4.3.3 Adiabatic Quantum Computing (AQC) and Quantum Annealing

Adiabatic quantum computing (AQC) encodes solutions to a problem in the ground state of a system and adiabatically changes the system Hamiltonian to target the ground state. This model is especially applicable to optimization problems and is very similar to quantum annealing methods adopted in systems like D-Wave. It is not suitable for all situations, but it is an important alternative paradigm for practical quantum computing [43].

4.3.4 Emerging Models: Topological Quantum Computing

Topological quantum computing relies on exotic quantum states which are intrinsically protected against local noise, and could also provide routes to fault-tolerant quantum systems [44]. Though at a preliminary stage of development, this model offers a solution to some of the major shortcomings discussed in Section 3.8 such as the issue of decoherence and susceptibility to errors.

There are several different models of quantum computers, each with its own level of abstraction, and with different advantages and disadvantages depending on the type of hardware and applications. The gate-based model is the most common one adopted in existing implementations as it is convenient for current hardware and programming frameworks, but other models such as the adiabatic model and the measurement-based model are more appropriate for some classes of problems such as optimization and distributed quantum systems [45].

4.4 Hybrid Quantum-Classical Architectures

In practice, most systems are hybrid quantum-classical systems, where the quantum processors are coupled with classical computing systems, due to current quantum hardware. In these, quantum devices are used for state preparation and transformation while classical processors are for optimization, control and post-processing. This paradigm is especially common in Variational Quantum Algorithms (VQAs), parameterised quantum circuits that are optimised with classical feedback loops [46].

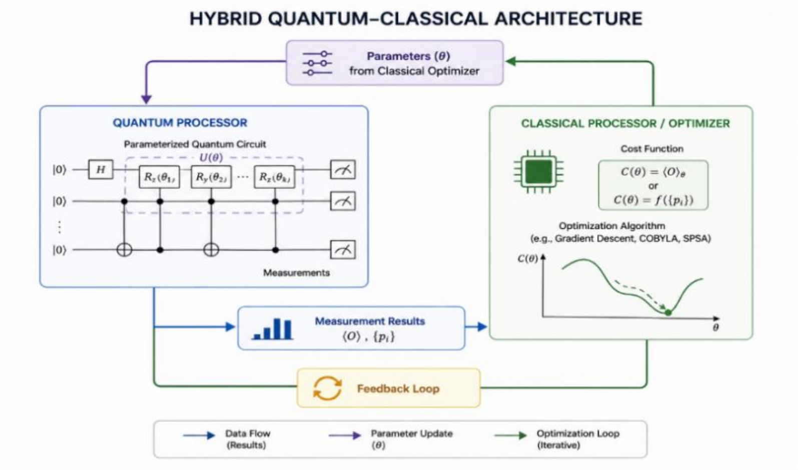

Figure 7. *Hybrid quantum-classical architecture illustrating the iterative optimization loop between parameterized quantum circuits and classical processors.*

Hybrid quantum–classical architectures are based on an iterative feedback process whereby a classical optimizer adjusts circuit parameters in response to the measurement outcome from the quantum processor as shown in **Figure 7**. Modern approaches to quantum computing, that connect classical optimization algorithms with quantum circuit execution, support this paradigm and allow experiments to be performed on NISQ devices.It is representative of the present NISQ (Noisy Intermediate-Scale Quantum) era where full fault tolerance cannot be realized and efficient use of limited quantum resources is crucial [47].

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4.5 Architectural Constraints and Research Challenges

There are a number of interrelated problems that limit the development of scalable quantum architectures:

- Decoherence and environmental noise, which restrict computation time (connected with Section 3.8)
- Qubit scalability and connectivity – circuit depth and complexity
- Overhead for error correction, which takes a lot of resources
- Hardware-specific constraints, such as temperature demands, and control accuracy

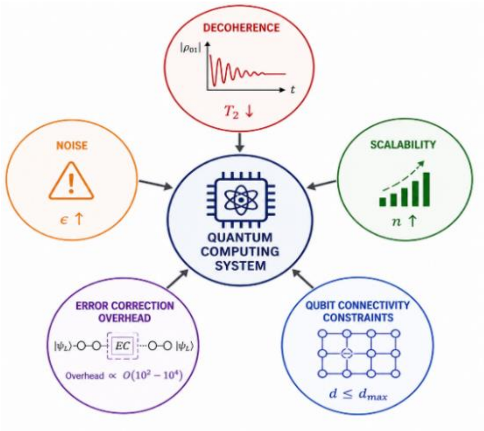

Figure 8. *Key architectural challenges in quantum computing, including decoherence, noise, scalability, error correction overhead, and qubit connectivity constraints.*

However, there are several obstacles to the performance and scalability of existing quantum computing architectures, including decoherence, noise, scalability, error correction overhead, and connectivity constraints, as shown in **Figure 8**. These challenges affect hardware design and the design of algorithms, tools, and frameworks, and suggest a need for co-design along many layers of the quantum computing stack [48].

This section has reviewed the architectural and computational models that bring the quantum principles to actual systems. From physical devices to computational models, it is clear that quantum computing is a vibrant and dynamic field with no single solution. These architectural considerations directly relate to the design and functionality of quantum computing tools and platforms. The subsequent section takes a look at quantum computing frameworks, tools, and technologies, offering a comparative view as to how the architectures are applied in practice. These architectural decisions also form the basis for the comparison of quantum computing approaches given in later sections.

5. QUANTUM COMPUTING TOOLS AND FRAMEWORKS

5.1 Role of Quantum Computing Frameworks

As described in Section 4, building quantum computers is made possible by a wide range of software tools and frameworks that build on the architectural and computational models. These platforms serve as an important bridge between abstract quantum algorithm design and physical quantum devices, providing the means to design, simulate and run quantum programs. In the current Noisy Intermediate-Scale Quantum (NISQ) era, such tools are needed to take the ideas to the implementations, especially in hybrid quantum-classical approaches [49].

A quantum computing framework offers a organized environment to assist with numerous stages of quantum system programming, such as circuit development, system simulation and execution on hardware. These frameworks hide low-level hardware specifics, allowing users to concentrate on algorithmic design while still providing the opportunity for hardware-specific optimizations [50]. Moreover, they are very close to the layered architecture discussed in Section 4.1, especially the control, measurement and classical feedback layers, and thus embody the theoretical and architectural concepts discussed earlier.

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5.2 Classification of Quantum Computing Tools

There are several different types of quantum computing tools that can be classified according to their functionality and level of abstraction, highlighting the variety of quantum computing models and hardware implementations.

5.2.1 Quantum Programming Frameworks

Quantum software development is based on quantum programming frameworks, which allow users to build and work with quantum circuits using high-level programming languages, usually Python. For instance, there is Cirq, TensorFlow Quantum and ProjectQ, with different sets of features for different purposes. Google's Cirq is geared towards optimizing quantum circuits for the near term, while TensorFlow Quantum is an extension of quantum computation to the workflows of machine learning, allowing for hybrid quantum-classical models. ProjectQ provides simulation or hardware execution in a flexible, modular environment [51].

Indeed, most of the existing frameworks are derived from the gate-based (circuit) model described in Section 4.3.1, the most widely-used model of quantum computing today. By contrast, there are specialized platforms like D-Wave systems which are oriented towards adiabatic quantum computing, and which are also dependent on the software tools used. The correspondence points out that the software frameworks are indeed tightly tied to the computational models: most of the tools are geared towards gate-based architectures, and there are platforms like D-Wave, specifically designed for "adiabatic" quantum computers [52].

5.2.2 Quantum Circuit Simulators

The quantum circuit simulators are crucial for enabling experiments without the need of actual quantum devices. The flexibility of these tools allows quantum algorithms to be tested, debugged and benchmarked in a controlled environment either in idealized or noise-aware simulations [53] and [54]. However, with the limitations of scalability, noise, and decoherence described in Section 4.5, simulators are essential for testing the performance and robustness of an algorithm before it is run on an actual quantum machine.

5.2.3 Quantum Hardware Platforms and Cloud Services

Quantum hardware is usually accessed via a cloud-based platform, which allows quantum circuits to be executed remotely on a real quantum hardware. A variety of different types of quantum processors are available through platforms like IBM Quantum Experience, Google Quantum AI, and trapped-ion or annealing-based processors from D-Wave. These platforms seamlessly integrate with programming frameworks, allowing for a seamless workflow from algorithm design to hardware execution [55], [56]. This integration is representative of the direct mapping between the software tools and the physical and control level of quantum computing architectures as described in Section 4.1.

5.2.4 Hybrid Quantum-Classical Toolchains

One of the hallmarks of modern quantum computing devices is the ability to perform hybrid quantum-classical tasks. In NISQ paradigm, the hybrid architecture is a key element as the quantum processors work alongside classical optimization procedures as discussed in Section 4.4. There are some tools that enable this interaction: TensorFlow Quantum and Cirq, which can be used to optimize parameterized quantum circuits in an iterative manner with classical feedback loops. It is this ongoing process that is the actual realization of a hybrid quantum-classical system, in which software frameworks play an important role in orchestrating the flow of information between a quantum processor and classical computing power [57].

The interaction is crucial for the efficient coordination of quantum and classical resources that is needed to fully realize the performance of NISQ systems, with software frameworks playing an important role.

5.3 Key Features and Capabilities

Quantum computing tools have several key characteristics that determine their functionality and effectiveness on various platforms. These include hardware abstraction to facilitate portability across different quantum devices, noise modelling to enable realistic simulation of quantum behaviour, scalability support to support growing circuit complexity within a hardware limitation, and interface to classical computing systems to support hybrid workflows [58], [59]. Moreover, user accessibility is important: many of the frameworks offer high-level APIs and development environments aimed at reducing the barrier to entry. Combined, these features overcome many of the architectural challenges mentioned in Section 4.5, including noise, error rate, and scalability. The performance of these features differs from one platform to another, thus impacting the appropriateness of particular features to the various domains of applications.

5.4 Comparative Perspective on Tools and Frameworks

Due to the heterogeneous nature of quantum architectures and computational models, there are many different kinds of quantum computing tools. There are various differences between frameworks, including supported computational paradigms, levels of abstraction, integration options and hardware compatibility [60]. For example, most frameworks have been developed for systems using gates while platforms like D-Wave are tailored towards annealing-only computation.These discrepancies show the need to choose the right tool for the job, given the nature of the application and its hardware specifications [61]. Significantly, these differences serve as the foundation for the systematic comparative analysis of tools, frameworks, models and methodologies in the next section.

These differences will constitute the basis for the systematic comparative analysis in the following section where the tools, frameworks and models of quantum computing are compared in terms of their capabilities, limitations and application areas.

5.5 Challenges and Limitations of Current Tools

Although there has been much progress, there are still some limitations in the current quantum computing devices that affect their usefulness. These frameworks are inherently limited in scalability by hardware capabilities and do not have any robust error correction mechanisms that ensure computational reliability [62]. Furthermore, the interoperability between platforms and ecosystems is an issue, and quantum programming has a steep learning curve, which hampers widespread adoption. These restrictions are similar to the architectural constraints mentioned in Section 4.5 and highlight the need for further research in the field of hardware and software co-design.

In the end, the quantum computing tools and frameworks are essential for the gap between theory and practice to be closed and also for designing and constructing quantum computers. Their progress has enabled improvement of the design and experiment of quantum algorithms—in particular those in the NISQ era. However, the available tools are diverse and have their pros and cons, so the capabilities and trade-offs need to be evaluated systematically [63]. Therefore, this section provides an in-depth comparative analysis of various quantum computing frameworks, tools, models and methodologies to understand the merits and scope of applicability of each.

6. COMPARATIVE ANALYSIS OF QUANTUM COMPUTING APPROACHES, TOOLS AND MODELS

The analysis of the selected literature is a comparative one composed of different perspectives on the models, tools, platforms and applications of quantum computing. In accordance with the description of the architectural (Section 4) and implementation (Section 5) aspects, the evaluation uncovers important characteristic aspects that have emerged in these works. This will enable a systematic assessment of the theory to practice transition in the age of NISQ.

6.1 Comparison of Quantum Computing Frameworks

The literature surveyed includes quantum computing frameworks from complementary angles: systematic surveys, hybrid computing studies and application-driven analyses (refer **Table 2**). Upama et al. list some of the essential tools, including Cirq, TensorFlow Quantum and ProjectQ, while others focus on hybrid computation and system level considerations [11].

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Table 2 : Quantum Computing Frameworks

Framework / Approach	Source (Paper)	Model	Key Capability	Strength	Limitation
Cirq	Upama et al. [11]	Gate-based	Circuit design & optimization	NISQ suitability	Hardware-specific focus
TensorFlow Quantum	Upama et al. [11]	Gate-based / Hybrid	Quantum–classical integration	Strong in ML workflows	Implementation complexity
ProjectQ	Upama et al. [11]	Gate-based	Simulation & execution	Modular design	Limited scalability
Hybrid frameworks (VQA-based)	Gultom et al. [10]	Hybrid	Classical–quantum integration	Practical NISQ use	Error sensitivity
Application-oriented framework view	Alabi (2024) [7]	Gate/Hybrid	Multi-domain applicability	Broad usability	Hardware dependency
Scalable framework perspective	Kumar [13]	Gate-based	System-level integration	Focus on scalability	Limited maturity

This comparison brings together tool-centric and application-driven views and shows the trend towards hybrid and NISQ oriented implementations.

6.2 Comparison of Platforms and Execution Environments

The literature (refer **Table 3**) highlights the increased significance of execution environments, especially cloud and virtual environments, in solving hardware accessibility and scalability problems.

Table 3 : Quantum Platforms and Execution Environments

Platform Type	Source (Paper)	Key Feature	Strength	Limitation
Cloud-based systems	Alabi (2024); Rajčević et al. [7], [14]	Remote hardware access	Broad accessibility	Resource constraints
Simulated environments	Upama et al. [11]	Algorithm testing	Controlled evaluation	Limited realism
Virtualized platforms (VQPU)	Zheng et al. [15]	Resource allocation	Improved throughput	Early-stage
Hardware–software integration view	Kumar [13]	System-level execution	Scalability focus	Limited deployment

These platforms are indicative that quantum infrastructures are becoming accessible and scalable and virtualization is a viable direction.

6.3 Comparison of Computational Models and Approaches

The chosen studies showcase several computational paradigms with varying capabilities and limitations (refer **Table 4**).

Table 4 : Quantum Computing Models

Model	Source (Paper)	Core Principle	Strength	Limitation	Application Focus
Gate-based	Takook & Djafari; Upama et al. [8], [11]	Quantum circuits	Universality	Noise sensitivity	General-purpose
Adiabatic	Alabi (2024); Kumar [7], [13]	Energy minimization	Optimization efficiency	Limited flexibility	Optimization
Hybrid (VQA/NISQ)	Gultom et al.; Alabi (2024) [7], [10]	Quantum-classical loop	Practical feasibility	Convergence issues	ML, optimization
Theoretical models	Takook & Djafari [8]	Alternative paradigms	Conceptual advantages	Implementation complexity	Research
Application-driven perspective	Rajčević et al. [14]	Model selection by domain	Broad applicability	Lack of specialization	Industry use

Selection of model type is application-specific and hybrid solutions are becoming more popular that compromise between capability and feasibility.

6.4 Key Insights and Research Implications

The comparative analysis shows that the gate model of quantum computing is the prevailing paradigm, largely because it can be roughly implemented with existing hardware and frameworks. At the same time, hybrid quantum-classical methods can play a crucial role in the practical implementation of quantum computers, allowing them to perform calculations within the bounds of NISQ devices [64]. One particular shift is from the theoretical models to tool oriented, application oriented systems, with the help of frameworks, cloud platforms and virtualization techniques like VirtualQPU. However, simulation environments still remain an important factor in algorithm validation because of hardware limitations [65].

The ecosystem, however, is still very disjointed and restricted by scalability, noise and error mitigation issues, which are preventing wider deployment. Therefore, no single framework or model can be best for all case, it depends on application and the limitation of the system. These restrictions highlight important research directions in scalable architectures, error correction, and integration with classical systems, which are further discussed in the next section on future challenges and directions.

7. APPLICATIONS OF QUANTUM COMPUTING

With the theoretical foundations, architectures, tools, and comparative analysis of quantum computing discussed in the previous sections, there are many problems in the realm of quantum computing that are extremely difficult to solve using classical computing systems. This capability is obtained from the basic quantum properties like superposition, entanglement and parallelism and is currently implemented mainly in hybrid quantum-classical strategies in the NISQ era [66].

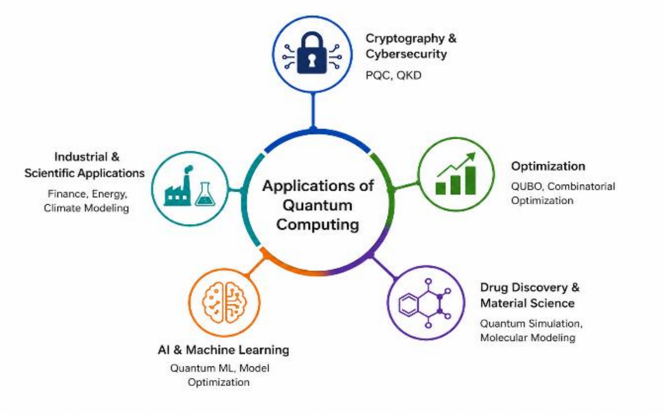

Figure 9. *Major application domains of quantum computing and their representative use cases.*

As depicted in **Figure 9**, the study of quantum computing is increasingly expanding to a variety of application areas, such as cryptography and optimization, artificial intelligence, and scientific computing. As Seiler pointed out, one of the most significant areas of application is cryptography and cybersecurity, where quantum algorithms could pose a threat to encryption methods like RSA and ECC that are widely used today [67]. To provide secure communication in the presence of quantum adversaries, this has led to the development of post-quantum cryptography and quantum key distribution. In addition to security, the promise of quantum computing is also strong in the area of solving complex optimization problems in logistics, finance, and manufacturing [68].

The other significant application is in drug discovery and material science, where a quantum system can be employed to simulate the interaction between molecules and atoms extremely accurately [69]. According to Alabi, this capability might overcome the drawbacks of current simulation techniques in the development of drugs and complex materials. Meanwhile, quantum computing paired with artificial intelligence and machine learning (AI/ML) is an exciting field, too. Besides, frameworks such as TensorFlow Quantum [70] can facilitate the integration between quantum and classical learning for optimization and pattern recognition, and have been highlighted in the literature surveyed here as possible solutions for this problem. In a wider sense, many industrial and scientific fields are considering the use of quantum computing, such as finance, chemistry and manufacturing, as mentioned by Rajčević et al [71]. The applications in this section show how the maturity level of the quantum hardware, tools and models of computation will have to be reached to make them usable in practice.

Overall, the literature indicates that the frameworks, cloud platforms, and virtualization methods that have been developed were more for deployment applications than theoretical possibilities. However, as indicated in the comparative analysis, there still remains some implementation issues that need to be dealt with such as scalability, noise and error rate [72]. These restrictions highlight the need for further research in scalable architectures, error mitigation and system integration which are discussed in the next section on future directions and open challenges.

8. CHALLENGES, EMERGING TRENDS AND FUTURE DIRECTIONS

While significant advances have been made in quantum computing architectures, tools, and applications, there are still some fundamental issues that are hindering the ability to practically deploy quantum computers on a large scale. One of the major challenges is decoherence and noise, which affect the quality of quantum states and limit the depth and reliability of the circuits in the NISQ era [73]. Quantum error correction has been suggested, but the huge resource overhead is a big obstacle to scalability. Meanwhile, hardware constraints such as limited connectivity and qubit count continue to limit the ability to perform more complex algorithms [74].

However, the software ecosystem is still quite immature and very fragmented, with a lack of standardization between platforms, and few, if any, mature, application-specific quantum algorithms. Hybrid quantum-classical methods offer a pragmatic route, but they tend to come with their own set of challenges, such as optimizing efficiency, stability in convergence, and resource utilization[75]. Importantly, a key research challenge lies in realizing, in real-world applications, consistent and provable quantum advantage over classical systems. The limitations raise some important research priorities such as the construction of fault-tolerant quantum architectures, design of better quantum error

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mitigation/correction methods, and better quantum-classical integration framework. Beyond that, there are no uniform mechanisms for benchmarking and interoperability, limiting systematic evaluation and cross-platform compatibility, highlighting the necessity of unified development ecology [76-85].

10. CONCLUSION

This review covers the basics and architecture of quantum computing, tools and applications, and implications, with emphasis on how quantum computing can be used to solve problems that classical computers cannot. Current progress reveals that the leading idea is that of gate based models, and hybrid quantum classical methods, but these are limited by hardware difficulties, noise, and scalability issues. The comparative analysis shows that the landscape is undergoing fast change but is highly fractured, with limited interoperability and standardization. Applications in cryptography, optimization, material science, and artificial intelligence show great promise, but are mostly limited to NISQ era constraints. However, the field is moving away from theoretical exploration and towards increasingly practical, application-oriented implementations, with the help of evolving frameworks, cloud platforms and machine learning integration. Even with this advancement, fault-tolerant and scalable systems along with consistent quantum advantage is a major challenge at hand.

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