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*Review*

# Quantum Computing: Navigating the Future of Computation, Challenges, and Technological Breakthroughs

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**Abstract:** Quantum computing stands at the precipice of technological revolution, promising unprecedented computational capabilities to tackle some of humanity's most complex problems. The field is highly collaborative and recent developments such as superconducting qubits with increased scaling, reduced error rates, and improved cryogenic infrastructure, trapped-ion qubits with high-fidelity gates and reduced control hardware complexity, and photonic qubits with exploring room-temperature quantum computing are some of the key developments pushing the field closer to demonstrating real-world applications. However, the path to realizing this promise is fraught with significant obstacles across several key platforms, including sensitivity to errors, decoherence, scalability, and the need for new materials and technologies. Through an exploration of various quantum systems, this paper highlights both the potential and the challenges of quantum computing and discusses the essential role of middleware, quantum hardware development, and the strategic investments required to propel the field forward. With a focus on overcoming technical hurdles through innovation and interdisciplinary research, this review underscores the transformative impact quantum computing could have across diverse sectors.

**Keywords:** computation; noise; quantum; quantum computers; reliability

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## 1. Introduction

Quantum computing, an emergent field at the forefront of technology, is predicated on the principles of quantum physics for data processing [1]. This paradigm significantly diverges from classical computing, which operates on binary bits representing states of 0 or 1 [2]. Quantum computing harnesses qubits, which, through quantum superposition, can exist in |0> and |1> states simultaneously [3]. Another fundamental aspect, quantum entanglement, augments the capabilities of quantum computing, enabling it to potentially outperform classical computers in tasks such as optimization and simulation [4]. Central to this topic are three primary elements: qubits, quantum gates, and quantum circuits. The field also explores methods to measure outcomes from quantum circuits by using either local simulations with random sampling or employing remote quantum devices [5].

Quantum computers, whose function is based on the fundamentals of quantum mechanics affecting atomic and subatomic particles, promise capabilities surpassing those of classical computers [6]. This advanced potential is particularly relevant in the fields of drug discovery [7], cryptography [8], finance [9], and logistics [10].

Market growth and investment in quantum computing are significant [11]. The industry, valued at USD 10.13 billion in 2022, is projected to reach approximately USD 125 billion by 2030. This growth is fueled by the demand for high-performance computing and the technology's applicability in industries such as petroleum, financial services, and aviation. Hybrid quantum computing, which combines quantum and classical computing, has become increasingly crucial for addressing complex problems that surpass the capacity of classical computing. This approach is essential for enabling non-quantum users to access quantum functionalities, particularly through cloud services.

Early quantum computer models encountered more problems than anticipated, resulting in disillusionment. Despite aiming to develop quantum computers with potentially millions of qubits, initial experiments with just a few qubits revealed unexpected noise issues. Nevertheless, the field has seen rapid advancements, transitioned from theoretical concepts to practical applications, and has overcome major technical obstacles. Today, substantial improvements in computational power and precision are evident, marking progress towards achieving operational, large-scale quantum computing and setting the stage for future innovations in this promising field.

Improving the reliability of quantum computing is essential, with the main challenge being environmental noise that increases error rates in qubits. Current efforts involve the development of fault-tolerant quantum processors and error-correcting algorithms, although full quantum error correction remains a goal [12]. This ability requires quantum processors with tens of thousands of qubits—a target that has yet to be reached.

### 1.1. Basics of Quantum Computing

Classical computers, which are deeply ingrained in the principles of classical physics, have been integral to the evolution of computational technology [13]. They function by using binary bits confined to 0 or 1 states, based on voltage or charge. The processing in these computers utilizes logic gates such as AND, OR, and NOT operating under Boolean algebra [14]; the solutions they provide are deterministic and limited by the design of such algorithms. Hardware-wise, classical computers employ macroscopic technologies (e.g., CMOS), which are renowned for their speed and scalability [15]. Quantum Dot Cellular Automata (QCA) is a non-transistor computing model that encodes binary information using the positions of electrons in quantum dots or mixed-valence molecules [16]. Unlike conventional transistors, QCA does not rely on electrical current for its operation. A standard QCA cell consists of four quantum dots, with two electrons occupying opposite corners to represent binary states (|0> and |1>) [17]. Information is transmitted across the system via interactions between neighboring cells, governed by Coulombic forces. QCA uses a clocking mechanism with four phases—relaxation, switching, hold, and release [18]—that synchronize state transitions. By arranging QCA cells in specific patterns, binary logic gates like AND, OR, and NOT can be constructed based on electron interactions [19]. Additionally, QCA circuits can be formed using mixed-valence molecules, such as diferoenyl acetylene (DFA), which are arranged in ordered arrays on a substrate and interact through Coulomb forces, controlled by a perpendicular electric field. Since the 1960s, semiconductor transistors have steadily decreased in size, fueling significant advancements in computing power. The timeline trend of this progression [20] is shown in Figure 1, which displays an exponential rise in computing power with forecasts up to 2025. However, contemporary computing power is reaching the limit of this progression due to transistors becoming so minuscule that problematic quantum effects (e.g., tunneling) are inevitable, which compromise semiconductor predictability.

In stark contrast, quantum computers represent a significant leap forward by employing the principles of quantum mechanics [21]. These systems are characterized by high-speed, parallel processing, storing information in quantum bits, or qubits [22]. Related to storing information, the authors [23] argue that a quantum bit can be more advantageous than a classical bit and that quantum memory is anticipated to surpass classical memory in any context. Thus, the implications of quantum advantage are multifaceted.

Quantum computers enhance the management and processing of large data volumes by utilizing quantum states. This efficiency stems from superposition, allowing quantum computers to manage multiple data states simultaneously. Additionally, entangled qubits can store and transmit complex data correlations that surpass the capabilities of classical systems.

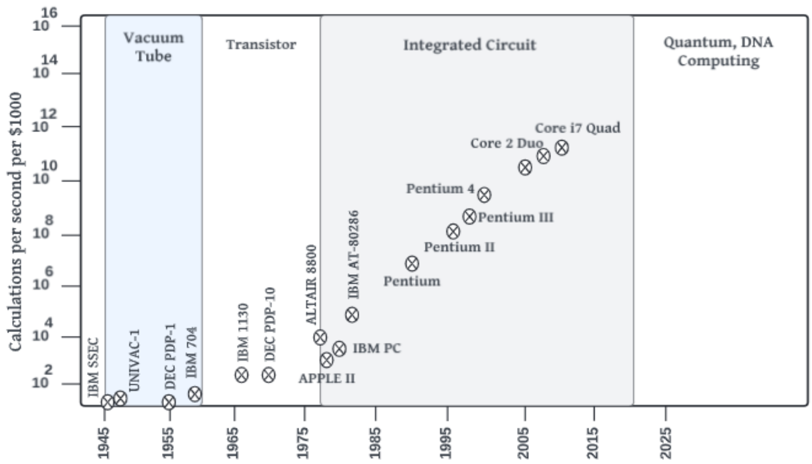


**Figure 1.** Time plot of current advances in classical computing power.

Quantum information storage facilitates the execution of quantum algorithms, making large-scale simulations, such as simulating molecular interactions and optimizing large systems, much more efficient. Furthermore, it significantly enhances the speed of searching and optimizing unsorted databases, achieving quadratic improvements over classical methods. However, reliable quantum storage and processing demand a fault-tolerant design, which is intricate and requires substantial advancements in quantum hardware.

Quantum information storage profoundly impacts cryptographic methods. It aids in breaking classical encryption, such as factoring large integers with Shor's algorithm, undermining the security of many traditional encryption systems. Additionally, it enables new cryptographic techniques like quantum key distribution (QKD), which are theoretically impervious to any computational attack, leading to the development of highly secure communication protocols based on quantum mechanics. These advanced capabilities raise privacy concerns: the ability to break current cryptographic systems poses significant risks, necessitating new frameworks and regulations to safeguard individual and organizational data.

For illustration purposes, classical bits and qubits are shown in Figure 2. Figure 2 demonstrates that qubits are unique in that they can represent the ∣0> or ∣1> states, or even exist in both states simultaneously due to quantum superposition, leading to an exponentially larger array of possible states [24]. Once another qubit is added, the number of possible combinations increases.

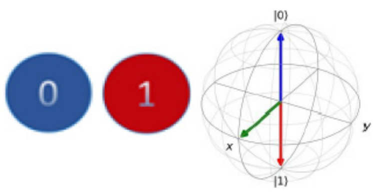


**Figure 2.** Classical computing bit vs. qubit (can exist in both states).

The outputs from quantum computers are probabilistic, as they are derived from computations on superposed states [25]. Quantum computing employs quantum logic gates for parallel processing, with operations rooted in linear algebra and represented by unitary matrices [26]. The solutions provided by quantum computers are multiple and probabilistic, as they leverage properties such as superposition and entanglement. Furthermore, the distinction between classical and quantum computers highlights a paradigm shift in computational capabilities. Classical computers have laid the foundation for modern computing with deterministic solutions and stable processing within a defined framework [27]. In contrast, quantum computers usher in a new era of possibilities, as they challenge conventional computing models with their capacity for processing complex, probabilistic solutions and conducting calculations at unparalleled speeds [28]. This contrast underscores a future where quantum computing could potentially revolutionize the landscape of data processing and problem-solving. However, it is crucial to note that quantum systems do not adhere to classical mechanics as laid out by Newtonian law. Instead, their behavior and interactions are dictated by the Schrödinger equation, which defines the fundamental nature of these advanced computing systems [29].

### *1.2. Overview of the Current State of Technology*

Since the enactment of the National Quantum Initiative Act in 2018, the quantum computing field has seen significant advancements [30]. A notable achievement is demonstrating quantum advantage, where quantum processors perform tasks faster than classical supercomputers [31]. For example, a Google-led team used a 54-qubit processor to complete a task that would take a classical supercomputer around 10,000 years in approximately 200 s [32]. Another team used a 70-qubit processor for a more complex task, which would have taken the Frontier supercomputer approximately 47 years [33]. The focus is also on practical quantum advantage, aiming to solve real-world problems beyond the reach of classical supercomputers. This task requires large-scale quantum computers with many qubits. IBM announced a 433-qubit processor in 2022 [34] with a subsequent launch of a 1000-qubit processor in 2024, while Google targets a 1000-qubit processor by 2025 and a one-million-qubit, error-corrected quantum computer within the next decade [35]. As quantum computing evolves, addressing technological and geopolitical diversity is crucial. This is highlighted by initiatives such as Deutsche Telekom's collaboration with IQM for cloud-based quantum computing access, emphasizing the global and multifaceted nature of quantum computing advancement [36].

The article [37] explores how companies are leveraging quantum hardware to address combinatorics problems across four industry sectors: cybersecurity, finance and banking, materials and pharmaceuticals, and manufacturing. Moreover, advancements in quantum machine learning provide promising alternatives to classical techniques, potentially enhancing the early stages of biochemical research in drug discovery [7]. A recent study [38] delves into the progress made in different forms of quantum computing, encompassing ion traps, superconducting setups, nuclear magnetic resonance, spintronics, and semiconductor spin-based methods. This research outlines the diverse physical implementations and potential uses of quantum computation across various fields.

Quantum gates perform operations on qubits based on quantum logic, forming the foundation of gate-based quantum computers like IBM's superconducting qubits and Google's Sycamore processor. Several competing technologies aim to develop scalable quantum computers, including superconducting, spin, topological, neutral, and photonic qubits. Superconducting qubits operate at low temperatures to avoid decoherence, using Josephson junctions [39] for potential large-scale computing, though challenges remain with cooling and control systems. Trapped ions, manipulated by lasers, encode qubits, but scaling beyond two qubits is difficult due to slow ion movement [40].

Photonic qubits rely on photons to represent qubits and operate probabilistically [41], with challenges like photon loss and maintaining fidelity. Neutral qubits use neutral atoms excited to the Rydberg state for two-qubit gates, but face difficulties with scaling and error rates [42]. Topological qubits, based on anyons, use topologically protected states but struggle with large-scale implementation. Spin qubits, using electron spins in quantum dots, face challenges with fidelity and control as they scale. Although quantum computing holds great promise, unique challenges must be overcome before it becomes widely adopted. Significant advances in hardware, scalability, and robustness are expected in the coming years.

In the sphere of quantum algorithms and applications, the integration of quantum and classical computing to create hybrid algorithms is an exciting development [43]. These hybrid algorithms are being applied in various fields such as machine learning, simulation tools in optics and materials science, and drug discovery in the pharmaceutical industry [44]. There has also been a noticeable increase in private equity investments in quantum computing, reflecting confidence in its long-term potential and the development of various solution patterns by different companies. In the military sector, quantum computing is poised to revolutionize operations, with applications in secure communication, logistics efficiency, enhanced encryption, and security, solving complex optimization problems, and advancing materials science [45].

In summary, quantum computing is transitioning to a stage of practical applications and tangible impacts across various sectors, attracting significant interest from both private and public entities [46]. Similar to the early days of 5G technology, quantum computing is in a developmental stage marked by high expectations and technical challenges. Despite these obstacles, progress is notable, with companies striving to create versatile, error-correcting quantum machines. The quantum Internet, another frontier in this field, is nearing realization sooner than anticipated [47]. The applications of quantum computing are broad and promise to revolutionize sectors ranging from air travel and logistics to precision medicine, enhancing everything from route optimization to disease treatment and prevention. Central to these advancements are high-quality qubits, the foundational elements of quantum computing. Current challenges include qubit instability and a propensity for errors, necessitating specialized software and calibration. Efforts are underway by some companies to improve qubit quality, as they aim for more efficient quantum computing with fewer qubits [48].

## 2. Quantum Computing Hardware

Due to the nature of quantum states, the hardware components of quantum systems face challenges, necessitating operation under environmental constraints. These components are built with cutting-edge materials with high purity and stability to preserve coherence. The longevity of these materials is crucial, as minor imperfections can greatly impact quantum computer performance over time.

Quantum systems are highly susceptible to environmental factors such as electromagnetic fields. Therefore, effective shielding is crucial to safeguard the hardware from these factors but ensuring this protection throughout the hardware's lifespan is a challenge. Current shielding techniques want to expel magnetic fields, and electromagnetic radiation up to 5G (or even above, by using sophisticated approaches). Moreover, quantum hardware is susceptible to errors stemming from decoherence, requiring robust QEC techniques. These error-handling methods are linked to the hardware's lifespan, as they counteract the effects of the operational environment.

Quantum computers can be broadly categorized [49] into four types based on their approach to reaching the solution:

- Gate-based quantum computing utilizes discrete gate operations to compute a logical outcome for a quantum algorithm
- Analog quantum computing [50] represents the physical state using continuous variables and continuous transformations. For example, fermionic atoms can be confined within a lattice to mimic electron behavior.
- Measurement-based quantum computing [51] creates a large, entangled state within a photonic lattice. The extraction of photons from this lattice acts as a gate, enabling the execution of quantum algorithms.
- Quantum annealers [52] are specialized for solving specific optimization, and function by seeking the system's lowest energy state, making them particularly effective for optimization tasks.

The paper [53] explores the array of technologies supporting quantum computers. It delves into quantum programming languages, hardware platforms, and software development kits, all of which contribute to revolutionary research, experimentation, and the exploration of the extensive capabilities of quantum computing platforms. Quantum gates manipulate qubits through operations based on quantum logic. Gate-based quantum computers use quantum gates to perform operations on qubits. Examples include IBM's superconducting qubits and Google's Sycamore processor. The main technologies that are competing to build a scalable universal quantum computer are discussed below, with a comparative illustration shown in Figure 3.

| Qubits | Pros | Cons | Applications |
|---|---|---|---|
| Superconducting Qubits | Fast gate times (ns-scale)<br>Maturity in design<br>Integrates with existing silicon | Requires extreme cooling<br>Noise and decoherence<br>Scalability challenges | General-purpose quantum computing<br>Optimization problems |
| Ion Trap Qubits | Long coherence times<br>High gate fidelity<br>Uniform qubits | Slower gate speeds<br>Complex laser control<br>Difficult to scale | Quantum simulation<br>Quantum cryptography<br>Quantum error correction |
| Photonic Qubits | Room temperature operation<br>Minimal decoherence<br>Ideal for quantum communication | Hard to achieve two-qubit gates<br>Detection inefficiencies<br>Loss in optical systems | Quantum communication<br>Quantum key distribution (QKD) |
| Topological Qubits | Resistance to noise<br>Fault-tolerant<br>Inherently protected quantum states | Early experimental stage<br>Extremely difficult to create and control | Fault-tolerant quantum computing<br>Cryptography |
| Neutral Atom Qubits | High scalability potential<br>Room temperature operation<br>Long coherence times | Slower gate operations<br>Complex laser and trapping control systems | Quantum simulation<br>Potential for scalable quantum networks |
| Spin Qubits | Compatibility with existing semiconductor technology<br>Long coherence times | Requires precise magnetic field control<br>Hard to scale for large systems | Quantum simulations<br>Crypto |

**Figure 3.** Various qubits and their pros and cons.

Superconducting qubits: Superconducting qubits, typically cooled to extremely low temperatures to avoid decoherence, are promising for quantum detection, hybrid experiments, and large-scale quantum computing. Superconducting circuits encode qubits using the energy levels of Cooper pairs, which are pairs of electrons bound at low temperatures, located on opposite sides of a Josephson junction [39]. Higher-frequency qubits could also operate at elevated temperatures, offering scalability due to the greater cooling power available [54]. Research has demonstrated qubits operating between 11 and 24 GHz using niobium Josephson junctions [55], which have fewer quasi-particles compared to aluminum junctions, enabling better performance at higher temperatures—however, calibration, control electronics, and cooling present significant implementation challenges.

Ion Trap qubits: Trapped ions (e.g., calcium or ytterbium ions) manipulated using lasers serve as qubits, with their internal states representing quantum information. In trapped-ion technology, qubits are encoded in two energy levels of an ion. Two-qubit gates leverage the interaction between electrons and phonons, which are quanta of vibrational energy, to couple the ion's excited electron state with the vibrational modes of the ion chain. The primary challenge for trapped-ion technology is increasing the number of qubits, as achieving entanglement among more than two qubits has proven difficult [40]. Moreover, qubit maneuverability is hindered by the slow physical movement of ions compared to changes in electronic states [55].

Photonic qubits: The system uses properties of photons, such as polarization, to represent qubit states. Quantum information is encoded and manipulated using optical components like beam splitters, waveguides, and detectors. In photonic networks, individual qubits are represented by single photons. A cluster state, which is a highly entangled state comprising multiple qubits, is first prepared [56]. Then, gate operations are performed by measuring the photons. Unlike other qubit technologies, two-qubit gates in photonic networks operate probabilistically rather than deterministically [41]. The challenges include maintaining fidelity at scale, dealing with photon loss during computations, and ensuring a photon source that can consistently produce identical photons for computations to be valid.

Neutral qubits: In neutral-atom technology, qubits are typically encoded in two hyperfine levels of an atom's ground state. Two-qubit gates are formed by exciting two atoms to the Rydberg state. The challenges include scaling to a million qubits, developing control electronics at scale, and managing higher error rates compared to other technologies [42].

Topological qubits: Based on anyons, quasi-particles that exist in two-dimensional systems and store information in the braiding of their worldlines. Topological quantum computers aim to exploit topologically protected states that are resistant to local perturbations. Creating and manipulating large-scale arrays of topological qubits in a controlled manner remains a significant challenge.

Spin qubits: In spin qubit systems, qubits are represented by the spin of an electron within a semiconductor quantum dot. Two-qubit gates are established between entangled electrons on a silicon chip, with qubit control achieved through microwave electronics. However, spin qubits face many of the same challenges as superconducting circuits, especially regarding fidelity at scale and control electronics. Similar to superconducting circuits, error rates in spin qubits increase with size.

As quantum systems expand in scale with additional qubits, their operational complexity grows, impacting the hardware's reliability. Moreover, integrating classical computing systems with quantum computers necessitates robust interfaces among them. Regular maintenance is essential to ensure the proper functioning of all components, and given the technological pace, hardware adaptability is crucial, either through replacements or upgrades. In essence, quantum computer hardware must endure extremely controlled environments, with reliability challenges being of paramount importance. Current efforts in materials science and engineering, along with QEC, aim to enhance the durability of quantum computing hardware.

Although the promise of quantum computing has the potential for positive societal impact, building the required hardware presents one of humanity's greatest technological challenges [57]. The study [58] offers insight into the noisy intermediate-scale quantum (NISQ) era, explores applications across diverse industries (e.g., optimization, cryptography, machine learning, and material science), and examines relevant quantum hardware, quantum gates, and basic quantum circuits. In another survey paper [59], the authors present rapid developments in quantum technologies that have accelerated the development of quantum machines. The recent breakthroughs in quantum technologies and computation are also scrutinized from the standpoint of design automation. The authors in [60] have introduced parallel allocation of quantum chips (QCs) as a novel compilation protocol to optimize quantum multiprogramming performance on NISQ processors and minimize unwanted interference. The experimental findings revealed a trade-off between execution time and success rate in multiprogramming.

Heat leakage from the system on a chip (SoC) to the qubits can interfere with their state, necessitating the relocation of the SoC into the cryogenic environment. In [61], the authors investigate the feasibility of using an off-the-shelf SoC for this task. Measurements were conducted on advanced 5 nm FinFETs at temperatures of 10 K and 300 K, with calibration of a transistor compact model and generation of standard cell libraries for each temperature. A RISC-V SoC was synthesized, its physical layout completed at 300 K, and its performance evaluated at 10 K. The results indicated that the SoC at 10 K was feasible, but its processing speed fell short of handling more than a few thousand qubits. The authors in [62] introduce a cutting-edge hardware platform meticulously crafted to oversee spin-based quantum systems. This platform integrates a two-channel arbitrary waveform generator boasting a 1-GSa/s sampling rate and 16-bit amplitude resolution, along with an eight-channel sequence generator, a two-channel analog-to-digital converter, and a two-channel high-speed time-to-digital converter—all seamlessly integrated onto a printed circuit board. These components were implemented using a field-programmable gate array (FPGA) with specialized data calculation modules seamlessly incorporated into the FPGA logic. To facilitate testing and deployment, the team utilized a pulsed electron spin resonance.

A trusted execution environment for quantum computers is discussed in [63], wherein user circuits are obscured by incorporating decoy control pulses during circuit transpilation. Before reaching the qubits, these decoy pulses undergo attenuation by trusted hardware located within the superconducting quantum computer's fridge. This initial research shows the feasibility of safeguarding against threats from malicious cloud providers using low-cost technology.

Study [64] introduces the Atos Q-score, a benchmark that is scalable to quantum advantage processor (superconducting and trapped-ion) sizes and beyond, as well as hardware-agnostic and application-centric. The Q-score quantifies the maximum number of qubits effectively utilized for solving the MaxCut combinatorial optimization problem via the quantum approximate optimization algorithm; its behavior is showcased through simulations of quantum processors, including both ideal and noisy conditions. The study [65] also introduces an open-source implementation of the Q-score, simplifying its computation for any cloud-accessible quantum computer. Moreover, a suite of open-source performance benchmarks is presented in the same study to evaluate the efficacy of quantum computing hardware in executing quantum applications.

The existing quantum technologies for quantum computing can be categorized into four generations based on their implementation [66,67]. The first generation includes quantum computers realized through ion traps, operating at a physical speed of kHz and a logical speed of Hz, with a size ranging from millimeters to centimeters [67–69]. The second generation technologies are implemented by the superconducting quantum circuits [70–72], distributed diamonds [73–75], and linear optical [67] technologies. These systems achieve physical speeds in the MHz range and logical speeds in the kHz domain, with sizes ranging from micrometers to millimeters.

The third generation quantum computers utilize quantum dots [76,77], monolithic diamonds [78], or donor [67,79,80] technologies. These systems operate at physical layer speeds in the GHz range and logical speeds in the MHz range, with sizes ranging from nanometers to micrometers. The fourth-generation quantum computers involve topological quantum computing technology [67,81] and are still evolving. Each generation represents advancements in speed, logical processing capability, and miniaturization, indicating a progression toward more powerful and compact quantum computing systems. An illustrative view of such an experimental quantum computing setup at IBM [82] utilizing superconductors is depicted in Figure 4.

**Figure 4.** A quantum processing unit suspended beneath refrigeration setup, maintaining the processor at ultracold temperatures necessary for its operation source: https://www.research.ibm.com/ibm-q/network/ (accessed on 1 April 2024).

## 3. Technical Challenges and Reliability Issues

Despite significant advancements, quantum computing is not yet a technology that is widely accessible or practical for everyday use. Quantum computers are not readily available for general consumer use due to their complexity, high cost, and the need for specialized operating conditions, such as extremely low temperatures for superconducting qubits [83], which makes them impractical for personal or typical business use. Moreover, cloud-based quantum computing services are being offered by major tech companies such as IBM, Google, and Microsoft [84]. These platforms enable researchers, developers, and businesses to experiment with quantum algorithms and applications. However, their primary use is still directed towards research and development rather than mainstream applications.

The focus of quantum computing at present is on specialized applications where its unique abilities (e.g., handling complex calculations and large datasets) offer significant advantages [85]. Fields such as cryptography, drug discovery, and materials science, as well as complex optimization problems, are some areas where quantum computing is being explored. Figure 5 illustrates major technical challenges currently being faced by quantum computing industry and academia [86]. It includes error correction, coherence, and the creation of a large number of stable qubits. Addressing these challenges is crucial for making quantum computing more accessible and practical for broader end-user applications. Currently, universities and research institutions are the main end users of quantum computing technology; they use it for advancing scientific research and educating the next generation of quantum scientists and engineers. Some industries with high computational needs (e.g., finance and pharmaceuticals) are beginning to explore the use of quantum computing [87]. However, these applications are in their early stages and not yet mainstream. In summary, although quantum computing continues to progress rapidly and holds significant promise, it largely remains a tool for specialized research and development. Widespread and practical use for everyday end users remains a goal for the future, with the technology yet to overcome several key challenges to reach this stage. Below, we briefly discuss each technical challenge. The respective details are discussed in later sections.

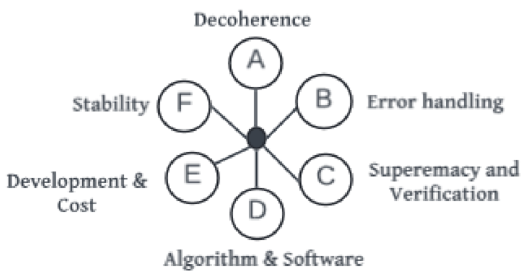


**Figure 5.** Challenges faced by quantum computing.

### *3.1. Quantum Algorithms*

One approach involves iteratively adjusting the probability amplitudes in a qubit vector until the target value is close to 1 and the other values are near 0. This technique is employed in Grover's algorithm, which searches through an unordered list of $n$ elements in $n$ iterations, thereby locating the desired key with high probability [88]. Another method is to structure the computation such that any of the random results measured from a qubit vector are acceptable. This strategy is utilized in Shor's algorithm for prime factorization of large numbers and is based on the quantum Fourier transform [89]. Here, qubits are manipulated to encode values with a specific period $r$. The Fourier transform converts the series to have a period $k/r$, where $k$ is the number of qubits. Since this period is fractional, many values have $r$ as their denominator. The result is measured, and continued fraction expansion is employed to determine $r$. If an integer is measured instead of a fraction, the calculation can be repeated. Given that prime factorization underpins most modern cryptographic security systems, Shor's algorithm has garnered significant attention. Both of these algorithms highlight the distinct approaches in quantum computing for solving specific problems efficiently.

Numerous strategies for quantum optimization have emerged. Quantum annealing, modeled after simulated annealing, is one such method designed for global optimization problems [90]. It executes a series of quantum fluctuations to gradually transform a simple energy landscape into a more intricate one. Its efficiency is primarily attributed to quantum tunneling, significantly mitigating the risk of getting stuck in local minima. Additionally, quantum walks have also been integrated with other quantum optimization algorithms, such as in Grover search [88], to expedite the search process. Additionally, several important quantum algorithms have recently been developed that leverage core principles of quantum mechanics, such as superposition, unitary transformations, and interference. Linear combinations of unitaries enable the efficient execution of complex tasks, such as Hamiltonian simulation and solving linear systems, by expressing non-unitary operations as sums of simpler unitary ones [91]. Quantum walk [92] generalizes classical random walks, utilizing superposition and interference for faster exploration, which benefits search and optimization tasks. Quantum phase estimation employs the quantum Fourier transform to estimate eigenvalues, a key step in factoring and simulations [93]. Amplitude amplification, a generalization of Grover's algorithm, enhances success probabilities in search and optimization [94].

An innovative model [95], the duality computer, utilizes quantum interference to potentially outperform both classical and quantum computers. It could enable efficient solutions to complex problems, such as NP-complete problems, and locate specific items in unsorted databases with a single query. Further development of the duality quantum algorithm is detailed in [96], where the linear combination of unitaries technique is applied to non-unitary dynamics on a single qubit, providing explicit decompositions of required unitaries and simulating arbitrary time-dependent single-qubit non-unitary operators. In short, the algorithms share foundational techniques, illustrating how quantum mechanics underpins computational advancements.

### *3.2. Quantum Supremacy and Verification*

Google's quantum supremacy experiment [97] represents a significant milestone, where quantum computers outperformed classical supercomputers in completing a specific task—random circuit sampling. It is anticipated that the computational prowess will persistently burgeon at a double-exponential pace equivalent to Moore's law [98,99], doubling computational magnitude every few years. In the Noisy Intermediate-Scale Quantum (NISQ) era, quantum computers handle tasks that exceed the capabilities of the most powerful classical systems, thereby achieving quantum supremacy. The most extensive circuits with directly verifiable fidelity currently encompass 53 qubits and employ a simplified gate configuration. Conducting random circuit sampling on these circuits at 0.8% fidelity requires one million cores for 130 s, indicating a million-fold acceleration of the quantum processor compared to a single core [97]. Quantum processors utilizing superconducting qubits can now undertake computations within a Hilbert space of dimension 253, surpassing the capabilities of today's swiftest classical supercomputers.

The study [100] showcases simulations of hard random quantum circuits, which were recently utilized as benchmarks for the first quantum supremacy demonstration, achieving an average performance of 281 Pflop/s (true single precision) on Summit, the fastest supercomputer globally. The results point to a substantial energy efficiency advantage of NISQ devices compared to classical supercomputers. The authors [101] investigate the constraints on quantum advantage for circuits involving a larger number of qubits and gates than those implemented in current experiments. They suggest that reducing error rates in components rapidly expands the regime of quantum advantage, underscoring the importance of minimizing errors. In a related study, the authors [102], using a next-generation Sunway supercomputer, took 8.5 days to verify three million exact amplitudes for experimentally produced bitstrings, achieving an XEB fidelity of 0.191% (compared to an expected value of 0.224%). The review study [103] offers a foundational overview of quantum computing and evaluates three key quantum supremacy experiments.

Quantum supremacy has been achieved through a series of breakthroughs, signaling the onset of the quantum era. During this time, quantum hardware has undergone significant integration and architectural improvements, a notable evolution from its early development stages. In a review study [104], the authors thoroughly examine the quantum supremacy experiments conducted to date and showcase various pioneering proof-of-concept studies in applied quantum computing. The review provides a detailed overview of the current state of quantum research and its potential influence across a wide range of scientific, industrial, and technological fields. These proof-of-concept examples highlight the immense promise of quantum computing and processors. The journey to fully realize the potential of quantum computing is ongoing, and its ultimate impact is still on the horizon. As we move from the NISQ era to the fault-tolerant phase, we are on the cusp of a remarkable future, where what seems impossible today may soon become both possible and routine.

### *3.3. Qubit Stability*

Quantum computers rely on stable qubits to perform complex calculations, but qubits are highly sensitive to external disturbances. Coherence stability and its impact on multi-qubit device performance are also important since superconducting qubits display large and correlated temporal fluctuations [105]. Some of the most problematic issues that limit the implementation of applications on Noisy Intermediate Scale Quantum (NISQ) machines are the adverse impacts of both incoherent and coherent errors. Through a detailed set of measurements, the authors [106] identify inter-day and intra-day qubit calibration drift and the impacts of quantum circuit placement on groups of superconducting qubits in different physical locations on the processor. In another study, the authors [107] highlight the potential of stable organic radicals as high-temperature spin qubits and explore their applications in quantum information science. The authors examine factors that influence their electron spin relaxation and decoherence times and analyze the primary challenges associated with stable organic radical qubits to provide tentative insights into future research directions. Various technologies, such as superconducting qubits and trapped ions, are being explored to extend coherence times. For instance, IBM's Quantum Hummingbird superconducting processor utilizes a hexagonal arrangement of qubits, allowing a maximum of 65 superconducting qubits with longer coherence times for extended computations. Quantum computer evolution has seen implementations with ion traps [108], second-generation quantum computers with distributed diamonds [109], quantum circuits [70], linear optical [110], third-generation quantum computers with monolithic diamonds [78], quantum dots [111], fourth-generation quantum computers implemented with topological quantum computing technology [81], etc.

### *3.4. Error Handling*

The error-related challenges are due to two main factors. Firstly, errors in quantum computation errors differ significantly from those in classical computing. While classical binary bits can only experience a bit flip, qubits are much more complex. They are described by continuous probability amplitudes, making their errors continuous as well. This means that small changes in the superposition of a qubit can be indistinguishable from the intended computation. Additionally, qubits can experience phase flip errors because their amplitude signs can be both positive and negative. Secondly, quantum states must be corrected without directly measuring them, as measurement would collapse the superpositions we need to maintain.

The cost of error correction includes the extra resources required for computation and to periodically perform error correction, which can be performed without decoding the data. Each of these steps is referred to as a fault-tolerant operation. For instance, implementing a fault-tolerant single-qubit operation using the Steane code necessitates approximately 153 physical gates [112].

### *3.5. Quantum Decoherence and Its Implications*

Quantum decoherence is a critical aspect of quantum mechanics with significant effects on quantum computing and related disciplines. It entails the degradation of a system's superposition of states due to interactions with its environment, erasing crucial quantum features. Although quantum systems, including qubits, can inhabit multiple states (|0> and |1>) at the same time, exposure to external influences causes them to transition into classical states, which results in the loss of encoded quantum information. This process is known as decoherence, which forces the system out of superposition and into a singular classical state [113]. This process can be best understood as illustrated in Figure 5. The blue dot in Figure 6 shows a point where a qubit interacts with its environment, leading to entanglement and disturbance [114]. This disrupts the superposition and quantum state, causing irreversible loss of coherence over time. Consequently, the qubit becomes unusable for quantum algorithms.

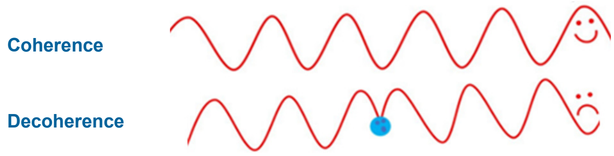


**Figure 6.** Illustration of quantum decoherence.

Quantum decoherence poses significant challenges for quantum computing, as it disrupts the superposition and entanglement of qubits, which are crucial for efficient computation. This process leads to computational errors and hampers the scalability of quantum machines; it also creates obstacles for QEC techniques, which must operate faster than decoherence. Decoherence also diminishes quantum entanglement by reducing the computational power and efficiency of algorithms. The rate of decoherence is crucial, with faster rates posing greater challenges for maintaining coherence during computations. Designing quantum systems often prioritizes isolation from environmental factors by employing techniques such as electromagnetic shielding and ultra-low temperatures. Additionally, the material choice and system architecture play key roles in reducing decoherence effects, as different quantum technologies exhibit varying susceptibility to it. Understanding decoherence provides insights into the transition from the quantum to the classical realms, which is crucial for advancing both quantum technologies and fundamental physics research.

Quantum decoherence is essential to the dynamical description of the quantum-to-classical transition. The authors [115] provide an overview of many experiments that have examined decoherence processes, and survey strategies for preventing and minimizing it. The possible relevance of decoherence in answering fundamental issues is also discussed. A survey article [116] analyzes the entire spectrum of practical qubit devices and alternates between elucidating discussions on the problem of quantum decoherence and its implications for the possible creation of these devices. The authors also examine qubit devices such as quantum key receivers, multiple quantum gates, interaction-free detectors, games, Bell-state analyzers, quantum dense coders, qubit entanglers, entanglement swappers, quantum teleporters and repeaters, quantum robots, and multiple quantum computers.

The article [117] introduces quantum decoherence to non-specialists and explains its associated ideas; it aims to illustrate the potential implications of quantum decoherence for more general philosophical discussions, regardless of specific quantum mechanical interpretations. For example, decoherence demonstrates that any approach that breaks nature down into tiers or components cannot be fundamentally grounded; rather, it stems from a classical understanding of the universe, which is maintained by the decoherence process.

In [118], the authors present a rigorous derivation of decoherence within a fully functional quantum spacetime model, which is conveyed at the Planck scale by non-commutativity. In particular, a generalized quantum system time evolution is obtained where mixed states can develop from pure states. When spacetime non-commutativity causes the action of the time translation generator to become distorted, it induces a time evolution for the density operator resembling that of Lindblad. The maximum permitted mass for elementary quantum systems is demonstrated to be the Planck mass by using the decoherence period governing the trajectory of a free particle. The authors of the article elucidate this matter by showcasing how the fundamental attributes of spacetime at the Planck scale govern quantum decoherence, which leads to the conversion of a pure quantum state into a mixed state.

The article [119] provides a survey of decoherence models and discusses their approximation into quantum Pauli channel models, which can then be implemented on classical computers. The authors also discuss how Monte Carlo simulations on a classical computer can yield the performance of the quantum error correction code for the approximated channel.

One essential task in creating useful quantum technology is the parameter identification of quantum systems. The research reported in [120] investigates the time-varying decoherence for open quantum systems, which can be expressed as an optimization problem given the measurement data of local observables. The authors take the expansion coefficients as optimization variables and expand the unknown decoherence rates into the Fourier series. Subsequently, a minimax issue is developed and solved using a sequential linear programming method. The efficiency of the algorithm is demonstrated through a numerical analysis of a two-qubit quantum system with a time-varying decoherence.

The authors in [121] study several definitions of decoherence and their quantification. Comparisons are made between decoherence occurring in quantum systems featuring an infinite number of eigenstates and spin systems. In the former scenario, the key difference between entanglement with the reservoir occurring at some initial moment and assuming "entanglement at all times" is pointed out. The best computational methods in both domains are discussed.

In summary, quantum decoherence is a major hurdle in the advancement and practical implementation of quantum technologies. Overcoming the challenges posed by decoherence requires a fine balance between isolating the quantum system from environmental interferences and allowing necessary interactions for control and measurement. Addressing these challenges remains a primary focus in current quantum physics and engineering research, which aims to unlock the full potential of quantum computing and other quantum-based technologies.

## 4. Noise and Error Correction in Quantum Systems

Quantum noise, differing from classical noise due to its intricate nature, is a major factor that affects quantum computing; it arises from interactions within the system and its surroundings, resulting in errors and decoherence, where qubits lose their quantum state. Multiple sources (e.g., thermal fluctuations and electromagnetic interference) contribute to this noise, and impact qubit phase relationships and state probabilities [122]. Quantum noise presents a significant hurdle in the development of fault-tolerant and scalable quantum computers. Decoherence can result from even minute amounts of this noise, which threatens the superposition and entanglement that are essential to quantum systems. This challenge restricts the practical use of complex quantum algorithms and makes it more difficult to remedy errors.

The article [123] explores the influence of physical qubit architecture properties on algorithm execution. Important factors include qubit connectivity and stability, native gate instructions, gate fidelities, and state preparation, and affect both the quantum execution time and the total wall clock time for users. Research into quantum defects within two-dimensional van der Waals (2D vdW) materials [124] is making significant strides. Notable advancements encompass the establishment of quantum guidelines aimed at comprehending and regulating spin defects in solid-state materials, the practical demonstration of quantum defects within 2D vdW materials, and the development of methods for generating and adjusting defects, thereby enabling meticulous control over their characteristics and behaviors.

The research [125] examines the microstructure and performance of devices made from two superconducting thin films, showing that tantalum oxide exhibits lower losses compared to niobium oxide. This is due to the formation of simpler oxides and a more crystalline oxide bonding structure. These results offer valuable insights for enhancing superconducting qubits through the optimization of surface oxide properties. In another study [126], the authors propose a transmon qubit fabrication method that significantly improves $T_1$ relaxation times by encapsulating the surface of niobium to prevent the formation of its lossy surface oxide. The results from the comparative investigation show that niobium oxides negatively impact the coherence times of superconducting qubits. The surface-encapsulated niobium qubits exhibited $T_1$ relaxation times that were 2–5 times longer than those of qubits with native niobium oxides.

Current research efforts are directed toward improving qubit isolation, optimizing control strategies, and generating reliable QEC codes to tackle these problems. Some notable algorithms, like the quantum approximate optimization algorithm (QAOA) [127], are being adapted to improve robustness to tackle defects in superconducting quantum circuits. Handling quantum noise requires advancements not only in algorithms but also in quantum hardware design. The design of quantum systems is susceptible to external factors, resulting in bit flips and phase flips, which are amplified by qubit entanglement. These errors can rapidly propagate, underscoring the need for sophisticated QEC techniques.

For quantum computing to be viable in practical applications, it must be fault-tolerant (i.e., capable of functioning correctly despite component failures or errors). This involves integrating error correction in a way that allows ongoing computations despite the presence of errors. The effectiveness of these QEC strategies is closely linked to the error threshold, which is the maximum error rate at which error correction remains effective. Current research is focused on reducing the physical error rates of qubits and gates to remain below this threshold.

Quantum bit errors are complicated because qubits have a phase—in addition to having a zero or one value—that can fluctuate. At each system level, a method for handling these two types of errors must be devised. Such methods include enhancing the ability to control the computational gear itself and incorporating hardware redundancy so that a correct calculation result may still be obtained even when one or more qubits malfunction. Error handling is a complex process that requires foresight and correction at each phase of system design. Error suppression, error mitigation, and error correction are the three main elements of error management.

Error suppression: Error suppression methods involve anticipating and avoiding adverse effects by introducing adaptations based on an understanding of such effects. The goal of error suppression is to ensure that the processor produces the intended outcome by adjusting control signals to handle errors at the hardware level. Some of these methods (e.g., spin echoes [128], a series of sequences that can assist in refocusing a qubit and enable it to sustain its state for an extended period) have already been incorporated into quantum computers. Spin echo belongs to a class of methods called dynamic decoupling. Derivative Removal by Adiabatic Gate (DRAG) incorporates a component into the usual pulse form to prevent qubits from entering states other than the $|0\rangle$ and $|1\rangle$ states used for calculations. The authors [129] conducted experiments to evaluate how the performance of logical qubits scales with different code sizes and show that the superconducting qubit system performs well enough to counteract the extra errors that come with having more qubits. In another research, the authors [130] suggest employing error filtration as a practical means to suppress errors for gate-based quantum computation without resorting to full quantum error correction. This approach offers a flexible error suppression protocol where the resources required for error suppression are independent of the size of the quantum operation and do not require its logical encoding. In [131], the authors suggest an effective technique to achieve exponential suppression by generating several separate circuit outputs and using symmetries to counteract errors that could skew the expected value and argue that this method is well-suited for present and upcoming quantum devices. Numerous additional approaches, established over decades, are being investigated and implemented in hardware when appropriate.

Error mitigation: Error mitigation reduces or eliminates the impact of noise on expectation values by utilizing the outputs of ensembles of circuits. Considering fault tolerance, error mitigation makes quantum computing viable. The probabilistic error cancellation approach is currently under investigation, which uses samples from an ensemble of circuits to approximate a noise-inverting channel on average to nullify noise. The approach functions similarly to that of noise-cancelling headphones; however, it cancels noise more generally than shot-by-shot. Another approach, zero-noise extrapolation [132], lowers error by extrapolating the circuit's measurement results at various noise strengths to determine the true value. Each of these approaches has a different overhead and degree of accuracy. The most potent of these methods, for example, has an exponential overhead, meaning that the run time grows exponentially with the problem size. A portfolio of approaches enables users to select the approach that suits their needs, considering their tolerance for overhead and desired level of accuracy. It is anticipated that error mitigation will remain useful for qubits in the hundreds range, despite the overhead. When the comparable circuit depth reaches several hundreds of qubits, a hybrid of mitigation and correction techniques is envisioned. One proposed novel technique for mitigating quantum noise [133] accurately computes the mean output of a quantum device affected by noise. The average behavior of the multi-qubit system is approximated as a modified Pauli channel, where the average output for circuits with varying depths is estimated using Clifford gates. The effectiveness of the technique used on four IBM Q 5-qubit quantum devices shows accuracy improvements reaching 88% and 69% compared to the uncontrolled and pure measurement error mitigation techniques, respectively.

The authors [134] present a quantum error mitigation scheme designed to address quantum computational errors resulting from environmental couplings during gate operations, known as decoherence. The authors argue that this scheme is versatile and can be applied to mitigate various types of quantum noise effects, making it useful for improving the performance of noisy quantum computing, especially for long-depth quantum algorithms. The authors [135] assess the effectiveness of quantum error mitigation techniques by testing them on different benchmark problems and quantum computers, and the findings show that, on average, QEM offers more advantages than not using it, even when considering the additional resources, it consumes. The article [136] presents a quantum error mitigation technique that employs machine learning to enhance the accuracy of quantum computations, and validates through two-, three-, five-, and seven-qubit quantum circuits. The authors claim that the performance of noisy intermediate-scale quantum algorithms without the need for extensive error characterization or full quantum. In [137], the authors argue that error mitigation is essential for achieving lower error levels. However, at higher error levels, QEM raises the variance of the stochastic gradient estimate, potentially necessitating more iterations of stochastic gradient descent when employing QEM.

The literature review [138] examines a range of quantum error mitigation techniques, evaluating their theoretical efficacy and detailing practical hardware demonstrations. It identifies shared characteristics and limitations of these approaches and explains how to choose the most suitable method based on the prevalent type of noise, including algorithmic errors. The review outlines current challenges in the field and discusses the potential for mitigation-based devices to achieve quantum advantage, which could significantly impact scientific research and business. While QEM methods are already crucial for applications, the field of QEM is still evolving and intricate, with much still to be investigated.

Error correction: QEC is complex due to the fundamental principles of quantum mechanics, such as the no-cloning theorem, which prohibits the copying of unknown quantum states. Therefore, QEC codes aim to identify and rectify errors without directly measuring quantum states, often by using redundant encoding with multiple physical qubits representing a single logical qubit. Surface codes are a promising QEC approach, wherein qubits are arranged in a two-dimensional pattern for efficient error detection and correction.

Fault-tolerant quantum computation is the process of adding redundancies to a system such that it can still produce accurate results for any program, even in the event that a few qubits encounter errors. QEC shares the same fundamental idea as that of classical computing, with the requirement that newly discovered error types are also considered. Furthermore, to prevent the state from collapsing, the system must be carefully measured. In QEC, the gates are built to handle a network of physical qubits as if they were nearly error-free logical qubits by encoding single qubit values across multiple physical qubits. To identify and fix errors, a particular set of procedures is carried out, which is collectively referred to as the error correction code.

For every logical qubit, the leading code, now in use, requires many physical qubits $O(d^2)$, where $d$ is the distance that corresponds to the errors that may be fixed. The distance $d$ must be set sufficiently large for error correction to meet the quantum device rate for the codes to correct enough errors to attain fault tolerance. However, the number of qubits required for error correction using the surface code is impractical due to the noisy nature of current quantum devices, which have error rates close to $1 \times 10^{-3}$. To continue reducing the error rates, researchers must both lower device physical error rates and find novel codes that require fewer physical qubits.

The authors [139] corrected associated phase errors occurring within an array of rubidium data qubits using a variety of cesium spectator qubits. By combining feedforward operations, data processing, and in-sequence readout, these errors were suppressed during the quantum circuit's operation. In another research [140], the authors encoded a lone logical qubit employing the [1,3,7] color code on a 10-qubit trapped-ion quantum computer utilizing quantum charge-coupled device technology. An encoding circuit was used to set the logical qubit's initial state to the eigenstates of three mutually unbiased bases. The average measurement error and logical state preparation error were contrasted with the average physical SPAM error of qubits. Various syndrome measurements were conducted on the encoded qubit using a decoder in real time to detect any required modifications that needed to be made physically as gates or as a software update. Iterative Bayesian unfolding [141] is a promising method for readout fault correction in universal gate-based quantum computers. It is shown that this method will prevent pathologies from common matrix inversion and least squares approaches. A true quantum processor that can execute a full quantum process tomography of a single qubit was used to realize echo experiments [142]. The obtained results from gate-based quantum computers revealed that coherence errors had a major impact on quantum computing, which was addressed by lengthening the quantum circuit length with the addition of random single qubit unitaries.

Researchers globally continue to develop various error correction strategies and qubit arrangements to identify those with the most promising potential for the future, and they have made notable progress. Recently, they have found a method to overcome the quadratic overhead $O(d^2)$, revealing a code that grows linearly with robustness (i.e., increasing the number of qubits increases the robustness). Figure 7 illustrates a $\mathrm{d} - 5$ surface code that corrects bit and phase flips [143]. In this example, the measure qubits, on the $(\mathrm{d}^2 - 1)$ layout, and shown on the white background represent data qubits. The qubits represented by smaller circles with a light grey background are called stabilizers. Each internal stabilizer acts on four adjacent data qubits, while the boundary stabilizer acts on three data qubits.

Although error correction, error mitigation, and error suppression may sound similar, each calls for a different set of skills and concerns and ensures that quantum computers provide actual benefits. Advancements in any of these domains move quantum computing closer to becoming a reality. Tech industrial giants are currently researching the critical challenge of noise in quantum computing.

In conclusion, addressing the challenges of quantum noise and effective error correction is central to advancing quantum computing. The field continues to evolve, with research focusing on achieving practical and efficient error correction as a key milestone towards scalable and functional quantum computing. Overcoming these challenges is essential, but it requires balancing the benefits of error correction against the complexities and resource demands introduced by additional qubits and technological advancements.

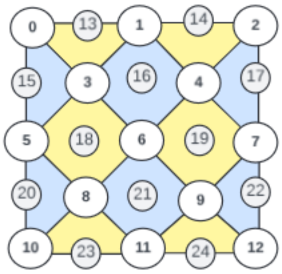


**Figure 7.** Surface code for error correction.

## 5. Scalability Challenges

Scalability challenges in quantum computers arise from the complex nature of quantum systems, as well as the need for/maintaining coherence and effective error handling. Increasing the number of qubits increases the challenge of preserving their states, as external factors can create decoherence and reduce computational power. Balancing qubit isolation from the environment is a major challenge in quantum computing scalability.

As the number of qubits in quantum systems grows, error rates increase, which must be mitigated by advanced QEC techniques. However, this adds to system complexity, as multiple physical qubits are needed for each logical qubit [143]. Developing fault-tolerant quantum systems that are capable of functioning correctly despite failures or errors is essential for scalability but remains a challenging task. However, the race for scalable quantum computing, also known as qubit count, is already on. Various companies are charting out their plans for scalable quantum computers. One such example is shown in Figure 8, which shows an increase in the number of algorithm qubits each year from 2021 to 2024 and projections until 2028, using 16 1-error correction coding during 2025–2026 and using 32 1-error correction coding during 2027–2028 [144].

The constraints in quantum computing present significant challenges. Ensuring high-quality qubits in large quantities is difficult due to variations in their quality. It is technically challenging to connect several qubits while maintaining their quantum states and enabling qubit–qubit interactions for quantum gates. Additionally, many models require extremely low temperatures, leading to increasingly complex and costly cooling infrastructure as systems scale up. Scaling up quantum computers necessitates additional infrastructure, such as clean room and vibration-free environments. Significant energy is required to maintain operational conditions, especially for cooling large-scale quantum computers. Precisely controlling numerous qubits demands scalable systems, with complexity increasing alongside qubit count. Moreover, higher qubit counts elevate the risk of interference, leading to errors.

Superconducting traveling-wave parametric amplifiers have emerged as highly promising devices for near-quantum-limited broadband microwave signal amplification, making them essential for high-efficiency microwave readout in quantum systems. The authors [145] introduce a Josephson-junction-based traveling-wave parametric amplifier isolator, utilizing third-order non-linearity for amplification and second-order non-linearity for frequency-up conversion of backward-propagating modes, achieving reverse isolation. This development paves the way for quantum-limited broadband microwave amplification without bulky magnetic isolators and with reduced back-action. In another study [146], the authors propose a new phase detection technique using a flux-switchable superconducting circuit, the Josephson Digital Phase Detector (JDPD), which can differentiate between two-phase values of a coherent input signal. Upon excitation by an external flux, the JDPD relaxes into one of two stable states based on the input phase. The study further explores how this method could be applied to superconducting qubit readout in future quantum systems.

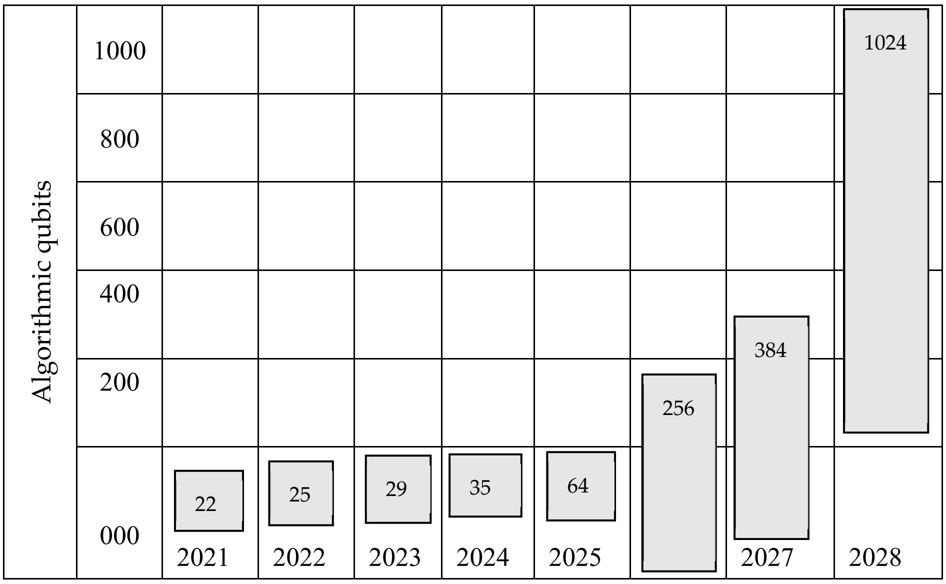


**Figure 8.** Algorithm qubit timeline by the end of the current decade.

The development of algorithms can efficiently leverage the capabilities of large-scale quantum computers but poses significant challenges due to the fundamental disparities between classical and quantum computing. Therefore, algorithms must be tailored for quantum hardware while considering its distinct features and constraints.

### 5.1. Scaling Quantum Systems

The ongoing quest for greater computational power continues to drive efforts to scale up quantum computers. The effectiveness of quantum computers significantly depends on expanding their scale and overcoming the limitations of qubit connectivity. However, achieving large-scale quantum machines faces challenges such as limited coherence time and increased instruction bandwidth, which can impede further scaling efforts. Employing a modular approach is crucial to scale current quantum processors and achieve the large quantities of physical qubits necessary for fault tolerance [147]. In the short term, modularity in superconducting qubits involves implementing short-range interconnections that link neighboring chips [148,149]. In the medium term, long-range gates operating in the microwave frequency range might be conducted over conventional cables spanning longer distances [150]. This approach could establish a non-planar qubit connectivity suitable for efficient error correction [147]. A long-term solution involves entangling remote quantum processor units using an optical link, leveraging microwave-to-optical transduction [151], although this achievement remains unproven. Moreover, dynamic circuits expand the range of operations of a quantum computer by facilitating mid-circuit measurements and classical control of a gate within the qubits' coherence time. They improve algorithmic quality [152] and qubit connectivity [153]. Error-mitigated dynamic circuits could also facilitate modularity by establishing real-time connections between quantum processor units.

Developing a scalable model for distributed quantum computation poses challenges due to the diverse spectrum of quantum systems ranging from small-scale to large-scale devices. Multichip, VQE, and circuit cutting technologies represent distinct facets of quantum computing, each tackling unique challenges and opportunities in the domain. These technologies frequently complement each other in the quest for more powerful and practical quantum systems. Below, each of these is briefly discussed.

### *5.2. Hardware Development Challenges*

A range of technologies have been employed to create successful quantum computing prototypes. However, scaling quantum machines to thousands or even hundreds of thousands of qubits requires more scalable technologies. The optimal spacing between qubits is currently a subject of debate in the physics community, with a trade-off between noise immunity and manufacturing challenges. In the near term, ion trap technologies offer a potential path to scaling up to thousands of qubits. Ion traps are well-understood and backed by extensive experimental data detailing their properties.

The essential aspect of scaling ion traps is the capability to transfer ions between traps using magnetic fields and a series of electrodes. Essentially, both ion traps and silicon-embedded ions depend on the spatial arrangement of qubits and control lines to execute quantum algorithms. Currently, both approaches encounter challenges in fabricating and validating the accurately positioned qubits and control signals, as well as in the quantum data communication within each system. One of the most evident challenges in fabricating quantum computers is the tiny scale of the components and the precision needed for their placement in the system. Given that achieving reliable quantum operations is already challenging with perfectly spaced and aligned components, minimizing, and detecting any variations is essential. The first hurdle in manufacturing is accurately placing the phosphorus atoms. Another issue is the scale of the classical control system, where each control line in the quantum data path is approximately 10 nm wide. Additionally, maintaining the device's temperature is crucial for the stability of qubits, requiring cooling to below one degree Kelvin. While cooling is relatively straightforward, it adversely impacts classical logic. Two major problems arise: conventional transistors cease functioning as electrons get trapped near their dopant atoms, preventing ionization, and the classical control lines start exhibiting behaviors like conductance quantization, etc.

Once qubits and their controls are manufactured, testing them poses significant challenges. Strict tolerances are necessary, and qubits that are improperly spaced or have misaligned control signals may need to be excluded from the system. Furthermore, issues arise with the spacing and alignment of the ions that constitute the qubits. Although quantum test programs can detect defects, they struggle to differentiate between errors in ion spacing, misalignment, and spacing errors of the control vias.

Quantum computers, which are still in their early stages of development, encounter various technical hurdles. It is noteworthy that not every problem is conducive to quantum computing, and uncertainties persist regarding the scalability of hardware and the feasibility of algorithms. The potential impact of quantum devices is significant, especially in fields such as cryptography, optimization, drug discovery, and materials science. Various approaches to building quantum computers are being explored—each based on different physical systems for creating and manipulating qubits—such as superconductors, ion traps, neutral atoms, photons, spins in semiconductors, and nitrogen-vacancy centers in diamond. Each method has its own set of advantages and challenges, with ongoing research to determine those that are the most suitable for practical quantum computing applications. Benchmarking the performance of quantum computers is a complex task due to their unique properties and architectural layers. Existing benchmarks focus on fundamental physical functionalities and overall characteristics but predicting application performance from these metrics is an intricate process.

### *5.3. Multichip Approach*

Networked and Multichip Technology aims to build larger and scalable quantum systems by connecting multiple chips. The authors of the study [154] define a scalable and distributed gate-model quantum computation tailored for near-term quantum systems. The architecture is shown to optimize for computational problems in a distributed fashion. In [155], the authors introduce an innovative strategy aimed at tackling the considerable hurdle of expanding quantum computers. They argue for a holistic architectural viewpoint, underscoring the importance of a complete resolution spanning from hardware to connectivity. Their concept revolves around scalable quantum computing designs wherein dispersed quantum cores are linked through quantum-coherent qubit state transfer connections and managed via a unified wireless interconnect setup.

The researchers in [156] introduce a major advancement in quantum networking with the development of a scalable framework termed a multichip multidimensional quantum entanglement network. This is realized by fabricating integrated nanophotonic quantum node chips using conventional semiconductor methods. Their study highlights the viability of constructing expansive quantum entanglement networks based on chips, representing a notable progression towards practical large-scale quantum communication.

The study [157] proposes an innovative approach to generate multiple qubits through magnetic resonance imaging (MRI). This technique relies on the "gradient" concept and several radiofrequency coils—one shared by all qubits and others designated for individual qubits using small Q-coils. In a separate study, the authors [158] use a floating tunable coupler to enable interactions between superconducting qubits on different chips, creating a modular architecture. They introduce three different designs for multichip tunable couplers, utilizing vacuum-gap capacitors or superconducting indium-bump bonds to connect the coupler to a microwave line on a shared substrate, which then links to the qubit on the neighboring chip.

The paper [159] delves into the possibilities of Quantum Data Networking (QDN), aiming to link multiple smaller quantum computers (QCs) to match the computational capabilities of a single large quantum computer. However, this endeavor requires the transfer of quantum state information, encoded in qubits, among QCs scattered across different locations. The research also identifies core limitations set by quantum physics and communication technologies, examining how they influence the structure and routing protocols of QDN on both basic and advanced levels.

The challenge of scaling quantum computing to meet the demands of its most powerful applications are addressed in [160]. There are restrictions to integrating many qubits into one chip, despite the inherent potential. Although quantum communications present difficulties due to their complexity and susceptibility, multicore architectures are thought to be a promising solution. Thus, it suggests a thorough design strategy that incorporates the communications stack into the architecture of quantum computers. This strategy seeks to overcome these obstacles by integrating computing and communications at the center of the architecture. The objective is to offer design principles that will enable quantum computing to reach its maximum potential.

### *5.4. Circuit Cutting Approach*

Circuit cutting technology enables running large quantum circuits on smaller quantum hardware by decomposing them into smaller pieces. The study [161] describes a low-power digital superconducting single flux quantum (SFQ) circuit-based scalable quantum computing infrastructure. This method makes use of SFQ pulses at base temperature, in contrast to current systems that rely on microwave control at room temperature. Using optical control theory, coherent SFQ pulse sequences are used to irradiate qubits to achieve qubit control. In [162], the authors delve into the partitioning of quantum circuits utilizing a hypergraphic representation with the goal of enhancing the efficiency of this process. To minimize communication qubits across partitions, a modified version of the Fiduccia–Mattheyses heuristic is then devised. Compared to existing algorithms, the method dramatically reduces partitioning costs by 10–50% through tuning and implementation. These results provide useful benchmarks for various methods and shed light on quantum progress in distributed contexts.

The study [163] presents Maximum-Likelihood Fragment Tomography (MLFT) as an improved method for circuit cutting, specifically for executing clustered quantum circuits on devices with a limited number of qubits. The results demonstrate that MLFT-enhanced circuit cutting provides a more accurate estimation of a clustered circuit's output than running the entire circuit. This highlights the potential of circuit cutting to become a standard technique for executing clustered circuits on quantum hardware.

The paper [164] investigates a technique for breaking down primary quantum circuits into smaller segments and evaluates the accuracy of the outcomes derived from these segments. The authors present a new analytical approach that considers multiple aspects of quantum characteristics, such as error data from qubits and the configuration of quantum processors, to efficiently divide the quantum circuits.

The research [165] presents an innovative method to enhance the capability of quantum computations beyond what is restricted by the number of qubits on one device. It involves integrating measure-and-prepare channels randomly, allowing the representation of a complex circuit's output state as separate across multiple devices. The technique shows notable speed enhancements supported by numerical tests, outperforming previous approaches.

The paper [166] presents a framework, which employs two primary methods to speed up quantum circuit simulation—circuit cutting and Clifford-based simulation. By isolating fragments of Clifford subcircuits within larger non-Clifford circuits, efficient Clifford simulation is made possible, leading to a significant reduction in runtime. After executing these fragments independently, techniques involving circuit cutting and recombination reconstruct the final output of the original circuit from the results of fragment execution. The results illustrate that Clifford-based circuit cutting accelerates the simulation of circuits, making it feasible to evaluate hundreds of qubits within acceptable timeframes.

In [167], a hybrid variational method called the quantum divide and conquer algorithm (QDCA) is presented, which is designed to efficiently solve large combinatorial optimization problems on distributed quantum structures. This is accomplished by integrating graph partitioning and quantum circuit cutting techniques. This method, which is a prime example of application–compiler co-design, is both suitable for near- and long-term distributed quantum systems and flexible enough to adjust to available classical or quantum processing resources. Simulations conducted on maximum independent set problem cases show that QDCA exhibits better performance than comparable conventional techniques.

The objectives outlined in [168] are to design quantum circuits that are efficient for execution on quantum computers and to limit the number of qubits and entanglement gates to help reduce computational time. Three approaches to dimensionality reduction and data management are explored and tested for quantum reinforcement learning in large-scale, real-world settings, with an emphasis on energy-efficient scenarios. The study also shows how quantum neural networks can be used in reinforcement learning applications and emphasizes how QML can be used to improve real-world settings such as energy efficiency scenarios. In [169], the authors present a comprehensive framework to imitate quantum computations using classical hardware acceleration. The framework includes structures such as the quantum Haar transform (QHT) and parts for the critical C2Q data encoding process. This framework is employed for exploring enhancements to the QHT and C2Q algorithms, leading to the development of highly efficient quantum circuits.

In conclusion, scalability in quantum computing involves not only increasing the number of qubits but also enhancing their quality, managing error rates, ensuring efficient interconnectivity, and developing suitable software and control mechanisms. Addressing these challenges is essential for realizing the practical applications of quantum computing and requires collaborative advancements in physics, engineering, materials science, and computer science.

### *5.5. Variational Quantum Eigensolver (VQE)*

VQE uses a specific algorithmic approach to solve problems by finding ground-state energies. The research conducted in reference [170] describes a method for achieving scalable variational quantum eigensolver (VQE) calculations in topological quantum phases. This is achieved by building scalable parameterized quantum circuits (PQCs) tailored to individual problems. This PQC is used for numerical simulations of the trivial dimmer phase and the symmetry-protected topological Haldane phase in the non-exactly solvable alternating Heisenberg chain using the VQE technique. The article [171] presents a modular quantum compilation framework for distributed quantum computing (DQC) that accounts for network and device characteristics. This framework was evaluated using circuits such as the VQE and quantum Fourier transform (QFT) on various network topologies. The results show that TeleData operations can positively influence the number of Einstein-Podolsky-Rosen (EPR) pairs used, depending on the compiled circuit's characteristics.

The article [172] introduces a novel algorithm designed to prepare the ground state of a gapped translationally invariant system on a quantum computer. The algorithm takes advantage of the exponential decay of correlations between distant regions in the ground state to develop scalable quantum circuits for state preparation. When applied to the Schwinger model, the algorithm demonstrates systematic improvability, with its accuracy improving exponentially as the circuit depth increases.

The article [173] investigates the effective use of the VQE for practical chemical modeling on near-term quantum processors. The authors detail the steps involved in writing and executing parallel code on a quantum computer to determine the bond dissociation curves for the diatomic hydride molecules TiH, LiH, NaH, and KH using VQE. By performing VQE in conjunction with Unitary Coupled Cluster Single Double (UCCSD) calculations on TiH, the study assesses the feasibility of modeling a molecule with d-orbitals on actual quantum hardware.

## 6. Quantum Computing and Cybersecurity

Quantum computing has a substantial influence on cybersecurity, especially concerning cryptographic protocols. Its effect on cybersecurity is deep and far-reaching, presenting a considerable challenge to current data encryption methods. This challenge necessitates a shift in approaches to securing data [174]. The rise of quantum computing threatens existing encryption methods, especially public-key cryptography, which relies on complex math with which traditional computers struggle. Quantum computers, with their superior processing power, could quickly solve these problems, making current encryption techniques vulnerable [175]. Shor's algorithm, introduced in 1994, threatens current encryption, as it can quickly factor large numbers on quantum computers, with potential use in decrypting data and intercepting communications. The current security mechanism highlighted in Figure 9 will likely be broken down as quantum computers significantly threaten public key encryption schemes. Therefore, it is suggested that post-quantum cryptography could effectively secure data against quantum computing threats [176].

The risk of retroactive decryption is a major concern, where adversaries collect encrypted data now to decrypt it in the future with quantum computing, posing a long-term threat to data privacy. This problem is particularly challenging for those who must protect data for decades, as it questions the reliability of current encryption methods. For example, the US fears that data stolen today could be decrypted by quantum computers in the next decade [177]. The arrival of quantum computers with millions of qubits could compromise data at all levels including the most existing public-key cryptosystems [178], as illustrated in Figure 9.

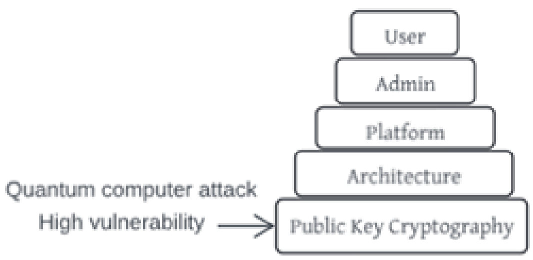


**Figure 9.** Quantum computer attack on public key cryptography.

In response, there has been a push for quantum-resistant cryptography to secure information and communications technology (ICT) infrastructure. Post-quantum cryptography aims to create secure algorithms that can withstand attacks from both classical and quantum adversaries. The US National Institute of Standards and Technology is spearheading the standardization process of developments in these algorithms. To safeguard communications against quantum computer attacks, quantum key distribution (QKD) and post-quantum cryptography (PQC) have been integrated into network security protocols, such as Transport Layer Security. These cutting-edge cyber-security technologies pave the way for quantum-resistant cryptography by developing new algorithms and modernizing existing systems. Moreover, the exploration of hybrid systems that merge classical and post-quantum methods offers a robust defense against future quantum threats [179]. QKD exemplifies this idea by leveraging quantum mechanics to securely share encryption keys, with the unique ability to identify any attempts at intrusion owing to the characteristics of quantum states [180]. The exploration of PQC covers its fundamentals and development, focusing on the Kyber encryption algorithm as a leading quantum-resistant solution [181]; it emphasizes the urgency of progressing quickly to effective PQC in response to quantum computing advances, discussing the field's achievements, challenges, and future directions. Hybrid systems are noted as interim protections, underlining the need for lasting, feasible PQC.

## 7. Quantum Computing Benchmark Metrics

Benchmark metrics in quantum computing play a pivotal role in evaluating both the performance and capabilities of quantum hardware and algorithms. By providing standardized measures, they enable effective comparisons across different systems and algorithms, thereby fostering progress and innovation within the field. These metrics cover various aspects such as hardware performance, algorithmic efficiency, and practical utility, thus offering a comprehensive framework for evaluation by researchers, engineers, and developers. Key benchmark metrics are outlined briefly, with further details available in [182].

### *7.1. Physical Benchmarks*

Gate Fidelity: Gate fidelity in quantum computing pertains to the precision of quantum operations, assessing their execution accuracy relative to their ideal forms. Typically, metrics such as average gate fidelity or diamond norm distance are employed for this evaluation. In [183], the authors accomplished an impressive 99.5% fidelity in deploying two-qubit entangling gates concurrently across up to 60 atoms, exceeding the requisite threshold for error correction via the surface-code technique. This approach entails the utilization of swift, single-pulse gates driven by optimal control, exploitation of atomic dark states to mitigate scattering, and advancements in Rydberg excitation and atom cooling methodologies.

Number of qubits: The quantum computer's capacity to describe information increases with the addition of qubits. Consequently, the performance of quantum computers is intuitively linked to the number of qubits. Measuring qubits involves sending a microwave tone to resonators and analyzing the reflected signal.

Connectivity: This dictates how qubits can engage with one another, a crucial aspect for conducting quantum operations and executing quantum algorithms. It influences the execution of quantum algorithms, the establishment of quantum entanglement, error correction processes, and the comprehensive scalability, efficiency, and speed of quantum computing systems. When qubits are interconnected seamlessly, they can execute algorithms more effectively, solving problems in fewer steps and maximizing the utilization of the qubits' limited coherence time. Hence, the enhanced quantum connectivity directly correlates with improved performance.

Relaxation time and Coherence time: The assessment of quantum computer quality can be conducted through the decoherence process, which is characterized by the relaxation time ($T_1$) and coherence time ($T_2$). $T_1$ time elucidates the characteristic of a quantum state decay from a high-energy level state, while $T_2$ time represents a transverse relaxation parameter, encompassing both energy relaxation and pure dephasing effects.

### *7.2. Aggregated Benchmarks*

Quantum Volume: This is a comprehensive measure pioneered by IBM, that encompasses various aspects of a quantum computer's performance, including gate error rates, crosstalk, and coherence times. This metric offers a singular value indicating the system's capacity to address practical challenges, rendering it a prevalent standard for assessing quantum hardware. A quantum volume of $2^n$ for a processor suggests its capability to accurately execute a square quantum circuit on a designated subset of n qubits using n layers of random two-qubit gates.

Algorithmic qubits: The quantity of algorithmic qubits (AQ) dictates the size of a quantum circuit that can be run on a quantum computer. AQ considers error correction and is closely tied to the qubit count. Essentially, the equation #AQ = N defines the dimension of the largest box, with a width of N and a depth of $N^2$, that can be accommodated in this spatial framework. This ensures that every circuit enclosed within this box satisfies the success criteria.

Circuit layer operations per second (CLOPS): The rate of operation is assessed through circuit layer operations per second (CLOPS). This metric considers the interplay between classical and quantum computing since real-world applications involve both forms of processing. CLOPS is defined as the quantity of Quantum Volume (QV) layers executed within a second.

### *7.3. Application-Based Benchmarks*

QPack: QPack comprises a comprehensive platform benchmark suite encompassing three common combinational optimization problems: the traveling salesman problem, the dominating set, and the Max-Cut. The objective of QPack benchmark scores is to provide a comprehensive understanding of quantum performance, facilitating swift and straightforward comparisons between various quantum computers [184].

Q-Score: The Q-score evaluates the proficiency of executing a representative quantum application, assessing a system's capability to tackle real-world challenges rather than solely its theoretical or physical performance. It gauges the practical performance of quantum processors in addressing optimization problems representative of the near-term quantum computing landscape. This score is derived from the maximum number of variables within such problems that a quantum technology can optimize.

Quantum LINPACK: Dong et al. [185] introduced a quantum LINPACK benchmark inspired by classical high-performance computing's LINPACK benchmark. They devised a random circuit block-encoded matrix to address quantum problems, leveraging quantum algorithms instead of classical ones to solve linear equations. This approach harnesses superposition, quantum parallelism, and entanglement to potentially achieve quicker solutions to linear algebra problems compared to classical methods.

## **8. Environmental and Sustainability Concerns**

### *8.1. Resource Requirements*

Environmental and sustainability concerns with quantum computing involve its significant use of resources and ecological footprint, including high energy consumption and material use, which pose unique environmental challenges. As digital silicon computers approach their speed limits, sparking a slowdown in progress, the shift towards quantum computing introduces new environmental challenges, particularly in terms of its substantial energy consumption, among others. The environmental considerations related to quantum computing [186] can be summarized as illustrated in Figure 10. These challenges include the extensive energy requirements for cooling systems to maintain superconducting qubits at near-absolute-zero temperatures, alongside the significant power needed for the operational demands of quantum processors. In response to these concerns, recent developments have focused on designing cryogenic systems, which are essential for the efficiency of solid-state quantum processors [187].

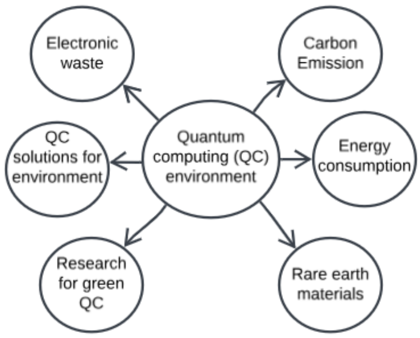


**Figure 10.** Environmental considerations in quantum computing.

Cryogenic systems aim to significantly reduce both passive and active heat loads, incorporating a wired, thermally optimized dilution refrigerator to ensure rapid qubit control and readout. Such advancements are pivotal for enhancing thermal management within the burgeoning field of large-scale quantum computing, which relies heavily on superconducting circuits. These efforts not only address critical environmental concerns but also mark a significant advancement in the sustainable development of quantum computing technology. Ongoing research aims to balance energy efficiency with computational power in large-scale operations and has identified quantum computing as a potential solution for complex power system challenges. Despite current limitations in the NISQ era, optimism persists that future advancements will enable quantum computing to address these challenges effectively [188]. Quantum computer production relies on rare, specialized materials (e.g., exotic superconductors), posing environmental concerns due to the impact of their extraction, refinement, and processing [189]. Sustainable sourcing faces challenges due to scarcity, geopolitical issues, and environmental costs. However, the development of exponentially more powerful machines offers the potential for significant emissions reductions, making the goal of limiting global warming more achievable [190]. Additional worries stem from the fast-paced advancements in quantum computing, which can potentially cause rapid obsolescence and contribute to a surge in electronic waste [191]. Moreover, the unique characteristics of quantum computing parts could pose challenges in recycling and safely disposing of them, especially for materials that might be hazardous. Quantum computing demands facilities with cryogenic systems and interference-free environments, increasing its environmental impact through construction and maintenance. Researchers are currently exploring various cooling techniques, including advanced cryogenic systems, to promote environmental sustainability in quantum computing [192]. As such facilities increase, urban planning, resource allocation, and environmental assessments will become more critical. Quantum computing could transform battery development and environmental sustainability by simulating quantum-mechanical phenomena for improved battery efficiency and discovering sustainable materials. This technology may also reduce prototype testing and enhance energy density, which is crucial for the shift toward renewable energy. Additionally, it has the potential to optimize energy consumption, advance energy storage, and speed up climate research, as compared to classical computing [193]. The creation of global standards to evaluate and handle the opportunities and risks associated with quantum technology is essential, necessitating the development of regulatory frameworks and policies for its sustainable advancement. Such guidelines would offer a unified set of rules for all involved parties, to steer the technology in a way that benefits humanity [194]. To ensure the sustainable advancement of quantum computing, it is essential to balance technological progress with environmental considerations. Guidelines should prioritize innovation while minimizing ecological impacts. As quantum computing develops, ongoing assessment and mitigation of its environmental footprint are crucial to aligning with broader sustainability goals.

### 8.2. Energy Consumption and Ecological Impact

The ecological impact of quantum computing is complex, as it involves significant energy consumption often from non-renewable sources, thereby increasing its carbon footprint. Quantum computers' main energy use stems from cooling chips to prevent temperature-induced qubit state changes, with operational energy needs varying by technology and architecture [195]. The supporting infrastructure (e.g., data processing units and environmental controls) also increases the overall energy consumption. Despite their higher energy demands for certain operations, quantum computers offer the potential for greater efficiency in specific tasks compared to classical computers; they can solve problems in significantly shorter times than classical supercomputers, potentially lowering the total energy usage for these computations. Despite facing challenges, the advancements in quantum computing showcase its potential as a significant innovation for the next generation, with broad implications for information systems research and beyond [196]. Furthermore, by contributing to materials science, climate modeling, and optimization challenges (e.g., energy grid management), quantum computing indirectly supports environmental conservation efforts. The merging of semiconductor physics and quantum technology, particularly through investigating Gallium Nitride (GaN) defects, presents a notable opportunity for innovation [197]. These defects, which were once considered mere imperfections, are now seen as key to advancing quantum computing and communication efficiently at room temperature, showcasing their potential to revolutionize quantum systems in practical settings. The transition of quantum computing from research to commercial applications brings its energy consumption and ecological impact to the forefront. Ensuring a balance between technological progress and environmental sustainability is essential, thus necessitating ongoing efforts to improve energy efficiency and mitigate ecological impacts.

## 9. Future Prospects and Developments

### 9.1. Upcoming Technological Breakthroughs

Quantum computing stands on the brink of a technological revolution, as it is poised to unlock unprecedented computational capabilities and address some of the most intricate challenges facing humanity [198]. This burgeoning field promises not only to transform industries but also to revolutionize the way society solves complex problems, thus demanding a reevaluation of existing ethical and security paradigms. At the heart of this revolution is the quest for scalability, with efforts focusing on augmenting the number of qubits while ensuring their coherence and minimizing errors [199]. Innovations in qubit technology, QEC, and chip design are crucial milestones on the path to creating fault-tolerant quantum computers capable of tackling real-world applications. The integration of quantum and classical computing elements heralds the advent of hybrid systems, which are poised to enhance accessibility and versatility in computing applications [200]. These systems, alongside the development of quantum networks, are setting the stage for a future with secure quantum communication and the potential for a quantum internet, reshaping cybersecurity, and global data exchange. In the scientific realm, quantum simulation is anticipated to drive breakthroughs in materials science and pharmacology, opening doors to novel materials and drug discoveries. Moreover, quantum computing's foray into machine learning and optimization problems presents new horizons in artificial intelligence, logistics, and finance. This impact of quantum computing in the top six application domains is illustrated in Figure 11.

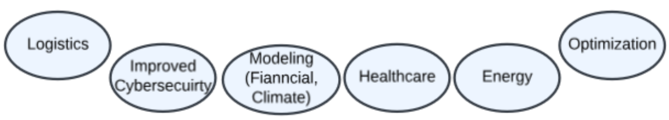


**Figure 11.** Quantum computing's impact on the future.

The journey toward realizing the full promise of quantum computing is both exhilarating and formidable, stretching across decades and necessitating a confluence of expertise from physics, engineering, computer science, and beyond. This endeavor calls for a proactive stance on ethical, societal, and environmental issues to ensure that privacy, security, and sustainability are at the forefront of quantum computing development. Quantum computing not only ignites a global technological race but also offers a unique platform for international research collaboration and standard setting [201]. As we navigate this journey, an emphasis on interdisciplinary collaboration, ethical considerations, and sustainability will be key to unlocking the transformative potential of quantum computing, making it a cornerstone of future scientific, industrial, and societal advancements. This narrative paints a vivid picture of a future where the capabilities of quantum computing are fully harnessed, driving innovation and solving critical challenges across the globe. Developers and end users are increasingly working together to develop specific applications. It is reasonable to anticipate that some applications will be available sooner than others, considering the varying complexities involved. Figure 12 illustrates such a timescale (2024–2029 and beyond) for the development of different business applications [202].

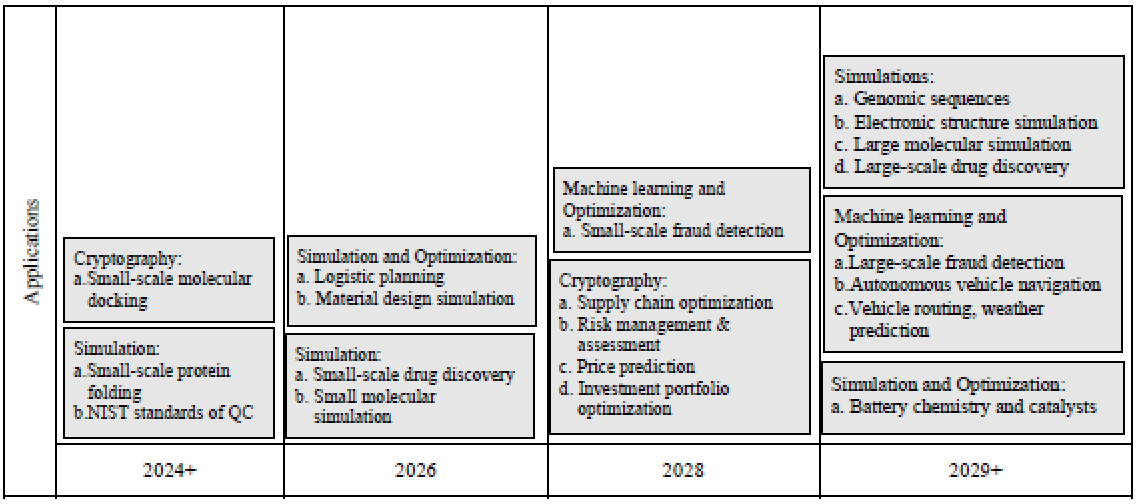


**Figure 12.** QC business application development timescale.

*9.2. The Roadmap for Quantum Computing Advancements*

The advancement of quantum computing is charted through a roadmap of stages, each with significant technological milestones and escalating capabilities. This roadmap, although not uniform across various quantum computing technologies, generally transitions from basic research to practical application. The initial research and proof-of-concept stage involves the development of fundamental quantum mechanics theories and initial quantum algorithms, such as Shor's and Grover's algorithms. During this stage, the creation and manipulation of the first qubits demonstrate the basic principles of quantum computing. This phase also includes the development of small-scale quantum computers capable of simple calculations and proof-of-concept demonstrations of quantum supremacy. Progressing further, enhancing coherence time, and developing QEC become pivotal. Extending the time qubits maintain their quantum state before decoherence and refining error correction methods to address inherent quantum computation errors are crucial milestones.

Scaling up qubits is also a significant step, transitioning from systems with tens of qubits to hundreds and then thousands, while maintaining stability and coherence. This stage also focuses on developing technologies for efficient qubit interconnectivity and information transfer.

In the era of NISQ computers, quantum computers operate with fifty to a few hundred qubits [203]. These systems start to perform tasks beyond the reach of classical supercomputers, with explorations of early applications in fields such as materials science and chemistry. The development of fault-tolerant quantum computers involves implementing full QEC to allow continuous operation despite errors. This stage aims to create quantum computers that can dynamically handle errors and maintain coherent states for extended periods. Achieving broad quantum advantage in practical applications marks a pivotal point; this includes consistently outperforming classical computers in various applications and making quantum computers more accessible. Integration and expansion involve integrating quantum computers with classical systems for broader applications and developing quantum communication networks for secure data transfer, possibly leading to a quantum internet. This stage also anticipates widespread adoption of quantum computing across various sectors.

Long-term developments include building large-scale quantum computers for complex, general-purpose computing tasks and using quantum computers for intricate simulations in physics, chemistry, and biology, potentially leading to discoveries and technologies. This final stage envisions establishing a global quantum computing infrastructure, including quantum networks and widespread services. The roadmap for delivering new prototypes, as pledged by the quantum computing ecosystem, is expansive, with new devices anticipated by the respective key players between now and 2030 [202], as illustrated in Figure 13. The figure shows how different vendor technologies have progressed recently concerning physical qubits and how they are projected until 2030.

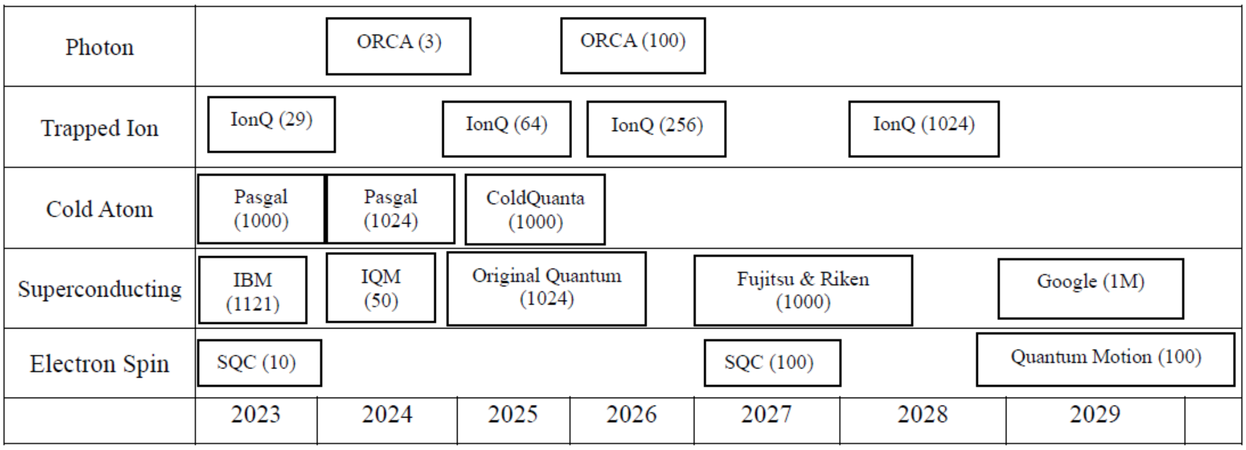


**Figure 13.** Vendor prototype roadmaps. Legend: Vendor (physical qubits).

In conclusion, the quantum computing roadmap is ambitious and encompasses numerous technical and theoretical challenges. However, the potential rewards are transformative, as they promise to advance computational capabilities for real-world applications.

### *9.3. Future Outlook and Recommendations*

Quantum computing, marked by its revolutionary approach and initial success with small-scale devices, faces the challenge of scaling up. Achieving a practical, large-scale quantum computer requires major technical breakthroughs, necessitating a strategic blend of current capabilities and long-term ambitions for gradual advancement [4]. Middleware is essential to bridge the gap between hardware manufacturers and software developers, which fosters collaboration. In quantum hardware development, superconducting circuits and trapped ions are key focuses. Superconducting circuits lead in scalability and speed, whereas trapped ions show promise but encounter technical challenges. Breakthroughs, including integrated ion traps and efficient cryogenic contacts, highlight the potential and future growth opportunities of quantum technologies [204].

Strategic investments and interdisciplinary research are crucial for realizing the nearly USD 700 billion value potential predicted by 2035 [205]. Strategic investment data by countries in billions [11], as shown in Figure 14, provides a healthy outlook toward goals set in prototype roadmaps. Achieving stability in quantum computing will unlock a multitude of opportunities and catalyze global technological advancement. Advancements could unlock and expedite progress in critical domains, potentially leading to swift commercialization. As a result, market growth forecasts vary significantly for quantum computing market growth projections [202], as displayed in Figure 15.

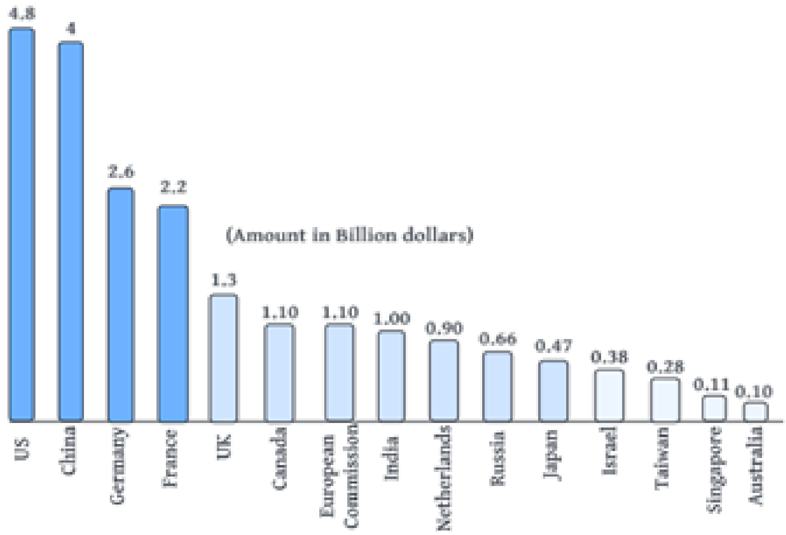


**Figure 14.** Quantum initiative funding by country (2014–2030).

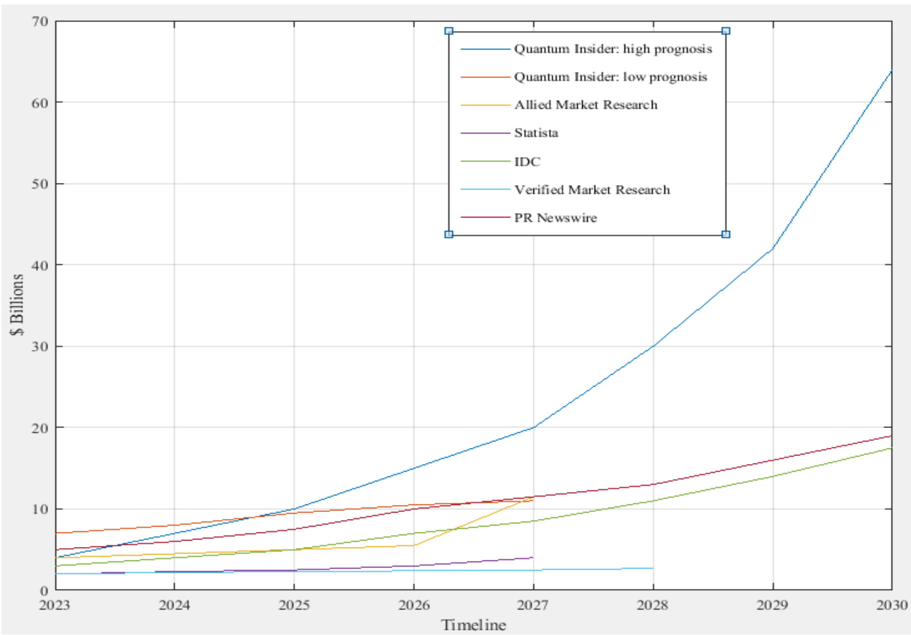


**Figure 15.** Quantum computing market growth projections.

## 10. Conclusions

The field of quantum computing presents significant challenges and opportunities for advancing computational capabilities beyond classical systems. The sensitivity of quantum computers to errors, noise, and decoherence poses substantial obstacles to the development and reliability of their hardware components. Technologies such as superconducting qubits, photonics, and trapped ions, although promising, face issues related to environmental sensitivity, scalability, and integration. Emerging technologies, including diamond color centers, topologically protected systems, and silicon quantum dots, offer potential solutions to these challenges but have yet to be commercialized. To address these issues, a variety of methods and metrics, including quantum process tomography, QEC, quantum benchmarking, and quantum certification, have been employed to test and enhance the reliability and performance of quantum computers. Furthermore, the construction of a quantum computer requires a sophisticated integration of various electronic components, such as qubit integrated circuits (ICs), quantum gate ICs, quantum memory ICs, quantum control unit ICs, and quantum measurement ICs. These components must be precisely designed and implemented to manipulate and measure quantum states effectively. Despite the hurdles, the ongoing research and development in quantum computing hold the promise of revolutionizing computing by harnessing the principles of quantum mechanics, potentially leading to breakthroughs in various fields, including cryptography, materials science, and complex system simulation.

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