

The Role of Quantum Computing in Shaping the Future of Advanced Computational Systems

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Abstract

Quantum computing is poised to revolutionize the future of advanced computational systems, offering unprecedented speed and efficiency for solving complex problems that are beyond the capabilities of classical computers. Traditional computational models, based on bits representing either a 0 or 1, are approaching their physical and performance limits. Quantum computers, however, leverage the principles of quantum mechanics—specifically, superposition and entanglement—to operate on quantum bits, or qubits, which can exist in multiple states simultaneously. This capability allows quantum systems to process vast amounts of data in parallel, potentially solving problems in seconds that would take classical systems millions of years. As the demands on computational systems grow in fields like cryptography, artificial intelligence (AI), drug discovery, and materials science, quantum computing offers solutions that can overcome the bottlenecks faced by classical computing architectures. This paper explores the foundational principles of quantum computing, its advantages over classical systems, and its potential applications in various industries. Additionally, we analyze the current challenges that quantum computing faces, such as error rates, quantum decoherence, and hardware scalability. We also consider the future trajectory of quantum computing, including the potential for quantum supremacy and the development of hybrid quantum-classical systems. Although quantum computing is still in its nascent stages, with practical quantum computers requiring further advancements in qubit coherence and error correction, its future impact on computational systems is undeniable. This paper aims to provide a comprehensive review of how quantum computing is shaping the future of computational systems, detailing the technologies, applications, and challenges ahead. With continuous technological advancements, quantum computing has the potential to redefine global industries, solve previously unsolvable problems, and fundamentally alter our understanding of computation in the coming decades.

1. Introduction

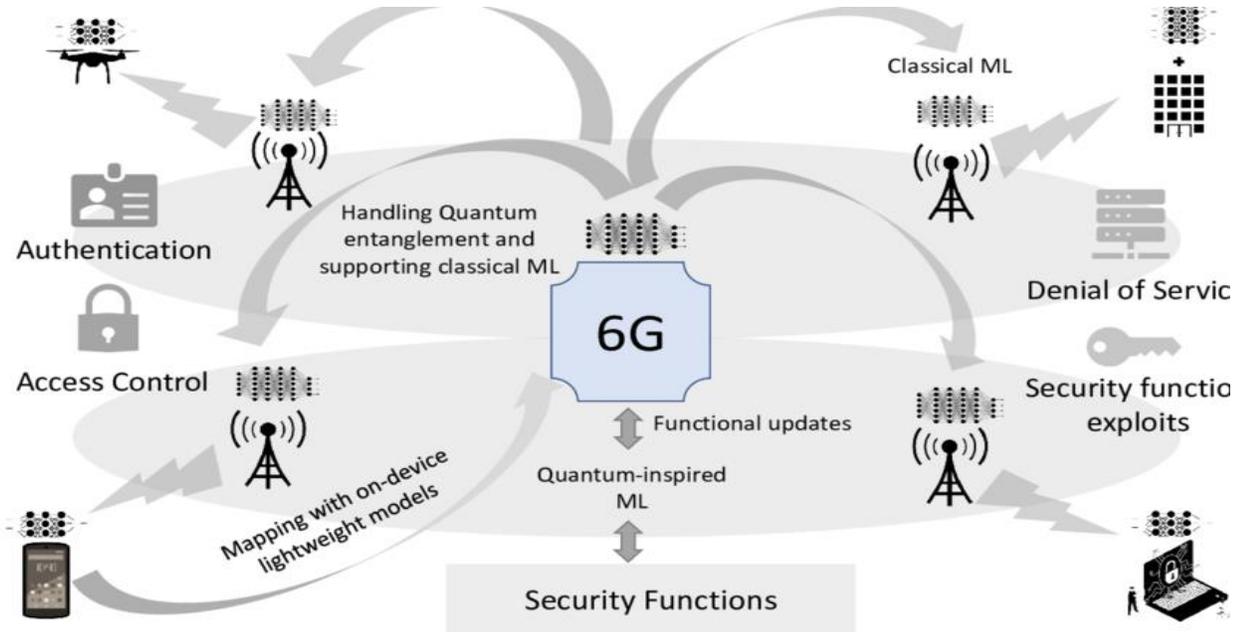
In today's increasingly interconnected world, the need for secure and private computing environments has never been more critical. Advanced computing systems, including cloud computing, edge computing, distributed computing, and emerging technologies like quantum computing and blockchain, play a pivotal role in various sectors such as healthcare, finance, manufacturing, defense, and beyond. These systems offer unparalleled

computational capabilities, enabling organizations to process vast amounts of data, run complex simulations, and make data-driven decisions in real-time. However, as these systems grow in complexity and scope, they introduce a range of security and privacy vulnerabilities that could expose sensitive data to potential breaches, unauthorized access, or cyber-attacks [1].

With the digital landscape continuously evolving, the significance of cybersecurity in advanced computing systems cannot be overstated. The integration of

technologies like the Internet of Things (IoT), artificial intelligence (AI), and machine learning (ML) into everyday operations has significantly expanded the attack surface for malicious actors. Organizations now face sophisticated threats that exploit vulnerabilities in both centralized cloud systems and decentralized

architectures, making traditional security mechanisms inadequate. Furthermore, issues related to data privacy, compliance with regulatory standards such as the General Data Protection Regulation (GDPR), and the rise of state-sponsored cyber-attacks have escalated the need for robust and scalable security solutions.



The rapid adoption of cloud computing platforms has facilitated the growth of businesses by providing on-demand access to storage, computing resources, and services. However, this convenience has brought with it security challenges such as misconfigurations, insider threats, and data leakage. Similarly, edge computing has revolutionized real-time data processing by moving computation closer to the data source, but this distributed nature creates additional points of vulnerability. As quantum computing moves closer to mainstream application, it also poses future security risks to existing cryptographic methods. These potential threats have accelerated the development of novel encryption methods and security protocols designed to protect data integrity and user privacy[2].

This research paper aims to provide a comprehensive analysis of the security and privacy concerns in advanced computing systems. It will explore current security practices, emerging threats, and potential solutions to safeguard these complex architectures. By examining the vulnerabilities inherent in cloud, edge, and quantum computing, as well as the role of blockchain in enhancing security, this paper seeks to contribute to the ongoing dialogue around building more resilient and secure computing infrastructures. The

findings of this research can serve as a foundation for developing more robust strategies to mitigate risks and enhance privacy in the digital era [3].

2. Background and Foundations of Quantum Computing

Quantum computing is built on the fundamental principles of quantum mechanics, a branch of physics that deals with the behavior of particles at the atomic and subatomic levels. Unlike classical physics, which can predict the behavior of objects with precision, quantum mechanics operates under the probabilistic nature of wavefunctions, which describe the probability of finding a particle in a particular state. This section delves into the quantum mechanical principles that form the foundation of quantum computing, explaining key concepts such as qubits, superposition, entanglement, and quantum gates.

2.1 Qubits: The Building Blocks of Quantum Computing

At the heart of quantum computing is the qubit. In classical computers, bits are the fundamental units of information, representing either a 0 or a 1. In contrast, a qubit can exist in a state of 0, 1, or any quantum superposition of these states. Mathematically, this superposition can be described as a linear combination of the two basis states, where a qubit's state can be written as:

$$|\psi\rangle = \alpha|0\rangle + \beta|1\rangle$$

where $|\psi\rangle$ represents the quantum state, and α and β are complex numbers that define the probability amplitudes for the qubit being in states $|0\rangle$ and $|1\rangle$, respectively. The probabilities of measuring the qubit in either state is determined by $|\alpha|^2$ and $|\beta|^2$, and these probabilities must sum to 1.

This ability of qubits to be in a superposition of states is what gives quantum computers their unique computational power. Whereas a classical bit can only represent one of two possible values at a time, a qubit can represent both 0 and 1 simultaneously, allowing quantum computers to perform many calculations in parallel. This property becomes particularly powerful when we consider systems of multiple qubits [4].

2.2 Entanglement and Quantum Gates

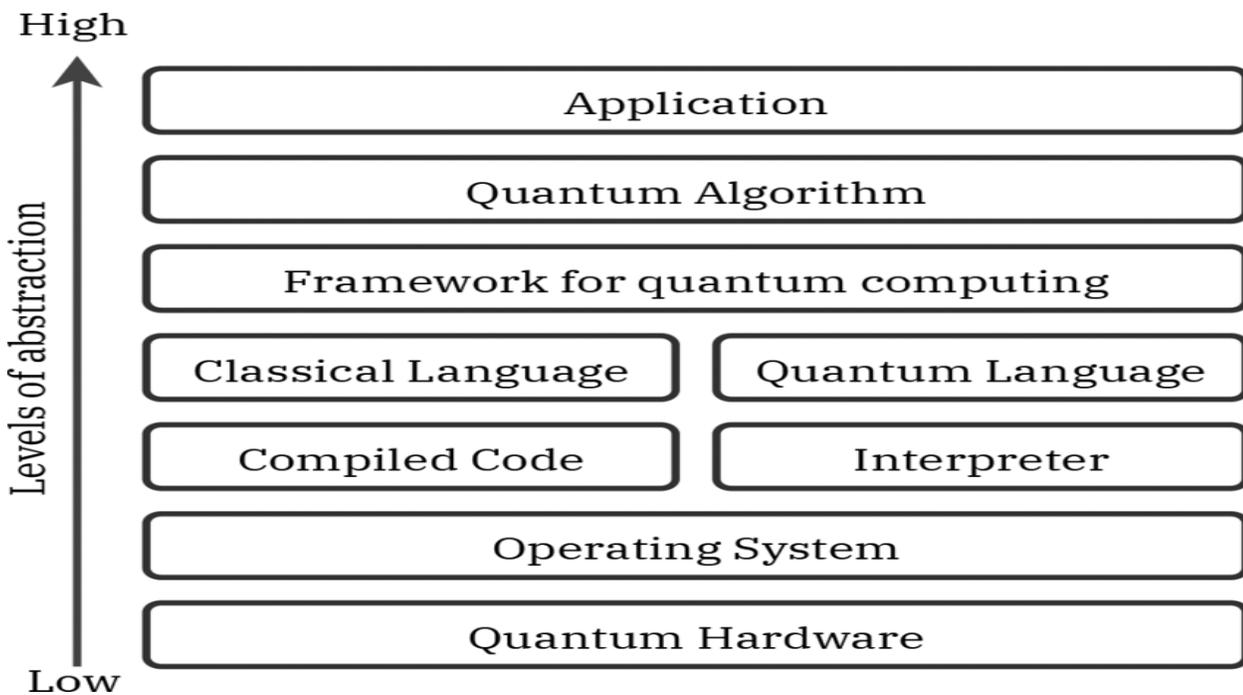
Another critical quantum mechanical phenomenon utilized in quantum computing is entanglement. When two qubits become entangled, the state of one qubit becomes dependent on the state of the other, no matter how far apart they are. This non-locality is one of the most intriguing aspects of quantum mechanics and has been experimentally verified in numerous tests of Bell's inequalities. Entanglement allows quantum computers to process information in ways that classical systems

cannot, enabling more efficient algorithms for specific tasks[5].

In addition to superposition and entanglement, quantum computers utilize quantum gates to manipulate qubits. Analogous to classical logic gates (AND, OR, NOT), quantum gates are unitary operations that change the state of qubits in a reversible manner. Common quantum gates include the Hadamard gate, which puts a qubit into a superposition state, and the CNOT gate, which entangles two qubits. These gates, combined with the quantum circuit model, allow for the development of quantum algorithms capable of outperforming classical algorithms in solving specific problems [6].

3. Quantum vs. Classical Computing: A Comparative Analysis

Quantum computing has often been described as a "paradigm shift" in the way we process and handle information. While classical computers have been monumental in their ability to handle complex computations, they are fundamentally limited by their reliance on bits, which can only represent one of two states. Quantum computers, on the other hand, exploit the principles of superposition and entanglement to process exponentially more data in parallel. This section provides a detailed comparative analysis between classical and quantum computing, highlighting their strengths, weaknesses, and potential applications.



3.1 Computational Power and Speed

One of the key areas where quantum computers hold a significant advantage over classical computers is in computational power and speed. Classical computers

process information sequentially, meaning that tasks that involve large datasets or complex algorithms can take an extensive amount of time to complete. For instance, the time complexity for solving certain problems, like factoring large numbers or solving optimization problems, increases exponentially with the size of the input. This is particularly relevant in cryptography, where classical algorithms such as RSA encryption depend on the difficulty of factoring large integers.

Quantum computers, by contrast, can process information in parallel due to the superposition of qubits. An algorithm like Shor's algorithm for integer factorization, which runs in polynomial time on a quantum computer, demonstrates how quantum computing can solve problems that would take classical computers millennia to crack. For instance, while factoring a 2048-bit number may take thousands of years on a classical supercomputer, a sufficiently large quantum computer could accomplish this task in a matter of hours [7].

Table 1: A Comparative Overview of Classical and Quantum Algorithms

Algorithm	Classical Complexity	Quantum Complexity	Applications
Shor's Algorithm	Exponential (N^k)	Polynomial ($O((\log N)^3)$)	Cryptography, Integer Factorization
Grover's Algorithm	$O(N)$	$O(\sqrt{N})$	Database Search, Optimization
Classical Sorting	$O(N \log N)$	$O(\log N)$	Data Sorting, Search

3.2 Problem-Solving Capabilities

Quantum computers excel at solving problems that involve complex systems with many variables. These include simulations of quantum mechanical systems, such as molecular structures and chemical reactions, which are notoriously difficult to model accurately on classical computers. In material science, for instance, quantum computers can simulate the behavior of electrons in materials at a quantum level, leading to breakthroughs in the discovery of new materials with unique properties[8].

In artificial intelligence, machine learning models could potentially benefit from quantum speedups. Classical machine learning algorithms often struggle with optimization problems in high-dimensional spaces, where finding the global minimum of a function can be computationally expensive. Quantum computing offers more efficient ways to navigate these complex search spaces, leading to faster and more accurate AI models.

4. Applications of Quantum Computing in Advanced Computational Systems

The practical applications of quantum computing span a wide range of industries, from cryptography to healthcare, logistics, and finance. As quantum

Table 2: Applications of Quantum Computing Across Various Industries

Industry	Quantum Application	Impact
Cryptography	Shor's Algorithm for Decryption	Breaks RSA and ECC encryption methods
Healthcare	Drug Discovery, Protein Folding	Faster discovery of new drugs and treatments
AI and Machine Learning	Quantum Machine Learning (QML)	Accelerates learning and optimization algorithms
Finance	Portfolio Optimization	More efficient and accurate financial modeling
Material Science	Quantum Simulation of Materials	Discovery of new materials and chemicals

technology continues to develop, its potential to transform advanced computational systems becomes more apparent. In this section, we will explore some of the key applications of quantum computing in various fields, demonstrating how it can solve complex problems that classical computers struggle to address [9].

4.1 Cryptography and Security

Cryptography is one of the fields most affected by the advent of quantum computing. Many classical encryption methods, such as RSA and ECC (Elliptic Curve Cryptography), rely on the difficulty of factoring large prime numbers or solving discrete logarithmic problems—tasks that are computationally intensive for classical machines. Quantum algorithms, particularly Shor's algorithm, pose a direct threat to these encryption systems.

However, quantum computing also offers solutions to the security challenges it presents. Quantum key distribution (QKD) allows for the secure exchange of cryptographic keys by using the principles of quantum mechanics to detect any eavesdropping attempts. This could lead to the development of quantum-safe encryption techniques, ensuring that sensitive data remains secure in the age of quantum computing.

5. Challenges and Limitations of Quantum Computing

While the potential of quantum computing is immense, the field is still in its infancy, facing numerous technical challenges that must be overcome before it can reach widespread commercial use. This section outlines some of the key challenges in the development of quantum computers, including error rates, decoherence, scalability, and the need for specialized environments.

5.1 Quantum Decoherence and Error Correction

One of the primary challenges in quantum computing is decoherence, a phenomenon where qubits lose their quantum state due to interactions with the external environment. Quantum systems are highly sensitive to noise and other disturbances, which makes maintaining a stable quantum state difficult. This limits the amount of time a quantum computer can perform calculations before errors start to accumulate.

To mitigate these issues, researchers are developing quantum error correction techniques. Unlike classical computers, where errors can be easily corrected using redundancy (e.g., error-correcting codes), quantum

error correction is more complex due to the no-cloning theorem, which prevents the exact duplication of quantum information. Instead, quantum error correction codes, such as the surface code, use entanglement and additional qubits to detect and correct errors without directly measuring the quantum state.

5.2 Scalability and Hardware Limitations

Another significant challenge is the scalability of quantum computers. Current quantum devices, such as those developed by IBM, Google, and Rigetti, contain only a few dozen qubits. To achieve practical quantum computing for most applications, systems with thousands or even millions of qubits will be necessary. However, building large-scale quantum computers is difficult due to the fragile nature of qubits and the complexity of quantum circuits [10].

In addition to scalability, quantum computers require highly specialized hardware environments, such as cryogenic temperatures close to absolute zero. Maintaining these extreme conditions is both expensive and technically challenging, making it difficult to develop quantum computers for everyday use.

Table 3: Current Challenges and Solutions in Quantum Computing

Challenge	Description	Proposed Solutions
Decoherence	Loss of quantum state due to noise	Quantum error correction (e.g., surface code)
Scalability	Difficulty in building large-scale systems	Advanced qubit architectures (e.g., topological qubits)
Hardware Limitations	Need for specialized environments	Research in room-temperature quantum computing

6. Future Directions and Potential Impact on Computational Systems

The future of computational systems is poised for dramatic transformation, as emerging technologies and evolving needs continue to shape the landscape of computing. Advanced computing systems, including cloud, edge, and quantum computing, are expected to become even more pervasive, significantly impacting industries across the board. As these systems evolve, new challenges and opportunities will arise, especially in areas like security, privacy, efficiency, and scalability. Understanding the potential future directions of computational systems and their broader impact is crucial for businesses, governments, and researchers alike [11].

6.1 The Rise of Quantum Computing

Quantum computing is arguably one of the most exciting areas of development in advanced computing systems. It promises to revolutionize problem-solving capabilities, particularly for tasks that are computationally intensive and beyond the reach of

classical computers. Quantum computers leverage principles of quantum mechanics—superposition and entanglement—to perform calculations at a scale far exceeding today’s most powerful supercomputer. This has vast implications for sectors such as cryptography, drug discovery, financial modeling, artificial intelligence (AI), and materials science.

However, the widespread adoption of quantum computing is not without significant challenges. Quantum hardware remains in its infancy, and scaling quantum systems for practical use is still a work in progress. Issues like qubit coherence, error rates, and the need for extremely low temperatures to maintain quantum states pose serious technical barriers. Moreover, developing quantum algorithms that can solve real-world problems more efficiently than classical counterparts remains an ongoing area of research [12].

One of the most critical future impacts of quantum computing is its potential to break current cryptographic systems. Many encryption methods, including RSA and ECC, which form the backbone of internet security,

could be rendered obsolete by a sufficiently powerful quantum computer. This prospect has already prompted the development of post-quantum cryptography, with researchers racing to develop encryption algorithms that are resistant to quantum attacks. The transition to quantum-resistant cryptography is likely to be one of the most significant security challenges of the coming decades.

Beyond cryptography, quantum computing is expected to transform industries that rely on complex simulations and optimizations. In pharmaceuticals, for example, quantum computers could dramatically accelerate drug discovery by simulating molecular interactions at an unprecedented scale and accuracy. Similarly, quantum algorithms for optimization problems could lead to breakthroughs in supply chain management, logistics, and financial modeling, unlocking efficiencies that are currently unattainable with classical systems [13].

6.2 AI and Machine Learning Integration

Artificial intelligence (AI) and machine learning (ML) will continue to play an integral role in the future of computational systems, with their influence expanding into nearly every sector. AI's ability to analyze vast datasets, learn from patterns, and make real-time decisions has already revolutionized industries like healthcare, finance, retail, and autonomous systems. As computing systems become more advanced, the integration of AI and ML will become deeper, with AI not only automating tasks but also optimizing the underlying computational processes [14].

One of the future directions for AI in computational systems is the enhancement of edge computing through AI-driven algorithms. Edge AI will allow real-time data processing and decision-making closer to the source of data, reducing the latency that comes with cloud computing models. This is particularly critical for applications like autonomous vehicles, industrial robotics, and smart city infrastructures, where immediate responses are necessary. AI at the edge can also improve energy efficiency by optimizing the use of computational resources, reducing the need for constant data transmission to central servers.

However, the increasing reliance on AI introduces new security and privacy challenges. AI systems can be vulnerable to adversarial attacks, where small perturbations in input data can lead to incorrect or harmful outcomes. Additionally, the use of AI for decision-making in sensitive areas like healthcare and finance raises ethical concerns regarding bias, transparency, and accountability. Future research will need to focus on developing robust AI systems that are secure, transparent, and fair.

Another significant development in AI and ML will be the rise of autonomous AI systems, which can operate

and make decisions without human intervention. These systems will be crucial in sectors like autonomous transportation, where they will need to navigate complex, dynamic environments in real time. Autonomous AI will also play a vital role in industries like agriculture, where AI-driven robots can optimize farming practices, reduce resource use, and increase yield without direct human oversight [15].

6.3 Blockchain for Enhanced Security and Privacy

Blockchain technology has emerged as a critical tool for enhancing security and privacy in computational systems, particularly in environments that rely on decentralized or distributed architectures. Blockchain's decentralized ledger system offers a transparent, tamper-resistant way to record transactions, ensuring data integrity and security. While blockchain is most commonly associated with cryptocurrencies, its applications extend far beyond digital currency.

In advanced computing systems, blockchain can be used to secure data transmission, authenticate devices, and ensure the integrity of distributed systems. For instance, in IoT networks, where numerous devices are connected and exchanging data, blockchain can provide a secure framework for device authentication and data sharing, preventing unauthorized access and reducing the risk of cyberattacks [16].

One of the future directions for blockchain in computational systems is its integration with AI and edge computing. Blockchain can enhance the security of AI models by providing a transparent, auditable record of how models are trained, tested, and deployed. This is especially important in industries like healthcare and finance, where the integrity of AI-driven decision-making processes must be ensured. Similarly, in edge computing, blockchain can provide a secure way to manage data provenance and ensure the authenticity of data being processed at the edge [17].

Moreover, blockchain's potential to enable decentralized computing models is another promising future direction. Decentralized cloud storage platforms, for instance, leverage blockchain to allow users to store data securely without relying on a single provider. This can reduce the risk of data breaches and ensure greater control over data privacy. As computational systems become more decentralized and distributed, blockchain will likely play an increasingly critical role in ensuring security and privacy [18].

6.4 Advancements in Edge Computing

Edge computing is expected to see significant growth in the coming years, driven by the increasing demand for real-time data processing in applications such as autonomous vehicles, smart cities, and industrial automation. One of the key benefits of edge computing

is its ability to reduce latency by processing data closer to the source, rather than relying on centralized cloud servers. This is particularly important for applications that require immediate responses, such as autonomous driving or industrial robotics, where even a slight delay in data processing can lead to catastrophic outcomes.

The future of edge computing will be shaped by advancements in AI, 5G networks, and IoT devices. AI-powered edge devices will be able to process complex data and make real-time decisions, enabling more efficient and responsive systems. For example, in smart city environments, edge AI can be used to manage traffic flow, optimize energy use, and enhance public safety by processing data from cameras, sensors, and other devices in real time.

5G networks will further accelerate the adoption of edge computing by providing the high-speed, low-latency connectivity needed to support real-time data transmission and processing. With 5G, edge devices can communicate with each other and with central servers more efficiently, enabling new applications in areas such as telemedicine, remote monitoring, and augmented reality.

However, as edge computing becomes more widespread, security and privacy concerns will become more pronounced. The distributed nature of edge environments makes them more vulnerable to cyberattacks, as each edge device represents a potential entry point for attackers. Ensuring the security of edge devices, protecting data in transit, and managing the authentication of devices in a decentralized network will be critical challenges for the future of edge computing.

6.5 Green Computing and Sustainability

As advanced computing systems become more powerful and pervasive, their energy consumption has become a significant concern. Data centers, cloud infrastructure, and high-performance computing systems require vast amounts of energy to operate, contributing to environmental issues such as carbon emissions and electronic waste. In response, there is a growing focus on developing green computing solutions that minimize the environmental impact of computational systems [19].

One of the key future directions in green computing is the development of energy-efficient hardware and algorithms. This includes the use of low-power processors, energy-efficient cooling systems, and optimized algorithms that reduce the computational load and energy consumption. For example, AI-driven algorithms can be used to optimize the operation of data centers, reducing energy use by dynamically adjusting resource allocation based on demand [20].

Renewable energy sources, such as solar and wind power, are also being integrated into data centers and computing infrastructures to reduce reliance on fossil fuels. Major tech companies, including Google, Microsoft, and Amazon, have committed to powering their data centers with 100% renewable energy, setting a precedent for sustainability in the computing industry.

Another promising area of green computing is the use of distributed computing models, such as edge and fog computing, to reduce the energy burden on centralized data centers. By processing data locally at the edge, these models can reduce the need for constant data transmission to central servers, thereby reducing energy consumption. Additionally, decentralized computing models can leverage idle resources, such as underutilized devices or servers, to perform computations more efficiently.

In conclusion, the future of advanced computing systems is shaped by numerous emerging technologies and evolving requirements. Quantum computing, AI, blockchain, edge computing, and green computing will play pivotal roles in driving innovation and addressing the challenges of security, privacy, and sustainability. As these systems continue to evolve, it will be crucial for organizations, researchers, and policymakers to stay ahead of the curve, ensuring that these powerful technologies are harnessed responsibly and effectively for the benefit of society [21].

7. Conclusion

In conclusion, quantum computing represents a revolutionary advancement in the field of advanced computational systems. By harnessing the principles of quantum mechanics, quantum computers have the potential to solve problems that are currently intractable for classical computers, from cryptography to drug discovery and optimization problems. Despite the many challenges that quantum computing still faces—such as decoherence, scalability, and hardware limitations—continued research and development are bringing us closer to realizing its full potential. As quantum computing technology matures, it will undoubtedly play a critical role in shaping the future of advanced computational systems, unlocking new possibilities in science, industry, and beyond.

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