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Quantum Computing: Harnessing Quantum Mechanics for Information Processing

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Abstract

Quantum computing represents a paradigm shift in information processing by leveraging the principles of quantum mechanics. This revolutionary field harnesses the extraordinary properties of quantum systems, such as superposition and entanglement, to perform computations that are fundamentally different from classical computing. This paper provides a comprehensive overview of quantum computing, exploring its theoretical foundations, key concepts, and potential applications. It delves into the principles of quantum mechanics that underpin quantum computing, including the qubit, superposition, entanglement, and quantum gates. Furthermore, it examines the various quantum computing models, such as the circuit model and the adiabatic model, and discusses the challenges associated with quantum error correction and decoherence. The paper also explores the current state of quantum hardware development, highlighting the progress made in quantum computing platforms such as superconducting circuits, trapped ions, and topological quantum computers. Additionally, it investigates the potential applications of quantum computing in fields such as cryptography, optimization, simulation, and machine learning. Finally, the paper addresses the future prospects and challenges of this rapidly evolving field, including the quest for scalability, fault tolerance, and the development of robust quantum algorithms.

Keywords: Quantum Computing, Information Processing, Quantum Mechanics, Superposition, Entanglement, Computation, etc.

1. Introduction

In the realm of information processing, quantum computing represents a revolutionary paradigm that draws its power from the counterintuitive principles of quantum mechanics. Unlike classical computing, which relies on binary bits (0 and 1) to represent and manipulate information, quantum computing harnesses the quantum mechanical properties of particles to perform computations [1]. This remarkable field promises to tackle computational problems that are intractable for even the most powerful classical computers, enabling breakthroughs in areas such as cryptography, optimization, simulation, and machine learning.

At the heart of quantum computing lies the concept of the qubit, the fundamental unit of quantum information [2]. Unlike classical bits, which can exist in either a 0 or 1 state, qubits can exist in a superposition of both states simultaneously, a phenomenon that defies our intuitive understanding of the physical world. This superposition principle, combined with the intriguing concept of entanglement, where the states of multiple qubits become inextricably linked, endows quantum computers with the ability to perform parallel computations on an unprecedented scale [3].

The potential of quantum computing is vast, and researchers worldwide are actively pursuing its development and application. However, harnessing the power of quantum mechanics for information processing is not without its challenges. Quantum systems are inherently fragile, and even the slightest interaction with the environment can disrupt their delicate quantum states, a phenomenon known as decoherence [4]. Overcoming this hurdle and achieving fault-tolerant quantum computation is a critical goal in the field.

This paper aims to provide a comprehensive overview of quantum computing, exploring its theoretical foundations, key concepts, and potential applications. It delves into the principles of quantum mechanics that underpin quantum computing, examines various quantum computing models, and discusses the challenges associated with quantum error correction and decoherence. Furthermore, it investigates the current state of quantum hardware development and the potential applications of quantum computing in various fields. Finally, the paper addresses the future prospects and challenges of this rapidly evolving field, shedding light on the quest for scalability, fault tolerance, and the development of robust quantum algorithms.

2. Theoretical Foundations of Quantum Computing

2.1 The Qubit and Superposition

The fundamental unit of classical information is the binary bit, which can exist in either a 0 or 1 state. In quantum computing, the analogous unit is the qubit, which can exist in a superposition of both 0 and 1 states simultaneously [5]. This superposition principle, described by the laws of quantum mechanics, is a departure from classical physics and allows qubits to encode and process information in a fundamentally different way.

Mathematically, the state of a qubit is represented by a vector in a two-dimensional complex vector space, commonly denoted as $|\psi\rangle = \alpha|0\rangle + \beta|1\rangle$, where $|0\rangle$ and $|1\rangle$ are the computational basis states, and α and β are complex numbers satisfying the condition $|\alpha|^2 + |\beta|^2 = 1$ [6]. This superposition of states enables quantum computers to perform parallel computations, as a single qubit can represent both 0 and 1 simultaneously, effectively exploring multiple computational paths at once.

2.2 Quantum Entanglement

Entanglement is another remarkable feature of quantum mechanics that plays a crucial role in quantum computing. When two or more qubits interact, their states become entangled, meaning they can no longer be described independently [7]. The state of one qubit is inextricably linked to the state of the others, even if they are physically separated. This phenomenon has no classical analog and is a fundamental resource for quantum computing, enabling quantum algorithms to achieve computational advantages over their classical counterparts.

Mathematically, the state of an entangled system of qubits is described by a joint quantum state that cannot be factored into the product of individual qubit states [8]. This non-separability of the joint state is what gives rise to the counterintuitive properties of entanglement, such as quantum correlations and non-local effects.

2.3 Quantum Gates and Circuits

Just as classical computers operate by manipulating bits using logical gates, quantum computers perform computations by applying quantum gates to qubits [9]. Quantum gates are unitary transformations that evolve the state of a qubit or a system of qubits in a controlled manner. These gates can perform various operations, such as single-qubit rotations, controlled operations, and multi-qubit entangling operations.

Quantum algorithms are typically expressed as sequences of quantum gates applied to an initial qubit state, forming a quantum circuit [10]. These circuits can be visualized as a series of horizontal lines representing the qubits, with quantum gates acting on specific qubits or combinations of qubits at different points in the circuit.

Table 1: Overview of Commonly Used Quantum Gates and Their Functions

Gate	Function
Hadamard Gate (H)	Creates a superposition of $|0\rangle$ and $|1\rangle$ states
Pauli-X Gate (X)	Flips the state of a qubit, $|0\rangle \leftrightarrow |1\rangle$
Pauli-Y Gate (Y)	Rotates the qubit state around the Y-axis
Pauli-Z Gate (Z)	Applies a phase shift to the $|1\rangle$ state
Controlled-NOT (CNOT)	Flips the target qubit if the control qubit is $|1\rangle$
Toffoli Gate	Applies a CNOT operation with two control qubits

2.4 Quantum Measurement and Decoherence

Quantum mechanics introduces a fundamental distinction between the act of measurement and the evolution of a quantum system [11]. When a measurement is performed on a qubit or a system of qubits, the quantum state collapses into one of the possible measurement outcomes, with probabilities determined by the squared amplitudes of the corresponding basis states.

However, this measurement process comes at a cost – the quantum state is irreversibly disturbed, and any information encoded in the superposition or entanglement of the pre-measurement state is lost [12]. This phenomenon, known as the quantum measurement problem, imposes limitations on the ability to extract information from quantum systems and highlights the inherent fragility of quantum states.

Decoherence is another major challenge in quantum computing, arising from the inevitable interaction between a quantum system and its environment [13]. Even the slightest disturbance from external factors, such as electromagnetic fields, thermal fluctuations, or stray particles, can disrupt the delicate quantum states and cause the loss of quantum coherence, effectively degrading the system's ability to perform quantum computations.

Overcoming decoherence and achieving fault-tolerant quantum computation is a critical goal in the field, as it is essential for realizing the full potential of quantum computing for practical applications [14]. Strategies such as quantum error correction and careful control of the quantum system's environment are being actively investigated to mitigate the effects of decoherence.

3. Quantum Computing Models

3.1Circuit Model

The circuit model is the most widely studied and prevalent model for quantum computing [15]. In this model, quantum computations are represented as sequences of quantum gates applied to an initial qubit state, forming a quantum circuit. These circuits can be designed and optimized to implement specific quantum algorithms or to perform particular computational tasks.

The circuit model is analogous to the classical circuit model, where logical gates manipulate bits to perform computations. However, in the quantum realm, the gates operate on qubits and can exploit quantum mechanical phenomena such as superposition and entanglement to achieve computational advantages over classical computing [16].

One of the key strengths of the circuit model is its ability to express a wide range of quantum algorithms, including famous examples such as Shor's algorithm for factoring large numbers and Grover's algorithm for quantum search [17]. These algorithms leverage quantum parallelism and quantum interference to achieve exponential speedups over their classical counterparts for specific problems.

3.2 Adiabatic Quantum Computing

Adiabatic quantum computing is an alternative model that takes a different approach to quantum computation [18]. Instead of relying on quantum circuits and gates, this model uses quantum annealing, a process inspired by the principles of adiabatic evolution in quantum mechanics.

In adiabatic quantum computing, the system is initialized in a known ground state and then slowly evolved through a controlled Hamiltonian evolution, guided by an external parameter [19]. The goal is to reach a final Hamiltonian that encodes the problem to be solved, with the ground state of this final Hamiltonian representing the solution.

One of the key advantages of adiabatic quantum computing is its potential for solving optimization problems, such as finding the ground state of complex quantum systems or identifying the global minimum of a high-dimensional cost function [20]. By encoding these problems into the final Hamiltonian, the adiabatic evolution process can potentially find the optimal solution more efficiently than classical methods.

3.3 Measurement-Based Quantum Computing

Measurement-based quantum computing (MBQC) is an alternative model that leverages the concept of quantum measurements to perform computations [21]. In this approach, a highly entangled multi-qubit resource state, often referred to as a cluster state, is first prepared. Subsequent computational steps are then performed by adaptively measuring individual qubits in this resource state, with the measurement outcomes and bases determined by the specific computation being performed.

One of the key advantages of MBQC is its potential for achieving fault tolerance through the use of topological error correction techniques [22]. By encoding quantum information in the topology of the cluster state, certain types of errors can be naturally suppressed, potentially offering a more robust approach to quantum computation.

MBQC has also been shown to be a universal model for quantum computation, meaning that any quantum computation can be expressed and implemented within this framework [23]. This universality, combined with the potential for fault tolerance, makes MBQC an active area of research in the quest for scalable and practical quantum computing.

3.4 Quantum Error Correction and Fault Tolerance

As mentioned earlier, quantum systems are inherently fragile, and even the slightest disturbance can disrupt their delicate quantum states, leading to errors in the computation. Achieving fault tolerance, the ability to detect and correct errors during quantum computations, is a critical challenge in the field of quantum computing [24].

Quantum error correction (QEC) is a key approach to addressing this challenge. Inspired by classical error correction techniques, QEC aims to encode quantum information redundantly across multiple physical qubits, allowing for the detection and correction of errors that may occur during the computation [25].

One of the most widely studied QEC schemes is the surface code, which encodes logical qubits onto a two-dimensional lattice of physical qubits [26]. By carefully monitoring the syndromes (error signatures) on this lattice, errors can be detected and corrected, effectively improving the fidelity of the quantum computation.

Table 2: Overview of Various Quantum Error Correction Codes and Their Properties

Code	Error Detection	Error Correction
Shor Code	Detects bit-flip and phase-flip errors	Corrects arbitrary single-qubit errors
Steane Code	Detects arbitrary single-qubit errors	Corrects arbitrary single-qubit errors
Surface Code	Detects and corrects arbitrary errors below a threshold	Fault-tolerant threshold ~1%

It is important to note that quantum error correction comes with a significant overhead in terms of the number of physical qubits required to encode a single logical qubit. This overhead grows with the desired level of error protection, making the scalability of quantum computers a major challenge [27].

In addition to QEC, other techniques such as dynamical decoupling, optimal control, and topological quantum computing are being explored to improve the fault tolerance and robustness of quantum computations [28].

3.5 Quantum Hardware Platforms

The realization of practical quantum computing requires the development of robust and scalable quantum hardware platforms. Researchers worldwide are actively investigating various physical implementations of quantum computers, each with its own strengths, challenges, and potential applications [29].

3.6 Superconducting Circuits

Superconducting circuits are one of the leading candidates for implementing quantum computers [30]. In this approach, qubits are realized using superconducting materials cooled to extremely low temperatures, typically below 100 millikelvin. The quantum information is encoded in the collective motion of superconducting electrons, often in the form of oscillating currents or magnetic flux.

Superconducting qubits offer several advantages, including scalability, fast gate operations, and the ability to integrate them with existing integrated circuit technologies [31]. However, they also face challenges related to decoherence, limited coherence times, and the need for complex cryogenic systems.

Table 3: Overview of Some Key Superconducting Qubit Types and Their Properties

Qubit Type	Advantages	Challenges
Charge Qubit	Simple design, fast gates	Short coherence times, sensitive to charge noise
Flux Qubit	Long coherence times	Sensitivity to magnetic flux noise
Transmon Qubit	Long coherence times, reduced sensitivity to charge noise	Longer gate times

3.7 Trapped Ions

Trapped ion quantum computing is another promising approach that exploits the unique properties of individual charged atoms (ions) confined in electromagnetic traps [32]. In this system, the qubits are encoded in the internal electronic states of the trapped ions, which can be manipulated using precisely tuned laser pulses.

One of the key advantages of trapped ion quantum computers is their long coherence times, which can exceed several minutes [33]. This is due to the well-isolated nature of the trapped ions, which are shielded from environmental noise and disturbances. Additionally, trapped ion systems have demonstrated high-fidelity quantum gate operations and the ability to create large-scale entangled states.

However, trapped ion quantum computing also faces challenges related to scaling and integrating large numbers of ions in a practical system [34]. The complexity of the trapping and laser control systems increases rapidly with the number of ions, making scalability a significant hurdle.

3.8 Other Platforms

Apart from superconducting circuits and trapped ions, researchers are exploring various other physical platforms for quantum computing, each with its own unique advantages and challenges.

Semiconductor quantum dots, which confine single electrons or holes in semiconductor nanostructures, offer potential scalability and integration with existing semiconductor technologies [35]. However, they face challenges related to decoherence and control of the quantum states.

Topological quantum computing, which relies on exotic quasiparticles called non-Abelian anyons, promises inherent fault tolerance due to the topological nature of the encoded information [36]. However, the experimental realization of non-Abelian anyons remains a significant challenge.

Other platforms under investigation include nitrogen-vacancy (NV) centers in diamond, linear optics, and quantum annealers based on adiabatic quantum computing [37].

Table 4: Overview of Key Quantum Hardware Platforms and Their Characteristics

Platform	Qubit Encoding	Advantages	Challenges
Superconducting Circuits	Collective motion of superconducting electrons	Scalability, fast gates, integration	Decoherence, cryogenics
Trapped Ions	Internal electronic states of trapped ions	Long coherence times, high-fidelity gates	Scaling, complex control systems
Semiconductor Quantum Dots	Confined electrons or holes in semiconductors	Scalability, integration with existing technologies	Decoherence, control
Topological Quantum Computing	Non-Abelian anyons	Inherent fault tolerance	Experimental realization of non-Abelian anyons
NV Centers in Diamond	Spin states of nitrogen-vacancy centers	Room temperature operation, long coherence times	Limited scalability, control challenges

4. Applications of Quantum Computing

The extraordinary capabilities of quantum computing have the potential to revolutionize various fields by enabling computations that are intractable for classical computers. Here, we explore some of the most promising applications of quantum computing.

4.1 Cryptography and Communication

Quantum computing poses significant challenges to current cryptographic systems, which rely on the computational difficulty of factoring large numbers or solving discrete logarithm problems [38]. Shor's algorithm, a quantum algorithm for factoring integers, has the potential to break widely used public-key cryptographic schemes, such as RSA and Elliptic Curve Cryptography (ECC).

However, quantum computing also offers opportunities for developing new, quantum-resistant cryptographic protocols and secure communication systems. Quantum key distribution (QKD) leverages the principles of quantum mechanics to enable the secure exchange of cryptographic keys, with the ability to detect any eavesdropping attempt [39]. Furthermore, quantum cryptography holds the promise of achieving information-theoretic security, which is unconditional and does not rely on computational assumptions.

Table 5: Potential Applications of Quantum Computing in Cryptography and Communication

Application	Description
Quantum Key Distribution (QKD)	Secure exchange of cryptographic keys using quantum mechanics principles
Post-Quantum Cryptography	Development of cryptographic algorithms resistant to attacks by quantum computers
Quantum Random Number Generation	Generation of truly random numbers using quantum processes
Quantum Communication Networks	Secure communication networks leveraging quantum properties

4.2 Simulation and Chemistry

One of the most promising applications of quantum computing is in the simulation of quantum systems and chemical processes. Classical computers are fundamentally limited in their ability to simulate complex quantum systems due to the exponential growth of computational resources required as the system size increases [40].

Quantum computers, by exploiting quantum phenomena such as superposition and entanglement, can efficiently simulate the behavior of quantum systems, potentially enabling breakthroughs in fields such as materials science, chemistry, and drug discovery [41]. For example, quantum computers could be used to accurately simulate the behavior of molecules and chemical reactions, leading to the development of new materials, catalysts, and drug compounds.

Moreover, quantum simulation could provide insights into fundamental questions in physics, such as the behavior of strongly correlated systems, high-temperature superconductivity, and the properties of exotic particles and states of matter [42].

4.3 Optimization and Machine Learning

Quantum computing has the potential to significantly impact the field of optimization and machine learning by enabling more efficient algorithms and accelerating certain computational tasks [43].

Quantum algorithms, such as Grover's algorithm and quantum annealing, have shown promise in solving certain optimization problems more efficiently than classical algorithms [44]. These algorithms could have applications in areas such as logistics, scheduling, financial portfolio optimization, and training of machine learning models.

Additionally, quantum computing could enhance specific tasks in machine learning, such as dimensionality reduction, clustering, and feature mapping, by leveraging quantum algorithms for linear algebra and optimization [45]. Quantum neural networks and quantum machine learning models are active areas of research, with the potential to achieve computational advantages over classical approaches.

However, the development of practical quantum machine learning algorithms and their integration with existing classical machine learning frameworks remains an active area of research, with numerous challenges to overcome [6].

5. Future Prospects and Challenges

While the potential of quantum computing is immense, several significant challenges must be addressed before it can become a practical reality. This section discusses some of the key challenges and future prospects in the field of quantum computing.

5.1 Scaling and Qubit Quality

One of the primary challenges in quantum computing is scaling the number of high-quality qubits while maintaining their coherence and stability. As the number of qubits increases, the complexity of controlling and manipulating the quantum states grows exponentially, making it increasingly difficult to perform reliable computations [7].

Researchers are actively working on improving the quality of qubits, exploring different physical implementations such as superconducting circuits, trapped ions, and semiconductor qubits. Additionally, efforts are underway to develop fault-tolerant quantum error correction techniques to mitigate the effects of noise and decoherence [1].

5.2 Quantum Error Correction and Fault Tolerance

Quantum error correction is a crucial aspect of fault-tolerant quantum computing, as it aims to protect quantum information from the detrimental effects of noise and decoherence. Various quantum error correction codes and techniques have been proposed, including stabilizer codes, topological codes, and concatenated codes [4]. However, implementing these codes efficiently and scaling them to larger quantum systems remains a significant challenge.

Achieving fault tolerance, the ability to perform reliable computations in the presence of errors, is a critical goal in the field of quantum computing. Researchers are exploring various approaches, such as error correction schemes, dynamical decoupling, and topological quantum computing, to address this challenge [10].

5.3 Quantum Algorithms and Software

While quantum computing holds great promise, the development of practical quantum algorithms and software is still in its infancy. Designing efficient quantum algorithms that can leverage the computational power of quantum computers is a non-trivial task, requiring a deep understanding of quantum mechanics and computer science [11].

Furthermore, the development of robust quantum programming languages, compilers, and software tools is essential for facilitating the creation and execution of quantum algorithms. Significant efforts are underway to address these challenges, with researchers exploring quantum programming models, quantum software development environments, and quantum programming languages [12].

5.4 Quantum Computing Hardware

The realization of practical quantum computing systems relies heavily on the development of advanced quantum computing hardware. Various physical implementations of qubits are being explored, each with its own strengths and challenges [13].

Superconducting circuits, trapped ions, semiconductor qubits, and topological qubits are among the promising candidates for quantum computing hardware. However, challenges such as scalability, qubit coherence times, and control precision must be addressed to achieve large-scale, fault-tolerant quantum computers [14].

5.5 Integration with Classical Computing

While quantum computing offers unique advantages for certain computational tasks, it is unlikely to completely replace classical computing in the near future. Instead, a hybrid approach that combines the strengths of both classical and quantum computing is expected to emerge [15].

Integrating quantum and classical computing systems poses challenges in areas such as data transfer, control and coordination, and the development of hybrid algorithms that can leverage the capabilities of both paradigms. Researchers are actively exploring architectures, programming models, and software frameworks to facilitate the seamless integration of quantum and classical computing resources [16].

5.6 Quantum Supremacy and Real-World Applications

Achieving quantum supremacy, where quantum computers can outperform classical computers on specific tasks, is a significant milestone in the field of quantum computing. While demonstrations of quantum supremacy have been reported [17], the practical applications of these achievements are still limited.

Translating the theoretical potential of quantum computing into real-world applications that can solve practical problems and provide tangible benefits remains a significant challenge. Researchers and industry leaders are actively exploring potential applications in areas such as cryptography, simulation, optimization, machine learning, and beyond [18].

6. Conclusion

Quantum computing represents a paradigm shift in information processing, harnessing the principles of quantum mechanics to perform computations in ways that are fundamentally different from classical computing. This emerging field holds immense potential for solving complex problems and unlocking new scientific and technological frontiers.

Throughout this paper, we have explored the fundamental principles of quantum mechanics that underpin quantum computing, including superposition, entanglement, quantum measurement, and decoherence. We have also examined the different computational models, such as the quantum circuit model and the quantum annealing model, and their respective strengths and limitations.

Furthermore, we have highlighted the potential applications of quantum computing in areas such as cryptography, simulation, optimization, and machine learning, showcasing the far-reaching impact this technology could have on various domains.

However, realizing the full potential of quantum computing requires overcoming significant challenges, including scaling and improving qubit quality, developing robust quantum error correction techniques, designing efficient quantum algorithms and software, advancing quantum computing hardware, integrating quantum and classical computing systems, and translating theoretical achievements into practical real-world applications.

As the field of quantum computing continues to rapidly evolve, collaborative efforts among researchers, industry leaders, and policymakers will be crucial in addressing these challenges and unlocking the transformative potential of this technology. Interdisciplinary approaches that combine expertise from physics, computer science, materials science, and engineering will be essential in driving the development of quantum computing forward.

Despite the challenges, the prospect of harnessing the power of quantum mechanics for information processing is an exciting and rapidly progressing frontier. As quantum computing continues to advance, it holds the promise of revolutionizing various domains, enabling breakthroughs in areas that were previously deemed intractable, and potentially reshaping our understanding of computation itself.

References

[1] Feynman, R. P. (1982). Simulating physics with computers. International Journal of Theoretical Physics, 21(6-7), 467-488.

[2] Nielsen, M. A., & Chuang, I. L. (2010). Quantum computation and quantum information. Cambridge University Press.

[3] Horodecki, R., Horodecki, P., Horodecki, M., & Horodecki, K. (2009). Quantum entanglement. Reviews of Modern Physics, 81(2), 865.

[4] Preskill, J. (2018). Quantum computing in the NISQ era and beyond. Quantum, 2, 79.

[5] Griffiths, D. J. (2005). Introduction to quantum mechanics. Pearson Prentice Hall.

[6] Rieffel, E., & Polak, W. (2011). Quantum computing: A gentle introduction. MIT Press.

[7] Einstein, A., Podolsky, B., & Rosen, N. (1935). Can quantum-mechanical description of physical reality be considered complete?. Physical Review, 47(10), 777.

[8] Jozsa, R., & Linden, N. (2003). On the role of entanglement in quantum computational speed-up. Proceedings of the Royal Society A, 459(2036), 2011-2032.

[9] Barenco, A., Deutsch, D., Ekert, A., & Jozsa, R. (1995). Conditional quantum dynamics and logic gates. Physical Review Letters, 74(20), 4083.

[10] Deutsch, D. (1989). Quantum computational networks. Proceedings of the Royal Society A, 425(1868), 73-90.

[11] von Neumann, J. (1955). Mathematical foundations of quantum mechanics. Princeton University Press.

[12] Zurek, W. H. (1991). Decoherence and the transition from quantum to classical. Physics Today, 44(10), 36-44.

[13] Deutsch, D. (1985). Quantum theory, the Church-Turing principle and the universal quantum computer. Proceedings of the Royal Society A, 400(1818), 97-117.

[14] Barenco, A., Ekert, A., Suominen, K. A., & Törmä, P. (1995). Approximate quantum Fourier transform and decoherence. Physical Review A, 54(1), 139.

[15] Shor, P. W. (1997). Polynomial-time algorithms for prime factorization and discrete logarithms on a quantum computer. SIAM Review, 41(2), 303-332.

[16] Grover, L. K. (1996). A fast quantum mechanical algorithm for database search. In Proceedings of the 28th Annual ACM Symposium on Theory of Computing (pp. 212-219).

[17] Harrow, A. W., Hassidim, A., & Lloyd, S. (2009). Quantum algorithm for linear systems of equations. Physical Review Letters, 103(15), 150502.

[18] Kadowaki, T., & Nishimori, H. (1998). Quantum annealing in the transverse Ising model. Physical Review E, 58(5), 5355.

[19] Farhi, E., Goldstone, J., Gutmann, S., & Sipser, M. (2000). Quantum computation by adiabatic evolution. arXiv preprint quant-ph/0001106.

[20] Das, A., & Chakrabarti, B. K. (2008). Colloquium: Quantum annealing and analog quantum computation. Reviews of Modern Physics, 80(3), 1061.

[21] Albash, T., & Lidar, D. A. (2018). Adiabatic quantum computation. Reviews of Modern Physics, 90(1), 015002.

[22] Raussendorf, R., & Briegel, H. J. (2001). A one-way quantum computer. Physical Review Letters, 86(22), 5188.

[23] Walther, P., Resch, K. J., Rudolph, T., Schenck, E., Weinfurter, H., Vedral, V., ... & Zeilinger, A. (2005). Experimental one-way quantum computing. Nature, 434(7030), 169-176.

[24] Shor, P. W. (1995). Scheme for reducing decoherence in quantum computer memory. Physical Review A, 52(4), R2493.

[25] Knill, E., & Laflamme, R. (1997). Theory of quantum error-correcting codes. Physical Review A, 55(2), 900.

[26] Fowler, A. G., Mariantoni, M., Martinis, J. M., & Cleland, A. N. (2012). Surface codes: Towards practical large-scale quantum computation. Physical Review A, 86(3), 032324.

[27] Terhal, B. M. (2015). Quantum error correction for quantum memories. Reviews of Modern Physics, 87(2), 307.

[28] Lidar, D. A., & Brun, T. A. (Eds.). (2013). Quantum error correction. Cambridge University Press.

[29] Ladd, T. D., Jelezko, F., Laflamme, R., Nakamura, Y., Monroe, C., & O'Brien, J. L. (2010). Quantum computers. Nature, 464(7285), 45-53.

[30] Devoret, M. H., & Schoelkopf, R. J. (2013). Superconducting circuits for quantum information: An outlook. Science, 339(6124), 1169-1174.

[31] Gambetta, J. M., Chow, J. M., & Steffen, M. (2017). Building logical qubits in a superconducting quantum computing system. npj Quantum Information, 3(1), 1-7.

[32] Häffner, H., Roos, C. F., & Blatt, R. (2008). Quantum computing with trapped ions. Physics Reports, 469(4), 155-203.

[33] Monz, T., Schindler, P., Barreiro, J. T., Chwalla, M., Nigg, D., Coish, W. A., ... & Blatt, R. (2011). 14-qubit entanglement: Creation and coherence. Physical Review Letters, 106(13), 130506.

[34] Blatt, R., & Wineland, D. (2008). Entangled states of trapped atomic ions. Nature, 453(7198), 1008-1015.

[35] Loss, D., & DiVincenzo, D. P. (1998). Quantum computation with quantum dots. Physical Review A, 57(1), 120.

[36] Nayak, C., Simon, S. H., Stern, A., Freedman, M., & Das Sarma, S. (2008). Non-Abelian anyons and topological quantum computation. Reviews of Modern Physics, 80(3), 1083.

[37] Ladd, T. D., Jelezko, F., Laflamme, R., Nakamura, Y., Monroe, C., & O'Brien, J. L. (2010). Quantum computers. Nature, 464(7285), 45-53.

[38] Shor, P. W. (1997). Polynomial-time algorithms for prime factorization and discrete logarithms on a quantum computer. SIAM Review, 41(2), 303-332.

[39] Bennett, C. H., & Brassard, G. (1984). Quantum cryptography: Public key distribution and coin tossing. In Proceedings of the IEEE International Conference on Computers, Systems and Signal Processing (pp. 175-179).

[40] Aspuru-Guzik, A., Dutoi, A. D., Love, P. J., & Head-Gordon, M. (2005). Simulated quantum computation of molecular energies. Science, 309(5741), 1704-1707.

[41] Cao, Y., Romero, J., Olson, J. P., Degroote, M., Johnson, P. D., Kieferová, M., ... & Aspuru-Guzik, A. (2019). Quantum chemistry in the age of quantum computing. Chemical Reviews, 119(19), 10856-10915.

[42] Georgescu, I. M., Ashhab, S., & Nori, F. (2014). Quantum simulation. Reviews of Modern Physics, 86(1), 153.

[43] Biamonte, J., Wittek, P., Pancotti, N., Rebentrost, P., Wiebe, N., & Lloyd, S. (2017). Quantum machine learning. Nature, 549(7671), 195-202.

[44] Farhi, E., Goldstone, J., Gutmann, S., & Sipser, M. (2000). Quantum computation by adiabatic evolution. arXiv preprint quant-ph/0001106.

[45] Rebentrost, P., Mohseni, M., & Lloyd, S. (2014). Quantum support vector machine for big data classification.