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(Review Article)

Quantum supremacy and its implications for classical computing

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Abstract

Quantum computing, leveraging the principles of superposition and entanglement, has emerged as a revolutionary technology with the potential to outperform classical computers in specific tasks. This paper explores the concept of quantum supremacy, marked by Google's Sycamore processor, and its implications for classical computing. It discusses the foundations of quantum computing, including qubits, superposition, and key quantum algorithms like Shor's and Grover's, highlighting their advantages over classical systems. This study addresses the milestones in achieving quantum supremacy, including experimental benchmarks and performance comparisons. The challenges in scaling quantum systems, mitigating decoherence, and addressing criticisms of quantum supremacy claims are examined. Additionally, the paper outlines emerging applications in cryptography, optimization, and artificial intelligence and emphasizes the importance of hybrid quantum-classical systems in bridging current technological gaps. The future of quantum computing lies in advancing fault-tolerant systems and fostering interdisciplinary collaborations to realize its transformative potential across industries.

Keywords: Quantum computing; Quantum supremacy; Qubits; Superposition; Entanglement; Hybrid quantum-classical systems; Cryptography; Optimization; Fault-tolerant systems

1. Introduction

Quantum computing is an emerging field that leverages principles of quantum mechanics, such as superposition and entanglement, to perform computations that are fundamentally different from classical computing. Unlike classical bits, which can only represent a 0 or 1, quantum bits (qubits) can exist in multiple states simultaneously, enabling quantum computers to solve certain problems exponentially faster than classical computers [1].

Quantum supremacy refers to the point at which a quantum computer can perform a specific task that is infeasible for any classical computer, even the most advanced supercomputers. This milestone was first demonstrated by Google's Sycamore processor, which completed a computation in 200 seconds that would have taken classical supercomputers approximately 10,000 years [2]. This achievement underscores the potential of quantum devices to outperform classical systems in specific tasks [3].

The concept of quantum supremacy has profound implications for various fields, including cryptography, optimization, and data science. Quantum computers could potentially break classical encryption schemes by using algorithms like Shor's algorithm for factorization [4]. However, it is crucial to note that classical computing will continue to play an essential role, particularly in hybrid systems where quantum and classical processors complement each other [5]. The ongoing development of quantum technologies signals a transformative shift in computational paradigms, but achieving practical quantum applications remains a significant challenge [6].

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This study explores the transformative potential of quantum computing, marked by the milestone of quantum supremacy, to outperform classical systems in specific tasks. It examines foundational principles, key algorithms, challenges, and emerging applications, highlighting the role of hybrid quantum-classical systems in advancing computational paradigms.

2. Foundations of Quantum Supremacy

2.1. Explanation of Qubits, Superposition, and Entanglement

Quantum computing relies on qubits, the fundamental units of quantum information. Unlike classical bits, which can only exist in states of 0 or 1, qubits can exist in a superposition of both states, enabling quantum computers to process a vast number of possibilities simultaneously [7]. Superposition enhances computational efficiency by allowing parallel computation. Entanglement, another cornerstone of quantum mechanics, creates strong correlations between qubits such that the state of one qubit instantly influences the state of another, regardless of the distance between them. This property is pivotal for tasks like quantum error correction and secure communication [8].

2.2. How Quantum Computers Differ Fundamentally from Classical Computers

Quantum computers differ from classical computers in their ability to exploit quantum phenomena such as superposition and entanglement. This allows quantum computers to perform certain calculations exponentially faster than classical computers. For example, classical computers process information sequentially or in limited parallel threads, whereas quantum computers can evaluate multiple outcomes simultaneously. Moreover, quantum computers operate on fundamentally different physical principles, leveraging unitary transformations and quantum gates instead of classical logic gates [9].

2.3. Key Quantum Algorithms Showcasing Potential Advantages

Two of the most notable quantum algorithms are Shor’s algorithm and Grover’s algorithm. Shor’s algorithm offers an exponential speedup in factoring large integers, which poses a threat to widely used cryptographic systems like RSA [9]. Grover’s algorithm provides a quadratic speedup for unstructured search problems, demonstrating the ability of quantum computers to outperform classical systems in specific scenarios [7].

These fundamental concepts and algorithms illustrate the transformative potential of quantum computing and underpin the pursuit of quantum supremacy.

3. Milestones in Achieving Quantum Supremacy

3.1. Overview of the First Claims of Quantum Supremacy

Google's Sycamore processor marked a significant milestone in quantum computing by achieving quantum supremacy in 2019. This was demonstrated by solving a random sampling problem in approximately 200 seconds, a task that would have taken a classical supercomputer an estimated 10,000 years [2]. The experiment showcased the ability of quantum computers to outperform classical systems in specific computational tasks, solidifying the concept of quantum supremacy as a reality [10].

3.2. Benchmarks Used to Establish Quantum Supremacy

The primary benchmark for the Sycamore experiment was the cross-entropy benchmarking (XEB) fidelity, which measured how closely the output distribution of the quantum processor matched theoretical predictions. A fidelity score of approximately 0.002 was achieved, which confirmed that the quantum output was not efficiently reproducible by classical simulation methods [11]. Additionally, the Sycamore circuit operated with 53 qubits and 20 cycles, further highlighting the computational complexity of the task [12].

3.3. Comparison of Quantum and Classical Computing Performance

The performance gap between Sycamore and classical supercomputers was significant. Sycamore completed the random sampling task in 200 seconds, while the same task would have required 10,000 years on a classical supercomputer like Summit. However, subsequent improvements in classical simulation methods have reduced this gap, with some simulations now achieving similar results within weeks or even days using optimized tensor network algorithms [13]. Despite this, Sycamore's achievement remains a landmark demonstration of quantum computational superiority for certain classes of problems [14].

4. Implications for Classical Computing

4.1. Areas Where Quantum Computers Outperform Classical Computers

Quantum computers excel in specific tasks where classical computers struggle, such as factoring large integers, simulating quantum systems, and solving optimization problems. Shor's algorithm provides exponential speedup in integer factorization, posing significant risks to classical cryptographic systems like RSA [6]. Additionally, quantum computers can simulate complex quantum systems far more efficiently, which is vital for fields like quantum chemistry and material science [4].

4.2. Limitations of Classical Algorithms in Simulating Quantum Systems

Classical algorithms face exponential complexity in simulating quantum phenomena due to the vast state space of quantum systems. For example, describing the state of a 100-qubit system requires more data than can be stored in all classical data storage available globally [15]. This limitation emphasizes why quantum computers are critical for simulating quantum systems, as classical methods become infeasible at larger scales [16].

4.3. Potential Disruptions in Fields Like Cryptography, Optimization, and Data Science

Quantum computers threaten the foundation of classical cryptography by breaking algorithms like RSA and ECC through Shor's algorithm [17]. In optimization, quantum annealers have shown promise in solving problems like portfolio optimization and logistics more efficiently than classical methods [18]. Quantum computing also holds the potential to revolutionize data science by enabling faster and more accurate machine learning algorithms [19].

4.4. Discussion on Whether Quantum Supremacy Implies the Obsolescence of Classical Computing

While quantum supremacy demonstrates the superior performance of quantum computers in specific tasks, it does not imply the complete obsolescence of classical computing. Classical computers will continue to be essential for tasks where quantum advantages are negligible or where hybrid quantum-classical systems can provide optimal solutions [1]. Furthermore, challenges like error correction and decoherence in quantum systems mean that classical computing will remain a critical component for many practical applications [4].

5. Challenges and Limitations of Quantum Supremacy

5.1. Technical Challenges (e.g., Error Rates, Decoherence, and Scalability)

One of the significant hurdles in achieving reliable quantum supremacy is managing error rates and mitigating decoherence. Quantum systems are highly susceptible to environmental noise, which leads to loss of quantum coherence, thereby affecting computational fidelity. Techniques such as error correction codes and optimized quantum gate designs are essential but remain resource-intensive [20]. Additionally, scalability poses a significant challenge, as increasing the number of qubits often exacerbates noise and decoherence issues [21].

5.2. Criticisms of Current Quantum Supremacy Claims

Critics argue that current demonstrations of quantum supremacy, such as Google's Sycamore experiment, may be overstated due to advancements in classical simulation techniques. Improved classical algorithms have closed some of the performance gaps, questioning whether true quantum supremacy has been conclusively achieved [11]. Furthermore, the tasks used to demonstrate supremacy are often highly specialized and lack practical applications, leading to debates about the real-world impact of such claims [22].

5.3. The Ongoing Role of Classical Computing in Hybrid Quantum-Classical Systems

Hybrid quantum-classical systems offer a promising pathway to overcome current limitations in quantum computing. These systems leverage classical computation to handle tasks that do not benefit from quantum speedup while utilizing quantum devices for specialized problems, such as optimization and simulation of quantum systems [23]. Variational Quantum Eigensolvers (VQE) and Quantum Approximate Optimization Algorithms (QAOA) exemplify this approach, where quantum and classical resources are integrated to achieve practical results [24].

6. Future Directions and Research Opportunities

6.1. Advancements Needed to Achieve Practical Quantum Computing

To achieve practical quantum computing, several critical advancements are necessary. These include the development of fault-tolerant quantum systems to address errors from noise and decoherence, as well as innovations in qubit scalability and interconnectivity. Improvements in quantum error correction and more efficient quantum gate designs will also play key roles in advancing quantum hardware [20]. Furthermore, research on materials to enhance qubit stability and coherence time is essential for building reliable quantum systems [21].

6.2. Emerging Fields of Application for Quantum Supremacy

Quantum computing is poised to revolutionize several industries. In cryptography, it may render classical encryption obsolete, necessitating the development of quantum-resistant cryptographic protocols. Additionally, quantum computers can solve optimization problems in logistics, finance, and machine learning far more efficiently than classical systems [4]. In scientific research, quantum simulations can accelerate drug discovery, chemical analysis, and high-energy physics experiments [25]. Emerging applications in artificial intelligence also show great promise for leveraging quantum-enhanced machine learning algorithms [26].

6.3. Collaboration Between Quantum and Classical Computing Technologies

Hybrid quantum-classical systems represent a practical bridge between current noisy intermediate-scale quantum (NISQ) systems and future large-scale quantum computers. Such systems leverage classical computers to manage tasks unsuitable for quantum processing while reserving quantum resources for specific problems where they offer a computational advantage, such as eigenvalue calculations and optimization [23]. By integrating quantum algorithms into classical high-performance computing workflows, researchers can enhance the efficiency and scalability of complex computations.

7. Conclusion

This study highlighted the transformative potential of quantum computing and its implications for classical computing. Quantum supremacy, marked by Google's Sycamore processor, demonstrates the superior performance of quantum computers in specialized tasks. The foundations of quantum computing, such as qubits, superposition, and entanglement, offer advantages over classical systems for solving complex problems. However, achieving practical quantum computing requires addressing challenges like error rates, decoherence, and scalability.

Quantum supremacy has implications across fields like cryptography, optimization, and data science, but it does not render classical computing obsolete; instead, hybrid quantum-classical systems offer complementary strengths. Future research should focus on advancing fault-tolerant quantum systems, exploring new applications, and fostering collaboration between quantum and classical technologies to unlock quantum computing's full potential.

In summary, while quantum computing is still in its early stages, its development promises to redefine computational paradigms, enabling breakthroughs across science, industry, and society.

Compliance with ethical standards

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Disclosure of conflict of interest

The authors declare that they do not have any conflict of interest.

References

[1] Harrow AW, Montanaro A. Quantum computational supremacy. Nature [Internet]. 2017 Sep 1;549(7671):203–9. Available from: https://doi.org/10.1038/nature23458

[2] Arute F, Arya K, Babbush R, Bacon D, Bardin JC, Barends R, et al. Quantum supremacy using a programmable superconducting processor. Nature [Internet]. 2019 Oct 23;574(7779):505–10. Available from: https://doi.org/10.1038/s41586-019-1666-5

[3] Boixo S, Isakov SV, Smelyanskiy VN, Babbush R, Ding N, Jiang Z, et al. Characterizing quantum supremacy in near-term devices. Nature Physics [Internet]. 2018 Apr 20;14(6):595–600. Available from: https://doi.org/10.1038/s41567-018-0124-x

[4] Gill SS, Kumar A, Singh H, Singh M, Kaur K, Usman M, et al. Quantum computing: A taxonomy, systematic review and future directions. Software Practice and Experience [Internet]. 2021 Oct 7;52(1):66–114. Available from: https://doi.org/10.1002/spe.3039

[5] Kalai G. The Quantum Computer Puzzle (Expanded Version). arXiv (Cornell University) [Internet]. 2016; Available from: https://ui.adsabs.harvard.edu/abs/2016arXiv160500992K/abstract

[6] Padamwar BV, Rao PH. Quantum Computing Mathematical foundations and practical implications. Türk Bilgisayar Ve Matematik Eğitimi Dergisi [Internet]. 2020 Dec 15;11(3):2911–5. Available from: https://doi.org/10.61841/turcomat.v11i3.14659

[7] Bawa NS. Exploring Quantum Computing: Principles and applications. Journal of Quantum Science and Technology [Internet]. 2024 Aug 30;1(3):57–69. Available from: https://doi.org/10.36676/jqst.v1.i3.27

[8] Moehring DL, Maunz P, Olmschenk S, Younge KC, Matsukevich DN, Duan L m., et al. Entanglement of single-atom quantum bits at a distance. Nature [Internet]. 2007 Sep 1;449(7158):68–71. Available from: https://doi.org/10.1038/nature06118

[9] DiCarlo L, Chow JM, Gambetta JM, Bishop LS, Johnson BR, Schuster DI, et al. Demonstration of two-qubit algorithms with a superconducting quantum processor. Nature [Internet]. 2009 Jun 28;460(7252):240–4. Available from: https://doi.org/10.1038/nature08121

[10] Cho A. Google claims quantum computing milestone. Science [Internet]. 2019 Sep 26;365(6460):1364. Available from: https://doi.org/10.1126/science.365.6460.1364

[11] Pan F, Zhang P. Simulating the Sycamore quantum supremacy circuits. arXiv (Cornell University) [Internet]. 2021 Jan 1; Available from: https://arxiv.org/abs/2103.03074

[12] Liu X, Guo C, Liu Y, Yang Y, Song J, Gao J, et al. Redefining the quantum supremacy baseline with a new generation Sunway supercomputer. arXiv (Cornell University) [Internet]. 2021 Jan 1; Available from: https://arxiv.org/abs/2111.01066

[13] Pan F, Chen K, Zhang P. Solving the sampling problem of the sycamore quantum circuits. Physical Review Letters [Internet]. 2022 Aug 22;129(9). Available from: https://doi.org/10.1103/physrevlett.129.090502

[14] Martinis JM. Quantum supremacy in a superconducting quantum processor. InPhotonics for Quantum 2021 2021 Jul 13 (Vol. 11844, p. 118440D). SPIE. Available from: https://doi.org/10.1117/12.2603523

[15] Gu M. A classical algorithm to mimic quantum decisions. National Science Review [Internet]. 2019 Jul 1;6(4):608–9. Available from: https://doi.org/10.1093/nsr/nwz081

[16] Movassagh R. Quantum supremacy and random circuits. arXiv (Cornell University) [Internet]. 2019 Jan 1; Available from: https://arxiv.org/abs/1909.06210

[17] Cyriac R, Sivaraman Eswaran, Shitharth Selvarajan. Quantum Computing in Cryptographic Systems. 2024;01(01). Available from: https://ijaitrd.com/wp-content/uploads/2024/08/Quantum-Computing-in-Cryptographic-Systems.pdf

[18] Hu F, Lamata L, Wang C, Chen X, Solano E, Sanz M. Quantum Advantage in Cryptography with a Low-Connectivity Quantum Annealer. Physical Review Applied [Internet]. 2020 May 26;13(5). Available from: https://doi.org/10.1103/physrevapplied.13.054062

[19] Upadhyay S, Roy R, Ghosh S. Designing Hash and Encryption Engines using Quantum Computing. In2024 37th International Conference on VLSI Design and 2024 23rd International Conference on Embedded Systems (VLSID) 2024 Jan 6 (pp. 571-576). IEEE. Available from: https://doi.org/10.1109/VLSID60093.2024.00101

[20] Waldherr G, Wang Y, Zaiser S, Jamali M, Schulte-Herbrüggen T, Abe H, et al. Quantum error correction in a solid-state hybrid spin register. Nature [Internet]. 2014 Jan 28;506(7487):204–7. Available from: https://doi.org/10.1038/nature12919

[21] De Leon NP, Itoh KM, Kim D, Mehta KK, Northup TE, Paik H, et al. Materials challenges and opportunities for quantum computing hardware. Science [Internet]. 2021 Apr 15;372(6539). Available from: https://doi.org/10.1126/science.abb2823

[22] Preskill J. Quantum computing and the entanglement frontier. arXiv (Cornell University) [Internet]. 2012 Jan 1; Available from: https://arxiv.org/abs/1203.5813

[23] McClean JR, Kimchi-Schwartz ME, Carter J, De Jong WA. Hybrid quantum-classical hierarchy for mitigation of decoherence and determination of excited states. Physical Review A/Physical Review, A [Internet]. 2017 Apr 6;95(4). Available from: https://doi.org/10.1103/physreva.95.042308

[24] Endo S, Cai Z, Benjamin SC, Yuan X. Hybrid Quantum-Classical Algorithms and Quantum Error Mitigation. Journal of the Physical Society of Japan [Internet]. 2021 Feb 1;90(3):032001. Available from: https://doi.org/10.7566/jpsj.90.032001

[25] Gray HM, Terashi K. Quantum computing applications in future colliders. Frontiers in Physics [Internet]. 2022 May 27;10. Available from: https://doi.org/10.3389/fphy.2022.864823

[26] Yamini B, Nithyanandhan R, Sudha K, Nithya T, Vijayakumar K, Subramanian RS. Maximizing the Revolutionary Potential of Quantum Computing: Challenges, Opportunities, and Future Directions. In2024 10th International Conference on Communication and Signal Processing (ICCSP) 2024 Apr 12 (pp. 756-761). IEEE. Available from: https://doi.org/10.1109/ICCSP60870.2024.10543947