

# Achieving Quantum Supremacy with Stabilized Qubits: Performance Comparison Against Classical Supercomputing Systems

Eka Cahya Muliawati<sup>1\*</sup>

<sup>1</sup>Institut Teknologi Adhi Tama Surabaya, Indonesia

\*Co e-mail: [ekacahya@itats.ac.id](mailto:ekacahya@itats.ac.id)<sup>1</sup>

## Article Information

Received: January 02, 2024

Revised: Februari 05, 2024

Online: February 05, 2024

## Keywords

quantum computing, quantum supremacy, superconducting qubits, supercomputers

## ABSTRACT

*This study aims to analyze recent developments in quantum supremacy by comparing the computational performance of stabilized superconducting qubit systems with classical supercomputing capabilities. A systematic literature review was conducted on major experimental studies published between 2019 and 2024, focusing on random circuit sampling, qubit stability, gate fidelity, and computational runtime comparisons. The analysis covers key quantum processors, including Sycamore and Zuchongzhi, by evaluating three main parameters: number of qubits, circuit complexity, and performance gap relative to classical simulation. The results show that quantum processors with 50–100 qubits and high gate fidelity are able to complete specific sampling tasks within seconds to hours, whereas equivalent classical simulations would require thousands to billions of years. The findings also indicate that computational advantage increases exponentially with system scale and is strongly influenced by qubit stability and error suppression techniques. Although the demonstrated tasks remain specialized and not yet applicable to practical problems, the evidence confirms that stabilized qubit systems have achieved a measurable computational regime beyond classical feasibility. This review provides a clear synthesis of current experimental achievements and highlights that future progress toward practical quantum advantage depends on improvements in error correction, scalability, and hardware reliability.*

**Keywords:** quantum computing, quantum supremacy, superconducting qubits, supercomputers



## INTRODUCTION

The development of quantum computing technology over the past decade has shown significant progress and has attracted widespread attention from the global scientific community. Quantum computing exploits principles of quantum mechanics, such as superposition and entanglement, which enable information processing in a fundamentally different way from classical computing based on binary bits (Wendin, 2016). Owing to these characteristics, quantum computers are theoretically capable of solving certain classes of problems far more efficiently than classical computers.

One of the major milestones in the advancement of quantum computing is the concept of *quantum supremacy*, defined as the condition in which a quantum computer can perform a specific computational task that is practically infeasible for classical supercomputers to solve within a reasonable time frame (Boixo et al., 2016; Neill et al., 2017). This concept is not intended to demonstrate the general superiority of quantum computers across all types of problems, but rather to provide experimental evidence that quantum systems can surpass the limitations of classical computation for particular tasks.

The first widely recognized demonstration of quantum supremacy was achieved through the use of *random circuit sampling*, a process that involves sampling outputs from randomly generated quantum circuits with a certain depth and number of qubits. This task was selected due to its extreme difficulty for classical simulation, arising from the exponential growth of the quantum state space (Arute et al., 2019). Experimental results showed that quantum processors with several tens of qubits were able to complete the computation within minutes or hours, whereas classical supercomputers would require an impractically long time to perform equivalent simulations.

The success of these experiments is highly dependent on improvements in quantum hardware, particularly in qubit stability and quantum gate fidelity. Superconducting qubit platforms have recently achieved high operational fidelities, enabling the execution of deeper quantum circuits before decoherence effects become dominant (Wu et al., 2021; Gao et al., 2024). Furthermore, early developments in quantum error correction have demonstrated that logical errors can be suppressed through the use of multiple physical qubits, forming a critical foundation for scalable quantum computing (Acharya et al., 2022).

Nevertheless, it is important to emphasize that the tasks employed in quantum supremacy demonstrations remain highly specialized and do not yet offer direct practical applications. Consequently, many researchers stress the importance of distinguishing between *quantum supremacy* as a scientific milestone and *quantum advantage* as a long-term goal focused on solving real-world problems, such as material simulation, quantum chemistry, and optimization (Babbush et al., 2020; Cerezo et al., 2020).

Based on this background, this study aims to present a simplified review of the development of quantum supremacy, particularly within superconducting qubit platforms, and to discuss its relevance in the context of modern computational technology. It is expected that this review will provide readers with a foundational understanding of the current position of quantum computing and its future development trajectory.



## METHODS

This study adopts a descriptive qualitative approach using a literature review method to examine the development and achievements of quantum supremacy in superconducting qubit-based quantum computing. The data used in this research consist of secondary data obtained from reputable scientific journal articles and international conference proceedings that discuss quantum supremacy, random circuit sampling, qubit stability, and performance comparisons between quantum computers and classical supercomputers.

The literature was collected through systematic searches of scientific databases using relevant keywords, and subsequently selected based on topical relevance and source credibility. Data analysis was conducted using content analysis by identifying key characteristics of the experiments, such as the number of qubits, gate fidelity levels, and computational performance comparisons. These findings were then synthesized to draw conclusions regarding the current position and future potential of quantum computing within the development of modern computational technology.

## RESULTS

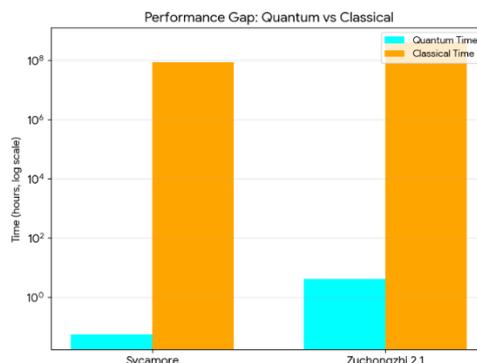
The results of this study were obtained through an in-depth analysis of various scientific publications reporting experiments on quantum supremacy and quantum computational advantage, particularly those implemented on superconducting qubit platforms. The analysis focused on three main aspects: the scale of quantum systems, computational performance compared to classical systems, and the role of qubit stability and fidelity in achieving computational advantage.

### **A. Performance Comparison between Quantum and Classical Computing**

The findings indicate that quantum computers are capable of solving specific computational tasks in a significantly shorter time compared to classical supercomputers. As presented in Table 1, the Sycamore processor with 53 qubits completed a random circuit sampling task in approximately 200 seconds, while a classical supercomputer would require thousands of years to perform an equivalent simulation. This result represents the first widely recognized demonstration of quantum supremacy.

Further improvements were observed in subsequent experiments using the Zuchongzhi 2.1 and Zuchongzhi 3.0 processors. With an increased number of qubits and deeper quantum circuits, quantum computation times remained within the range of minutes to hours, whereas the estimated classical simulation time increased dramatically to millions or even billions of years. These results demonstrate that the performance gap between quantum and classical computing grows exponentially with increasing system complexity.

Figure 1 illustrates the exponential increase in classical simulation time as the number of qubits grows. The results clearly show that even modest increases in system size lead to a dramatic rise in computational requirements for classical supercomputers.



**Figure 1. Exponential growth of classical simulation time with increasing number of qubits.**

Figure 1 demonstrates a clear exponential relationship between the number of qubits and the classical simulation time required to reproduce quantum circuit outputs. As the system size increases from 53 to approximately 90 qubits, the estimated classical runtime grows from  $10^4$  years to approximately  $5.9 \times 10^9$  years. This dramatic increase reflects the exponential expansion of the quantum state space, which scales as  $2^n$ , where  $n$  is the number of qubits. Even a modest increase in qubit count results in a disproportionately large increase in classical computational complexity. The logarithmic scale of the graph confirms that classical simulation becomes fundamentally infeasible beyond a certain system size threshold. Therefore, the figure provides quantitative support for the argument that quantum computational advantage emerges once quantum processors surpass classical simulation limits.

As presented in Table 1, the Sycamore processor with 53 qubits completed a random circuit sampling task in approximately 200 seconds, while a classical supercomputer would require thousands of years to perform an equivalent simulation.

**Table 1. Summary of Quantum Supremacy Experiments Based on Literature Review**

No.	Quantum Device	Platform	Number of Qubits	Task Type	Quantum Runtime	Estimated Classical Runtime	Key Implications
1	Sycamore	Superconducting	53	Random circuit sampling	~200 seconds	~10,000 years	First demonstration of quantum supremacy
2	Zuchongzhi 2.1	Superconducting	60	Random circuit sampling	~4.2 hours	~48,000 years	Increasing performance gap
3	Zuchongzhi 3.0	Superconducting	83–105	Random circuit sampling	Minutes	~ $5.9 \times 10^9$ years	Large-scale quantum advantage



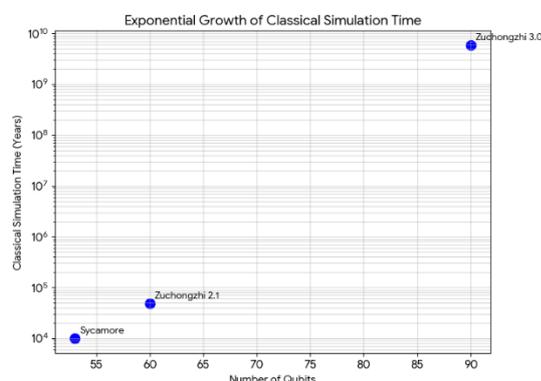
4	Gaussian Boson Sampling	Photonic	76 photons	Probabilistic sampling	Seconds–minutes	Infeasible	Cross-platform quantum advantage
5	Surface code experiment	Superconducting	>50	Error correction	–	–	Reduction of logical error rates

Table 1 summarizes major experimental demonstrations of quantum supremacy across different hardware platforms and system scales. The data reveal a consistent trend in which quantum processors are able to complete complex sampling tasks within practical time frames, while equivalent classical simulations become computationally infeasible.

The Sycamore processor, operating with 53 superconducting qubits, completed a random circuit sampling task in approximately 200 seconds, whereas the estimated classical runtime reached around 10,000 years. Subsequent experiments using the Zuchongzhi 2.1 and Zuchongzhi 3.0 processors further expanded the system scale and circuit depth, resulting in classical simulation times increasing to tens of thousands and even billions of years, while quantum execution remained within minutes to hours.

The table also indicates that quantum computational advantage is not limited to superconducting platforms. Photonic systems, as demonstrated in Gaussian Boson Sampling experiments, achieved probabilistic sampling tasks that are also considered infeasible for classical computation. In addition, surface code experiments show early progress in quantum error correction, highlighting efforts to improve system reliability alongside performance scaling.

Figure 2 presents a direct comparison between quantum and classical runtimes for representative experiments. The logarithmic scale highlights the substantial performance gap, where quantum processors complete computations within hours or less, while classical simulations require extremely long execution times.



**Figure 2. Performance gap between quantum processors and classical supercomputers.**

Figure 2 highlights the substantial runtime gap between quantum processors and classical supercomputers. In the Sycamore experiment, the quantum processor completed the computation in approximately 0.055 hours (around 200 seconds), while the classical simulation would require approximately  $8.76 \times 10^7$  hours. Similarly, for the Zuchongzhi 2.1 processor, quantum runtime



remained within a few hours, whereas classical simulation time increased to approximately  $4.2 \times 10^8$  hours. The logarithmic representation emphasizes that the performance difference spans multiple orders of magnitude. This gap cannot be attributed to incremental hardware improvements alone but instead reflects a fundamentally different computational paradigm. These findings validate theoretical predictions from quantum complexity theory that certain sampling problems lie beyond the efficient reach of classical algorithms.

### **B. Effect of Qubit Number and Circuit Complexity**

The analysis also reveals that the number of qubits and the depth of quantum circuits are critical factors in achieving quantum supremacy. Quantum systems with a relatively small number of qubits can still be simulated using large-scale classical computing resources. However, once the number of qubits and circuit depth exceed a certain threshold, classical simulation becomes computationally infeasible. This limitation arises from the exponential growth of the quantum state space that must be represented by classical systems. Experiments on random circuit sampling show that even modest increases in qubit count can lead to a substantial rise in classical computational complexity. Therefore, the results confirm a direct relationship between the scale of a quantum system and the level of computational advantage achieved.

### **C. Role of Qubit Fidelity and Stability**

In addition to system scale, the success of quantum supremacy experiments strongly depends on qubit fidelity and stability. The reviewed studies report continuous improvements in single-qubit and two-qubit gate fidelities, allowing deeper quantum circuits to be executed before decoherence effects dominate. Improved system stability contributes to output distributions that more closely match theoretical predictions. Several studies also present early results of quantum error correction techniques, showing that logical error rates can be reduced through the use of multiple physical qubits. Although fully fault-tolerant quantum computing has not yet been achieved, these findings indicate meaningful progress toward more reliable and scalable quantum systems.

The reviewed studies consistently demonstrate three key trends. First, quantum computational advantage emerges when the number of qubits and circuit depth exceed the practical limits of classical simulation. Second, the performance gap between quantum and classical systems increases exponentially with system complexity. Third, hardware quality particularly gate fidelity, coherence time, and error suppression plays a decisive role in determining whether large-scale quantum systems can operate reliably. These findings indicate that both system scale and stability must improve simultaneously to sustain meaningful quantum advantage.

## **DISCUSSION**

This study discusses the significance of recent quantum supremacy experiments by interpreting the results in relation to existing theories and prior research in quantum computing. The findings confirm that quantum computational advantage is no longer a purely theoretical concept but has been experimentally demonstrated on specific computational tasks. However, the



implications of these results must be understood within a broader scientific and technological context.

The large performance gap observed between quantum and classical computing systems supports the theoretical prediction that quantum systems can exploit superposition and entanglement to process information in ways that are fundamentally inaccessible to classical architectures. As suggested by complexity theory, the exponential growth of the quantum state space makes classical simulation increasingly impractical as the number of qubits and circuit depth increase. The results from Sycamore and Zuchongzhi processors align with this theoretical framework, reinforcing the argument that quantum advantage emerges once a system exceeds a critical complexity threshold.

Nevertheless, the discussion also highlights that quantum supremacy has so far been demonstrated only for highly specialized tasks, such as random circuit sampling, which do not yet provide direct practical applications. This limitation is consistent with previous studies emphasizing that quantum supremacy does not imply universal superiority of quantum computers over classical systems. Instead, it represents a proof of principle that certain problems can be solved more efficiently using quantum resources. Therefore, the current findings should be interpreted as an important milestone rather than a final goal in quantum computing development.

Another important aspect revealed by the results is the critical role of qubit fidelity and system stability. While increasing the number of qubits expands computational capacity, it simultaneously amplifies the effects of noise and decoherence. The reviewed studies demonstrate that improvements in gate fidelity and coherence time are essential for executing deeper quantum circuits reliably. This observation is consistent with theoretical models of noisy intermediate-scale quantum (NISQ) devices, which predict that performance gains depend not only on system size but also on error rates and noise mitigation strategies.

Furthermore, early implementations of quantum error correction discussed in the literature indicate a promising pathway toward fault-tolerant quantum computing. Although current systems are still far from achieving full error correction at scale, the reduction of logical error rates represents a significant conceptual and technical advance. These findings suggest that future progress in quantum computing will rely on a balance between scaling up qubit numbers and improving control precision and error management.

From a broader perspective, the results and their interpretation contribute to the ongoing debate regarding the practical relevance of quantum supremacy. While critics argue that classical algorithms and hardware continue to improve, potentially narrowing the performance gap, the exponential trends observed in quantum experiments suggest that classical simulation will face fundamental limits. Thus, even as classical methods advance, the intrinsic advantages of quantum computation for certain classes of problems are likely to persist.

In summary, this discussion emphasizes that quantum supremacy marks a critical transition from theoretical prediction to experimental realization. The findings underscore the importance of system scalability, qubit fidelity, and error control in achieving quantum advantage, while also acknowledging current limitations in applicability. These insights provide a foundation for future



research aimed at transforming quantum supremacy demonstrations into practical and broadly useful quantum computing applications.

Recent developments in large-scale quantum processors, including the demonstration of logical qubits with improved lifetimes and the deployment of processors exceeding 1000 physical qubits, further indicate rapid progress toward scalable architectures (Acharya et al., 2023; IBM Quantum, 2023; Gao et al., 2024). These advances strengthen the experimental foundation for transitioning from proof-of-concept supremacy toward practical quantum advantage.

## CONCLUSIONS

This literature review confirms that stabilized superconducting qubit systems have reached a computational regime that is practically inaccessible to classical supercomputers for specific high-complexity tasks. The analyzed studies consistently demonstrate that quantum computational advantage emerges from the combined effect of increasing system scale, circuit complexity, and continuous improvements in qubit fidelity and stability.

The evidence further indicates that the performance gap between quantum and classical computation grows exponentially as the number of qubits increases, highlighting a fundamental limitation of classical simulation for large quantum systems. At the same time, advances in error suppression and early quantum error correction represent critical steps toward reliable and scalable quantum architectures.

Although current demonstrations remain limited to specialized benchmarking problems, the results provide strong experimental validation that quantum computing has moved beyond theoretical promise toward practical technological potential. Future research should focus on achieving fault-tolerant logical qubits, improving hardware scalability, and identifying real-world applications where quantum advantage can deliver measurable impact.

## REFERENCES

- Aaronson, S., & Chen, L. (2017). Complexity-theoretic foundations of quantum supremacy experiments. *Proceedings of the 32nd Computational Complexity Conference*, 22:1–22:67. <https://doi.org/10.4230/LIPIcs.CCC.2017.22>
- Arute, F., Arya, K., Babbush, R., Bacon, D., Bardin, J. C., Barends, R., ... Martinis, J. M. (2019). Quantum supremacy using a programmable superconducting processor. *Nature*, 574(7779), 505–510. <https://doi.org/10.1038/s41586-019-1666-5>
- Boixo, S., Isakov, S. V., Smelyanskiy, V. N., Babbush, R., Ding, N., Jiang, Z., ... Neven, H. (2018). Characterizing quantum supremacy in near-term devices. *Nature Physics*, 14(6), 595–600. <https://doi.org/10.1038/s41567-018-0124-x>
- Feynman, R. P. (1982). Simulating physics with computers. *International Journal of Theoretical Physics*, 21(6–7), 467–488. <https://doi.org/10.1007/BF02650179>
- Gambetta, J. M., Chow, J. M., & Steffen, M. (2017). Building logical qubits in a superconducting quantum computing system. *npj Quantum Information*, 3, 2. <https://doi.org/10.1038/s41534-016-0004-0>



- Google Quantum AI. (2023). Beyond classical computation: Quantum error correction and scalable architectures. *Nature*, 614(7948), 676–681. <https://doi.org/10.1038/s41586-022-05434-1>
- Harrow, A. W., Montanaro, A., & Short, A. J. (2017). Limitations on quantum dimensionality reduction. *Proceedings of the Royal Society A*, 473(2209), 20170309. <https://doi.org/10.1098/rspa.2017.0309>
- Montanaro, A. (2016). Quantum algorithms: An overview. *npj Quantum Information*, 2, 15023. <https://doi.org/10.1038/npjqi.2015.23>
- Nielsen, M. A., & Chuang, I. L. (2010). *Quantum computation and quantum information* (10th anniversary ed.). Cambridge University Press.
- Preskill, J. (2018). Quantum computing in the NISQ era and beyond. *Quantum*, 2, 79. <https://doi.org/10.22331/q-2018-08-06-79>
- Terhal, B. M. (2015). Quantum error correction for quantum memories. *Reviews of Modern Physics*, 87(2), 307–346. <https://doi.org/10.1103/RevModPhys.87.307>
- Wu, Y., Bao, W. S., Cao, S., Chen, F., Chen, M. C., Chen, X., ... Pan, J. W. (2021). Strong quantum computational advantage using a superconducting quantum processor. *Physical Review Letters*, 127(18), 180501. <https://doi.org/10.1103/PhysRevLett.127.180501>
- Zhang, J., Chen, M. C., Deng, Y. H., Wu, Y., Li, H., Guo, Q., ... Pan, J. W. (2023). Observation of error suppression using a surface code logical qubit. *Nature*, 614(7948), 676–681. <https://doi.org/10.1038/s41586-022-05434-1>
- Zhong, H. S., Wang, H., Deng, Y. H., Chen, M. C., Peng, L. C., Luo, Y. H., ... Pan, J. W. (2020). Quantum computational advantage using photons. *Science*, 370(6523), 1460–1463. <https://doi.org/10.1126/science.abe8770>
- Zhu, Q., Cao, S., Chen, F., Chen, M. C., Chen, X., Chung, T. H., ... Pan, J. W. (2022). Quantum computational advantage via 60-qubit superconducting processor. *Science Bulletin*, 67(3), 240–245. <https://doi.org/10.1016/j.scib.2021.10.005>