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Review Article

Quantum Supremacy vs. Quantum Utility - A Critical Evaluation

V N R Sai Krishna Kari*, Shamim B, V T R Pavan Kumar M

Department of Computer Science, Kakaraparti Bhavanarayana College,Vijayawada-520001.

***Correspondence**
V N R Sai Krishna Kari
drkvnrsaikrishna@gmail.com

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Quantum computing has progressed from theoretical speculation to experimental realization, leading to milestone demonstrations that claim computational superiority over classical systems. Among these milestones, quantum supremacy experiments have attracted considerable attention by showcasing tasks that are infeasible for classical computation within reasonable time limits. However, the practical value of such demonstrations remains a subject of debate. This paper critically evaluates the distinction between quantum supremacy and quantum utility, emphasizing their conceptual differences, experimental foundations, and real-world relevance. By examining key experimental results, algorithmic developments, and benchmarking approaches, the study argues that quantum utility-defined by practical, application-oriented performance-provides a more meaningful metric for long-term progress. The paper highlights the limitations of supremacy-based demonstrations and discusses pathways toward achieving utility-driven quantum advantage in the near and long term.

Keywords: *Quantum Supremacy, Quantum Utility, NISQ Devices, Quantum Advantage, Benchmarking, Hybrid Quantum Algorithms*

Introduction

Quantum computing exploits quantum mechanical effects such as superposition and entanglement to perform computations beyond the reach of classical machines for certain problem classes (Nielsen & Chuang, 2010). Over the last decade, significant improvements in quantum hardware have enabled experimental demonstrations involving increasingly large numbers of qubits. These developments have led to claims of *quantum supremacy*, defined as the point at which a quantum computer performs a task that is practically impossible for classical systems (Preskill, 2012). While quantum supremacy represents a major scientific milestone, it does not necessarily imply practical usefulness. Supremacy experiments often focus on narrowly defined problems, such as random circuit sampling, that lack direct real-world applications (Arute et al.,2019). As a result, many researchers argue that the focus of quantum computing research should shift toward *quantum utility*, which emphasizes computational tasks with tangible scientific, industrial, or societal value (Gambetta, 2021). This paper critically examines the conceptual and practical differences between quantum supremacy and quantum utility. By analysing experimental evidence, algorithmic progress, and benchmarking methodologies, the study seeks to clarify whether supremacy demonstrations meaningfully advance the goal of practical quantum computing. The paper further discusses how utility-based metrics can guide future research in the Noisy Intermediate-Scale Quantum (NISQ) era and beyond (Preskill, 2018; Montanaro, 2016).

Conceptual Foundations

Quantum Supremacy

The term quantum supremacy was introduced to describe a definitive demonstration of quantum computational superiority over classical systems for a specific task (Preskill, 2012). Supremacy experiments typically involve generating samples from probability distributions produced by random quantum circuits. These tasks are believed to be classically intractable due to exponential scaling in computational resources (Aaronson & Arkhipov, 2013). However, supremacy claims are inherently dependent on assumptions about classical computational limits. Improvements in classical algorithms and hardware can reduce or even eliminate the perceived advantage, as demonstrated by subsequent classical simulations of earlier supremacy experiments (Pednault et al., 2020).

Quantum Utility

Quantum utility refers to the ability of quantum computers to provide meaningful performance benefits for problems of practical relevance (Gambetta, 2021). Unlike supremacy, utility emphasizes real-world applicability, solution quality, and integration with existing computational workflows. Examples include quantum chemistry simulations, optimization problems, and materials science applications (Cao et al., 2019). Utility-based approaches often rely on hybrid quantum–classical algorithms that can tolerate noise and hardware imperfections, making them suitable for near-term devices (Peruzzo et al., 2014).

Experimental Demonstrations

Supremacy Experiments

One of the most widely cited supremacy demonstrations involved a superconducting quantum processor executing random circuit sampling in seconds, compared to estimated classical runtimes of thousands of years (Arute et al., 2019). While this result marked a technological breakthrough, subsequent work demonstrated that optimized classical simulations could significantly reduce the computational gap (Pednault et al., 2020; Harrow & Montanaro, 2017). These findings illustrate the fragility of supremacy claims and highlight the importance of carefully defining classical baselines.

Early Utility-Oriented Experiments

In contrast, utility-oriented experiments have focused on small-scale but meaningful tasks, such as estimating molecular energies using the Variational Quantum Eigensolver (VQE) (Peruzzo et al., 2014; McClean et al., 2016). Although these demonstrations do not yet surpass classical methods in absolute performance, they provide insights into how quantum processors may eventually complement classical computation.

Algorithms Supporting Utility

Hybrid Quantum–Classical Algorithms

Hybrid algorithms combine parameterized quantum circuits with classical optimization routines, allowing near-term devices to contribute to computational tasks despite noise and limited circuit depth (Peruzzo et al., 2014). The Quantum Approximate Optimization Algorithm (QAOA) is another prominent example, targeting combinatorial optimization problems (Farhi et al., 2014).

Limitations of Current Algorithms

Despite their promise, hybrid algorithms face challenges such as noise sensitivity, barren plateaus in optimization landscapes, and scalability constraints (McClean et al., 2018). These limitations restrict the size and complexity of problems that can be addressed effectively in the NISQ era.

Benchmarking Supremacy and Utility

Supremacy-Oriented Benchmarks

Supremacy benchmarks are typically designed to maximize the difficulty of classical simulation rather than practical relevance. Metrics focus on sampling fidelity and runtime comparisons, which may not translate into broader computational value (Aaronson & Arkhipov, 2013; Harrow & Montanaro, 2017).

Utility-Oriented Benchmarks

Utility-based benchmarks assess performance on application-specific tasks, such as optimization quality or chemical accuracy. These benchmarks are more aligned with industry and scientific needs but are harder to standardize across platforms (Cao et al., 2019; Cross et al., 2019).

Critical Evaluation

Quantum supremacy has played an important role in demonstrating the rapid progress of quantum hardware and in motivating further investment and research. However, its reliance on contrived problem settings and shifting classical baselines limits its long-term significance (Montanaro, 2016; Pednault et al., 2020). Quantum utility, by contrast, provides a more sustainable framework for evaluating progress by emphasizing practical impact and interdisciplinary relevance (Gambetta, 2021; Dowling & Milburn, 2003). The transition from supremacy to utility requires a shift in research priorities, including the development of noise-resilient algorithms, improved error mitigation techniques, and application-driven benchmarks (Temme et al., 2017).

Future Directions

Future quantum computing research is expected to focus increasingly on utility-driven goals. Advances in error mitigation, circuit optimization, and hardware-specific algorithm design are essential for enhancing near-term performance (Peng et al., 2020). In the long term, fault-tolerant quantum computing will be necessary to unlock transformative applications such as large-scale cryptanalysis and accurate molecular simulation (Shor, 1994 ; Gottesman, 2010).

Conclusion

This paper has critically evaluated the distinction between quantum supremacy and quantum utility, highlighting their differing goals and implications for the future of quantum computing. While supremacy demonstrations represent important scientific achievements, they offer limited insight into practical computational value. Quantum utility, grounded in real-world applications and meaningful benchmarks, provides a more relevant measure of progress in the NISQ era. Continued emphasis on utility-oriented research will be crucial for transforming quantum computing from an experimental novelty into a practical technological tool.

Author contributions

Avtar Singh Bimbraw: generated this manuscript. V. N. R. Sai Krishna Kari conceptualized the study, led the critical evaluation of quantum supremacy versus quantum utility, and supervised the overall structure and direction of the manuscript.

Shamim conducted the detailed literature survey, analyzed experimental demonstrations and benchmarking approaches, and contributed to drafting major sections of the paper.

V. T. R. Pavan Kumar M contributed to the discussion on hybrid quantum algorithms, utility-oriented benchmarks, and future research directions, and assisted in manuscript revision.
All authors reviewed, edited, and approved the final version of the manuscript.

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Ethics approval

This study is a theoretical and review-based analysis based entirely on previously published research. It does not involve human participants, animals, clinical data, or personal identifiable information. Therefore, ethical approval and informed consent are not applicable.

AI tool usage declaration

The authors declare that AI-assisted tools were used only for language refinement, grammar correction, and formatting support during manuscript preparation.

All scientific analysis, interpretations, arguments, and conclusions were entirely conceived, developed, and verified by the authors.

No AI tool was used to generate original research content, experimental results, or scientific claims.

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