Introduction to Quantum Advantage

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What is Quantum Advantage?

- Definition: Performing tasks on quantum computers that are beyond the reach of classical computers
- Current Achievement: Random circuit sampling experiments have demonstrated quantum advantage in specific tasks:
  - More than 100 qubits and 40 layers of two-qubit gates
  - Google Quantum AI's Willow processor (103 qubits)
  - IBM Quantum's Heron processor (5000 gates)
- Limitation: These demonstrations are important milestones but not of great practical interest yet

The Road to Practical Quantum Advantage

- Current State: NISQ (Noisy Intermediate-Scale Quantum) devices:
  - Limited by error rates and qubit counts
  - Can execute fewer than 10^4 two-qubit operations
- Future Goal: FASQ (Fault-Tolerant Application-Scale Quantum) machines:
  - Target: $\sim 10^{12}$ operations (a 'teraquop')
  - Will pass through 'megaquop' ($\sim 10^6$), 'gigaquop' ($\sim 10^9$) regimes
- The Gap: The transition is described as 'arduous, expensive, and prolonged'

Key Challenges to Overcome

1. From error mitigation to active error detection and correction
2. From rudimentary error correction to scalable fault tolerance
3. From early heuristics to mature, verifiable algorithms
4. From exploratory simulators to credible advantage in quantum simulation

Potential Applications

- Optimization Problems:
  - VQAs
  - QAOA
- Machine Learning:
  - Quantum neural networks
  - Quantum-enhanced training algorithms
- Quantum Simulation:
  - Strongly correlated matter
  - Chemical compounds and exotic materials
  - Static and dynamical properties of quantum systems

Timeline Expectations

- Early Applications: Primarily scientific exploration
- Near-Term: Scientific value before economic impact
- Long-Term: Broader economic and societal benefits
- Key Insight: 'Quantum utility will unfold gradually, fueled by advances in both technology and theory'

Reference

[1] J. Eisert and J. Preskill, "Mind the gaps: The fraught road to quantum advantage," arXiv:2510.19928v2, Nov. 4, 2025. [Online]. Available: https://arxiv.org/abs/2510.19928v2
[2] S. K. et al. (Google Quantum AI), "Quantum Supremacy Using a Programmable Superconducting Processor," Nature, vol. 574, pp. 505–510, 2019. (The foundational experiment, similar principles apply to the newer Willow processor).
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[4] IBM, "IBM Quantum Heron Processor," IBM Research Blog, Dec. 2023. (Or use a formal paper if one has been published on the 5000-gate demonstration).