IBM Research Gets Us Closer to Quantum Advantage

A New Era Of Useful Quantum Computing Is Here

Situation Analysis

Quantum advantage, a key milestone in quantum computing, refers to the yet-to-be-achieved stage where a quantum computer can surpass the performance of a traditional computer. Essentially, it's all about the comparison of computational power between quantum and classical computers. Because it is such an important concept, it isn't uncommon to see an occasional scientific paper written by a company or university claiming to have attained quantum advantage in some narrow slice of quantum computing.

This article discusses a new IBM research paper that demonstrates how error mitigation was used to obtain superior quantum performance compared to a classical supercomputer running state-of-the-art approximation methods. This experiment resulted in some of the largest quantum circuits ever run on a quantum computer.

We may not quite be there yet, but quantum computing is clearly approaching quantum advantage.

Key areas of research for quantum advantage

IBM defines quantum advantage as a significant improvement in quantum algorithm runtime for practical cases over the best classical algorithm. It further explains that the algorithm needed to prove quantum advantage must have an efficient representation as quantum circuits, and that there should be no classical algorithm capable of simulating those circuits efficiently.

As yet there have been no useful applications demonstrating quantum advantage, and the reason is simple: today's quantum computers are too noisy, too error prone and too small to solve large, real-world problems. Unfortunately, most claims about quantum advantage put forward in papers are usually based on either random circuit sampling or Gaussian boson sampling, neither of which are considered to be useful applications.

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According to IBM, three major problems must be solved for quantum machines to perform useful problems:

- A method is needed to deal with quantum noise.
- Qubits must be scalable to large numbers.
- Quantum processors must have sufficient speed (measured in circuit layer operations per second, or CLOPS).

There is a direct relationship between quantum computing noise and the size of a problem you can tackle. The chain is simple—noise causes errors, and uncorrected errors limit the number of qubits you can incorporate in your circuit, which in turn limits algorithm complexity. Clearly error control is important.

IBM has a long history of error correction research, going back as far as investigations in 1996 by David DiVincenzo, Charlie Bennett and John Smolin. In 2015, IBM developed the first system to detect quantum bit flip and phase flip errors. Today, almost every corporate and academic quantum computing program has some form of error correction research in progress.

That said, quantum error correction (QEC) is a complex engineering and physics problem, and a truly satisfactory answer for it appears to be many years away. This is important because scaling a quantum computer to tens of thousands of qubits simply isn't possible without error correction.

On the other hand, IBM believes quantum advantage without fault tolerance is possible. It recently published a paper illustrating that quantum qubits and gates can be used deeper and wider than we previously thought.

NEW THEORIES, NEW SOLUTIONS

IBM compares scaling error-mitigated quantum circuits to the scaling of classical computers. For the first time, IBM has shown that quantum error mitigation provides a more efficient path to run circuits with a higher complexity (and at a minimal increase in simulation cost) than is possible with classical computers.

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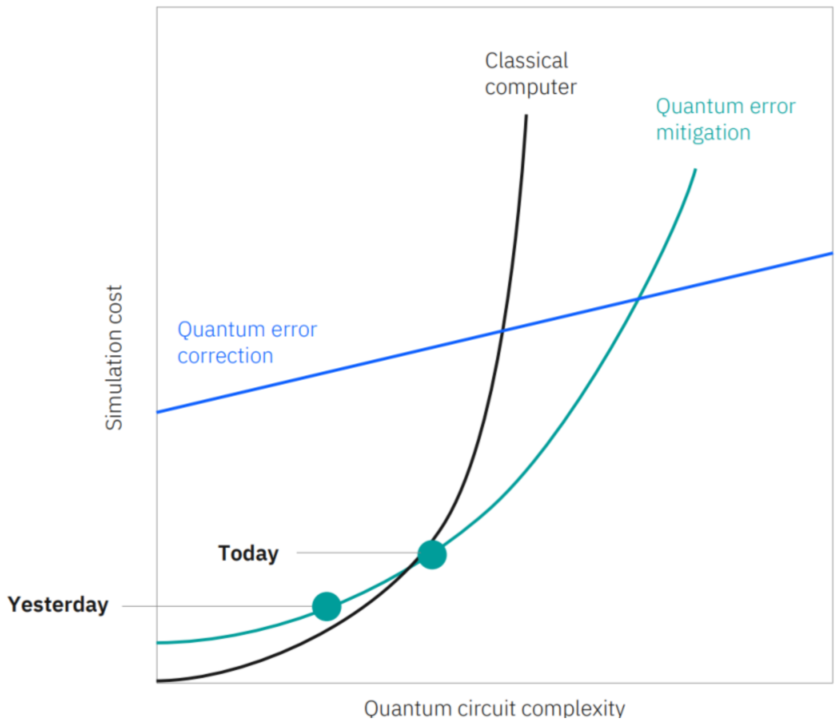
FIGURE 1. QUANTUM ERROR CORRECT VS ERROR MITIGATION



GOING FOR UTILITY ADVANTAGE

Instead of relying on fault-tolerant error correction, which is still several years away, dramatic speed-ups now appear to be possible through the use of error mitigation and error suppression techniques. IBM published proof of this concept in a new research paper published in *Nature* titled "Evidence for the utility of quantum computing before fault tolerance." This paper was produced in collaboration between IBM and researchers at the University of California, Berkeley, RIKEN iTHEMS and the Lawrence Berkeley National Laboratory.

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IBM used its 127-qubit Eagle R3 processor to simulate 127 interacting spin states. For the simulation, each qubit played the role of a spin, using two-qubit gates with a depth of 60. UCBerkeley ran the equivalent problem using cutting-edge tensor network techniques on powerful classical supercomputers at the National Energy Research Scientific Computing Center and at Purdue University.

The research team deliberately picked a problem known to be challenging for classical hardware. The research was structured to provide a comparison between the quantum solution and the classical solution. It did this by alternating solution attempts back and forth between the two teams while shifting from Clifford to non-Clifford gates and varying the weight of observables.

There were computational regions of the problem that caused the classical supercomputer's brute-force methods to fail. However, when the supercomputer failed, the quantum processor didn't falter, but rather continued to provide solutions. Given that the workflow called for a comparison on every run, on the occasions when an actual classical solution wasn't available, comparisons to the quantum results were still provided by advanced classical approximation methods. Those approximated solutions revealed that the quantum processor delivered more accurate results than the classical methods.

Based on the performance against the brute-force methods, the quantum simulation was still able to run and produce reasonable results, versus the classical approximation methods. Overall, quantum processing provided greater accuracy and in shorter timeframes.

Although a comparison of power consumption wasn't specifically part of the project, estimates put power consumption for quantum computing at 1.4 MWh per day and classical supercomputing at 10–15 MWh per day. So it appears that quantum provides a significant advantage in this respect as well.

FUTURE RESEARCH TARGETS

Traditional thinking supports the notion that useful quantum computation can't be done without fault tolerance. Although IBM's paper isn't conclusive proof, it provides an important data point that demonstrates current quantum computers can provide value much sooner than expected by using error mitigation.

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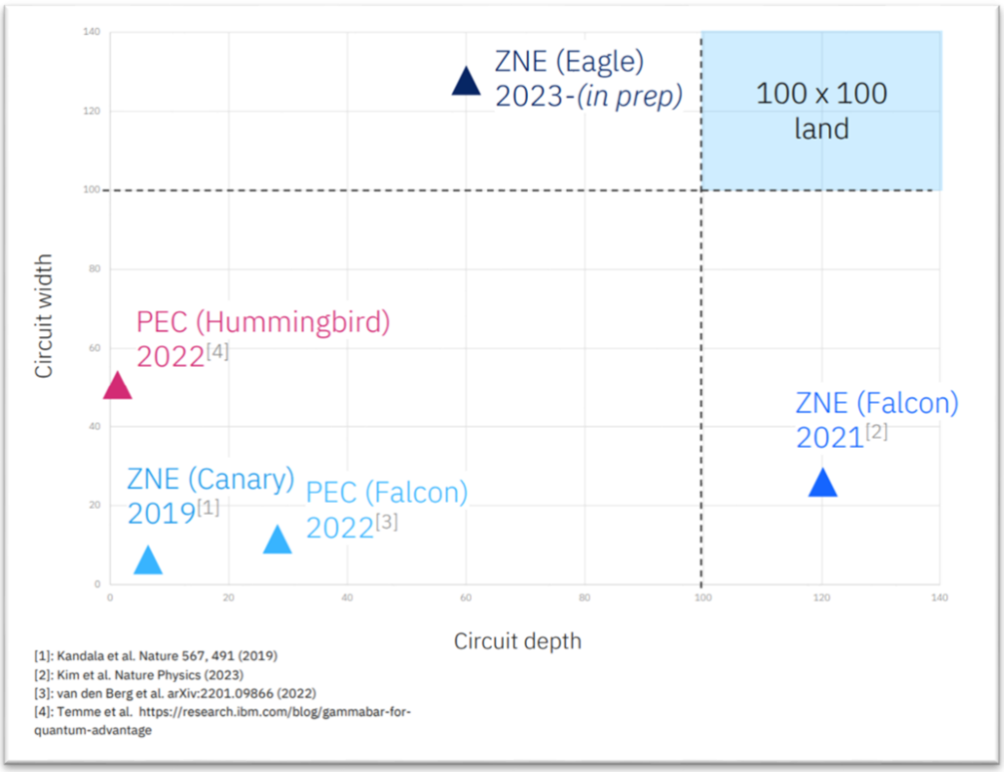
FIGURE 2: THE 100 X 100 QUBIT SWEET SPOT



As shown in the above graphic, IBM believes the door to successful quantum advantage is through the 100 x 100 section of the chart, which represents at least 100 qubits with a depth of 100 gates. IBM believes that if enough third-party research is conducted in that part of the chart, solid evidence of quantum advantage may become evident.

IBM credits much of the experiment's success to the quality of its quantum hardware and new error mitigation methods such as PEC and ZNE.

IBM's roadmap calls for error mitigation to provide a continuous development path to quantum error-correction. Once QEC is attained, it will enable us to build fault-tolerant quantum machines running millions of qubits in a quantum-centric supercomputing environment. These machines will have the ability to simulate large many-body systems, optimize complex supply chain logistics, create new drugs and materials, model and react to sophisticated financial market behavior and much more.

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Fault-tolerant quantum computers will signal that a new era of quantum-centric scientific investigation has arrived. And with that new capability will come the potential to responsibly change the world.

CONCLUSIONS

Error mitigation is the leading method that IBM believes will bridge the gap between today's error-prone hardware and tomorrow's fault-tolerant quantum computers. Error mitigation's interim purpose is to enable early achievement of quantum advantage. IBM has done more continuous error mitigation research than any other institution.

Although IBM has already begun using error mitigation, its roadmap shows a more extensive focus on error mitigation beginning in 2024 and leading to fault tolerance later in the decade.

During the project discussed above, the research teams operated like a ping pong match. Researchers at IBM Quantum and the University of California, Berkeley alternately took turns running increasingly complex computations. IBM Quantum tested the algorithms on the 127-qubit IBM Quantum Eagle processor, then the Berkeley researchers would run the equivalent calculations using state-of-the-art classical approximation methods on the Lawrence Berkeley National Lab and Purdue University supercomputers.

It's important to note that IBM isn't claiming that any specific calculation tested on the Eagle processor exceeded the abilities of classical computers. Other specialized classical methods may soon return correct answers for the calculation IBM was testing.

For more information about IBM's quantum error correction strategy, read this article, "IBM On Track To Achieve Quantum Advantage By 2026 Using Error Mitigation."

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