Physicists Pushing Boundaries Of Physics Using Quantum Computers

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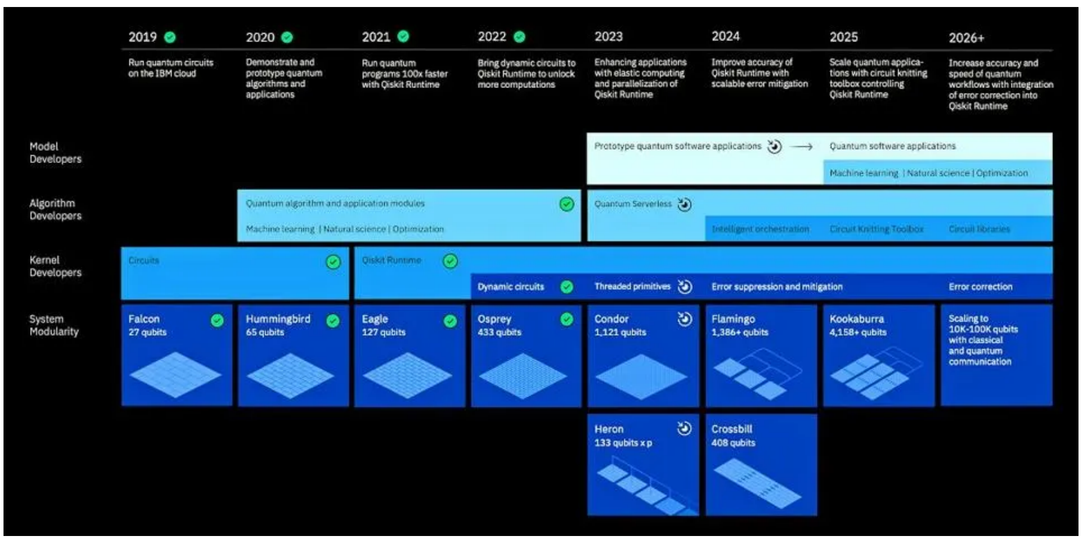

IBM's quantum computing roadmap leads to the development of quantum processors with thousands of ... [+] IBM

Like the early developers of conventional computing methods back in the 1940s, today's researchers are just beginning to explore the uses for quantum computers. Although no one expects quantum computers to completely replace classical computers, researchers believe that quantum computers can be used to tackle extremely complex computing challenges that classical computing machines either can't tackle at all or can only solve with great difficulty over long periods measured in months or years. IBM Research has developed several generations of progressively more capable quantum computers. The latest accessible fleet of IBM quantum computers, based on the company's 127-qubit Eagle processor, is just rolling out now. The company has announced plans to rapidly scale up the number of qubits in future machines and has shown a development roadmap leading to quantum processors with thousands of qubits by 2025 (see illustration above).

As was discovered in the 1940s with classical computers starting with ENIAC, building working hardware is one thing. Learning how to do useful work with the hardware is quite another. To that end, IBM has teamed with organizations and institutions around the world to create four quantum working groups to plan for the harnessing of quantum computing's emerging capabilities. The four working groups are focused on:

- Healthcare and Life Sciences: Organizations such as Cleveland Clinic are exploring the use of quantum computers in applications such as accelerated molecular discovery and patient risk prediction models. (See "Cleveland Clinic Gets Its Own IBM Quantum Processor For Advanced Biomedical Research.")
- High Energy Physics (HEP): International research institutions such as CERN and DESY are exploring ways to employ quantum computers to reconstruct particle collision events and to expand theoretical models for high energy physics.
- Materials Research: Companies and organizations including Boeing, Bosch, The University of Chicago, Oak Ridge National Lab, ExxonMobil and RIKEN are exploring new

methods for simulating the behavior of materials in various environments.

- Financial Optimization: Global financial institutions such as E.ON and Wells Fargo are trying to use quantum computers to solve practical financial and sustainability optimization problems that are currently beyond the reach of classical computers.

To spur this research, IBM Research has posed what the company calls the "100 ⊗ 100 challenge," which asks the question, "If you could produce unbiased results in less than one day from a quantum computer with 100 qubits running gate circuits with a depth of 100 layers, what problems could you solve?" No quantum computer can currently run such a program. The question is rooted in IBM's confidence in being able to produce its next-generation quantum computers, based on the parallelizable 133-qubit Heron processor that IBM announced last year. IBM has stated that Heron-based quantum computers will be able to run 100 ⊗ 100 circuit layers and produce accurate results using IBM-supplied quantum-computing tools, to be made available sometime next year.

However, working group researchers are not waiting for the arrival of these quantum computers to catalog the challenges they think that quantum computers will be able to tackle. They're thinking about the potential uses for these quantum computers now, before they're available. For example, the Quantum Computing for HEP (QC4HEP) Working Group, started by IBM and two of the top HEP labs in the world, CERN and DESY, last November, has just published a 41-page article titled "Quantum Computing for High-Energy Physics State of the Art and Challenges, Summary of the QC4HEP Working Group" on arXiv.org that details some of the high-energy physics problems that the HEP Working Group hopes to run on sufficiently capable quantum computers when they become available. (CERN is the European Center for Nuclear Research and is the home of the Large Hadron Collider (LHC). DESY, the Deutsches Elektronen-Synchroton, is the Federal Republic of Germany's national research center for fundamental science and focuses on particle physics, including high-energy physics.)

Spurred by IBM's 100 ⊗ 100 challenge, the article discusses HEP problems that might be amenable to quantum computing solutions, including examples of theoretical and experimental target applications that could be addressed by sufficiently capable quantum computers. The article's two lead authors are Alberto Di Meglio, Coordinator of CERN's Quantum Technology Initiative, and Karl Jansen, the head of DESY's Centre for Quantum Technologies and Applications.

All of physics has two branches: theoretical and experimental. Theoretical physicists develop mathematical models to explain and predict the behavior of fundamental particles and natural phenomena. Experimental physicists conduct experiments to probe these natural phenomena and to verify or falsify the theories. The two branches work hand in glove, except when experimental results refuse to follow theory. In such cases, either the theories are wrong, or the experiments aren't measuring what they're supposed to measure, or possibly both.

According to Di Meglio, HEP has many common problems on both the experimental and theoretical sides that cannot be solved by classical computing techniques due to their complexity. For example, on the experimental side, the LHC produces particle collisions that generate tremendous amounts of data. Analysis of that data requires that 98 or 99 percent of the data be discarded when looking for specific particle collisions. One way to reduce the amount of data to be analyzed is to reduce the data set by eliminating all of the data that's clearly not of interest and leaving only the data of interest for a particular experiment.

Di Meglio thinks that a computing technique that combines classical and quantum computing technologies might be used to analyze the large volumes of data generated by LHC experiments. A classical technique such as AI could be used to compress the data, which would then be analyzed by quantum computing techniques. This approach is currently needed because quantum computers currently offer only a limited number of qubits and simply cannot work with large data sets. This approach might fit into IBM's 100 ⊗ 100 challenge, says Di Meglio.

Another problem that might be addressed by quantum computing techniques is the correlation of rare events. With the possible development of quantum machine learning sometime in the future, quantum computers might be able to detect anomalous events more easily and more efficiently than classical computing techniques. A third challenge is the simulation of physical effects in the LHC's detectors to better understand the detectors' characteristics. If quantum computing can provide additional precision to the simulations of HEP experiments, physicists would better understand how different particle interactions produce data from those detectors, which would make the analyses of data from those detectors more precise.

On the theoretical side, Jansen says that classical supercomputers have been very successful in solving many-particle QED (Quantum Electrodynamics) and QCD (Quantum Chromodynamics) problems with high accuracy using lattice field theory methods. However, classical computers, even supercomputers, cannot tackle problems when the particle density becomes large, which is the situation for modeling early conditions of the universe, when the entire universe consisted of a quark-gluon plasma, or for modeling the conditions inside of a neutron star. Attempts to develop classical Monte Carlo computing methods for handling high particle densities or tackling real time phenomena have not been fruitful because classical computers would do not have sufficient computational horsepower or simply cannot solve these problems at all for conceptual reasons. It's possible that quantum computing techniques might be used to solve these more complex QED and QCD problems under such extreme conditions, says Jansen.

In addition, classical computing techniques are proving ineffective for working on theories related to violations of CP-symmetry (charge conjugation parity symmetry), which states that the laws of physics should work in the same manner if a particle is interchanged with its antiparticle (C-symmetry) while its spatial coordinates are mirrored (P-symmetry). The existence of CP violation in the very early universe, just after the Big Bang, could explain the dominance of matter over antimatter in our universe. CP violations have been observed since 1964, but currently, says Jansen, observations of CP violations differ by orders of magnitude from the results predicted by theory. Jansen believes that quantum computing techniques might help to refine the related theories and bring them more in line with experimental results.

Both Di Meglio and Jansen observe that the HEP community seems to have made a transition over the past year with respect to quantum computing. Instead of looking for problems where there might be an advantage to using quantum computers – the so-called "quantum advantage" – researchers are now looking to find problems where a combined quantum-classical computing approach might be best. In addition, Di Meglio and Jansen have both seen a friendly competition between classical and quantum computing advocates. Advances and breakthroughs on one side spur similar advances and breakthroughs by researchers on the other side.

According to Jansen, IBM's $100 \otimes 100$ challenge is spurring quantum-computing advocates to evolve their work from proofs of principles to demonstrations for problems that quantum computers may be able to solve with future capabilities. The goal, says Jansen, is to create a catalog that tells HEP researchers where classical computing techniques might best be suited, and where to use quantum computing techniques.

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