QUANTUM COMPUTERS SHOOT FOR THE MOON

By bringing together scientists with a broad range of expertise, A HIGH-RISK, HIGH-REWARD PROGRAMME is seeking to deliver fault-tolerant quantum computers by 2050.

The days of individual scientists making solo ground-breaking advances in technology are long gone. Science is a collaborative affair, and the development of a technology as revolutionary and disruptive as quantum computers demands collaboration between people with a wide range of expertise from theoreticians to experimentalists, engineers and programmers.

That is why one of the nine projects in the Moonshot programme of the Japanese government is devoted to developing fault-tolerant universal quantum computers by 2050. As an indication of its importance, it is included alongside projects seeking to control and modify the weather, create a sustainable global food chain, and prevent and treat diseases at ultra-early stages.

Quantum computers promise to solve problems that are too thorny for conventional information processing, speed up certain calculations, provide a new level of security, and accelerate machine learning. They achieve this by storing and processing information in qubits: small physical systems governed by the laws of quantum mechanics.

MULTIPLE ROUTES

There are numerous routes to creating a qubit — silicon-based devices, superconducting circuits, trapped atoms, pulses of light — and the Moonshot programme includes many individual research groups of physicists each developing one of them.

But the real benefit of the approach taken by the Moonshot programme is that it also brings together researchers with expertise in a broad range of other fields. This is because — while qubits harness the power of quantum mechanics — classical electronics systems and advanced theoretical frameworks will be essential to building a complete system.

One of the greatest challenges is dealing with errors. Like all quantum systems, qubits eventually lose their 'quantumness' through interactions with their surroundings. This is an intrinsic property that results in data loss, and it cannot be fully solved through improved qubit design alone, so developing an overarching computer architecture is just as critical as creating qubits.

The most likely way of dealing with errors, and making a quantum computer fault tolerant, is by adding redundant or ancillary qubits in addition to those needed to run an algorithm. However, the more complex the quantum calculation, the more qubits are required, which in turn requires even more ancillaries. Consequently, the computer must exceed a certain size in order to reap the benefits of the fault-tolerant architecture.

The largest quantum computers constructed to date consist of about a few hundred superconducting qubits. While these first prototypes can do simple error correction, they fall short of realizing full fault tolerance. Instead, they operate in a region known as the noisy intermediate-scale quantum regime. Some calculations have indicated that at least a million qubits may be needed to realize a fully fault-tolerant quantum computer.

But theoretical research coming out of the Moonshot programme has given hope that an intermediate stage might also be achievable.

"We've shown that a new technology using 10,000 qubits, which we call early fault-tolerant quantum computer, can perform qualitatively better than the current noisy, intermediate-scale quantum computers," says Masato Koashi, from the University of Tokyo, the project manager of the theory and software side of the quantum Moonshot programme.

While experimentalists are trying to increase the number of qubits they can build and combine, Koashi and his colleagues are seeking to cut the number of qubits needed. They are developing new quantum computation algorithms, by creating a model that views each element of the computer architecture — the qubits, the system that control them, the error correction and so on — as different layers of the final design. This so-called cross-layer co-design model is a mathematical simulator that helps orchestrate the different research groups working on the Moonshot project.

SEEING THE BIG PICTURE

"Each researcher specializes in a single technological layer, and it is difficult for them to know how their good ideas might impact the entire performance of a quantum computer," explains Koashi. Or, extending this concept, how problems in one layer might be solved by innovation in another.

He cites the example of natural variations in the performance of each qubit: some are good and some are bad. But they have shown that the solution to this lies not just in the physical layer — improving the qubits — but it can also be compensated for in the error-correction layer.

The project manager overseeing the development of a practical quantum error-correction system is Kazutoshi Kobayashi, from the Kyoto Institute of Technology. Kobayashi is an electrical engineer with a background in very-large-scale integrated (VLSI) semiconductor circuits. In particular, field program gate arrays (FPGAs) are programmable VLSI circuits that are applicable to small-volume markets.

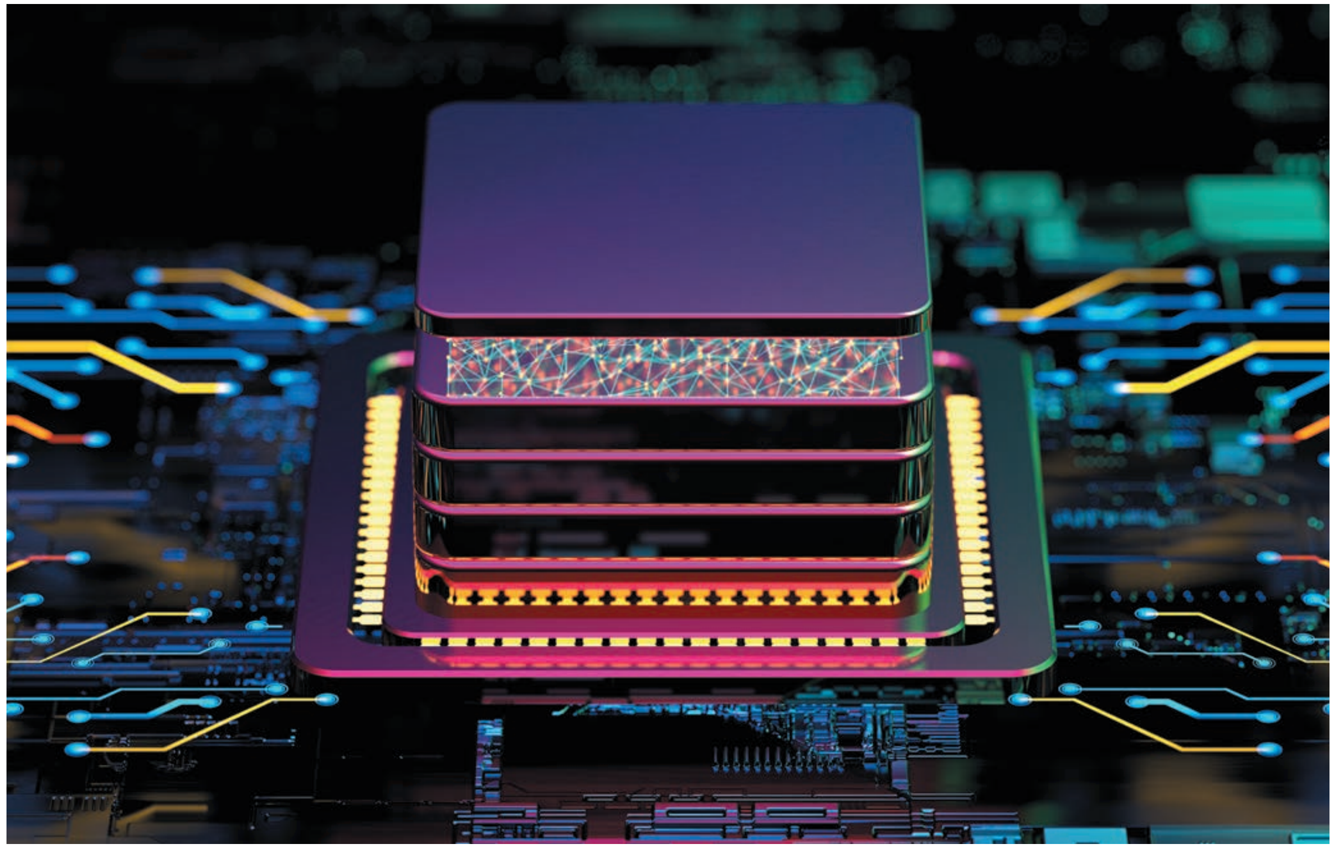
"An FPGA can essentially program hardware," he says. "Meaning you can change the prebuilt system to adapt to the specifics of the quantum system." This technology will be used to control the qubits and correct errors in a prototype quantum computer built using superconducting qubits.

SHOWING FAULT TOLERANCE

"To control a superconducting qubit, we need a high-accuracy microwave controller," explains Takefumi Miyoshi from QuEL, Inc., an industrial partner on the Moonshot programme, based in Tokyo. "This requires a real-time system; a software program is not sufficient, so we must implement it in the hardware using FPGA technology." In the next few years, the team is hoping to demonstrate sufficiently good error correction to make fault tolerance feasible in larger qubit systems.

So why place the development of a fault-tolerant quantum computer on an equal footing with some of the world's most serious global challenges such as climate change and improving healthcare? Because quantum computers will help uncover solutions to these problems.

"In my opinion, the most important task for a quantum computer will be simulating the properties of molecules," says Koashi. "Because these also follow the laws of quantum mechanics, it is a natural fit. And if you can simulate chemical reactions such as nitrogen fixation or artificial photosynthesis or drive drug discovery, then quantum computers will have a huge impact." ■



▲ A conceptual image of a quantum computer. Quantum computers promise to be solve problems that are unsolvable using conventional computers.

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▲ A quantum computer at Osaka University based on superconducting qubits developed by RIKEN and using a controller made by QuEL and others.

Osaka University

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