New quantum error correction method uses 'many-hypercube codes' while exhibiting beautiful geometry

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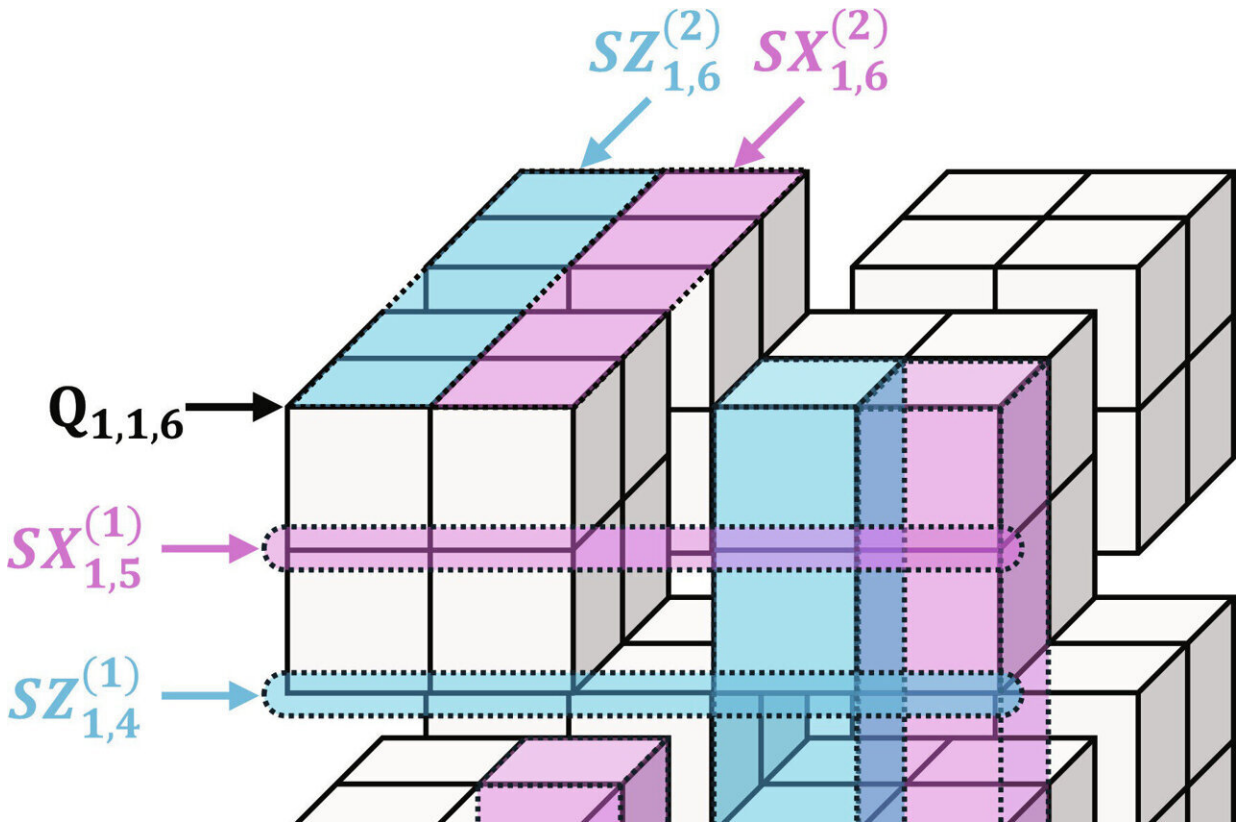

Visualization of the structure of the level-3 many-hypercube code. Credit: *Science Advances* (2024). DOI: 10.1126/sciadv.adp6388

In work published in *Science Advances*, Hayato Goto from the RIKEN

Center for Quantum Computing in Japan has proposed a new quantum error correction approach using what he calls "many-hypercube codes."

This approach, which turns out to have an elegant geometry, could help realize extremely efficient error corrections and contribute to highly parallel methods that will allow fault-tolerant quantum computing, the next stage in the evolution of quantum computers.

According to Goto, "Thanks to recent experimental progress, there is now great hope that we will be able to build fault-tolerant quantum computers, meaning quantum computers that can correct errors and surpass the power of conventional computers on certain tasks. To achieve this, however, it is important to develop efficient quantum error correction."

Scientists have proposed many different methods of error correction over the last several decades. The conventional approach to quantum error correction is typically based on encoding a single logical qubit—the qubit being the equivalent of a bit on a classical computer—onto many entangled physical ones, and then using a decoder to retrieve the logical qubit from the physical ones.

However, scalability is a problem with this approach, since the number of physical qubits required goes up enormously, and this results in huge resource overheads. To overcome this problem, high-rate quantum codes, such as quantum low-density parity-check codes, have been considered.

With this approach, the logical gates, which make calculations possible, have to be set up quite sequentially rather than fully parallel, making them less efficient time-wise.

As a means to remedy this, Goto proposed using an approach that he

calls "many-hypercube codes." Specifically, it is a method with a complex name—high-rate concatenated quantum codes—and what is innovative is that the logical qubits can be visualized mathematically as forming what is known as a "hypercube"—a type of shape, including squares and cubes as well as higher-order shapes such as the tesseract.

The beautiful mathematical and geometric structure of the code is remarkable, as most high-rate quantum codes have complicated structures.

Goto emphasizes that in order for the new codes to result in higher performance, he needed to develop a novel dedicated decoder that could interpret the result from the physical qubits. This innovative technique is based on level-by-level minimum distance decoding, which allows for high performance.

Unlike other similar methods, it also allows for logical gates to be put in parallel rather than in a series, which makes the system analogous to parallel processing in classical computers, leading Goto to call it "high-performance fault tolerant computing" as an analogy to "high-performance computing" which is used for massively parallel computing.

The work paid off. The codes achieve an encoding rate—a number that indicates the ratio between logical and physical qubits—of up to 30% which Goto says appears to be the world's highest among the codes used for fault-tolerant quantum computing. And even with this high rate, the performance is comparable to conventional low-rate codes.

Goto says, "In practice, this code could be implemented with physical qubit systems such as laser-trapped neutral-atom qubits."

More information: Hayato Goto, High-performance fault-tolerant quantum computing with many-hypercube codes, *Science Advances*

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