Highlights of 2023

https://doi.org/10.1038/s42254-024-00706-3

A series of fast-paced advances in Quantum Error Correction

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Over the past few years, and most notably in 2023, quantum error correction has made big strides, shifting the community focus from noisy applications to what can be achieved with early error-corrected quantum computers. But despite the breakthroughs in experiments with trapped ions, superconducting circuits and reconfigurable atom arrays there are still several technological challenges – unique to each platform – to overcome.

The theory of quantum error correction (QEC) was first formulated by Peter Shor in 1995, providing hope that quantum systems could one day be used to perform quantum computations reliably. Since then, the experimental control of quantum states has advanced, culminating in the early 2020s with the first compelling demonstrations of practical QEC[1,2] followed by more advances reported last year[3,4].

That QEC is even theoretically possible is remarkable. Classical devices also use error correction, the simplest way being via many copies of the information; then errors can be corrected by a bit-wise majority vote across the copies. However, copying quantum information is forbidden by the no-cloning theorem, a consequence of Heisenberg's uncertainty principle, so instead of repeated clones, quantum information is encoded in the non-local degrees of freedom of many physical qubits. Through encoding, the qubit's observables are mapped to so-called 'logical observables' acting on many physical qubits.

The most influential QEC approach, Kitaev's surface code, is defined on a 2D array of qubits with information encoded by string-like logical observables with errors detected by so-called stabilizer measurements (see Fig. 1). The results of stabilizer measurements do not directly reveal where errors occurred. Rather, they give hints to the most likely cause. Deciphering these clues requires the assistance of sophisticated classical algorithms known as decoders, and the QEC is successful if the decoder returns the correct outcome.

The ingredients of a QEC experiment have been routinely demonstrated in small systems for several decades. However, just executing a QEC protocol is not sufficient for a compelling demonstration. The hallmark feature of QEC is the exponential suppression of the failure probability when scaling to bigger codes, capable of correcting more errors and using more physical qubits to encode the same logical information. This is only possible if the physical qubits are good enough and then they are said to be below the QEC threshold required by the specific QEC code and decoder used. However, if the qubits are not good enough, increasing the code size only degrades the logical information further, as the operations involved pump more noise into the system than they remove. Demonstrating sub-threshold QEC is a clear landmark that deserves celebration.

Early QEC success came from trapped-ion qubits. In 2021, a 10-qubit device developed by Quantinuum was used to perform QEC on a small color code[1], a cousin of the surface code, and the so-called 5-qubit code. With only one code size, researchers could not observe evidence of sub-threshold error scaling. Instead, they looked for evidence of 'break-even', which is the idea of error-corrected operations becoming good enough that they are on par with the equivalent physical operations. By varying the number of QEC rounds, the researchers were able to break up the total QEC failure probability into components attributable to logical memory, and logical SPAM (state preparation and measurement), concluding that logical SPAM errors had reached break-even with physical SPAM. More recently, using a 20-qubit trapped-ion device (also from Quantinuum), they saw similar results when performing error-corrected logic between two small QEC codes[2].

Remarkable progress has also been made with superconducting qubits. In 2021, a group at ETH Zurich[5] demonstrated a 17 transmon qubit surface code with very good results, close to break-even, yet not quite there. Last year, a team from Google achieved a milestone QEC result[3] using their Bristlecone chip, which has 72 qubits arranged in a 2D grid tailored precisely for the surface code. With Bristlecone, the Google team performed repeated rounds of QEC (up to 25) using surface codes with 17 and 49 qubits capable of correcting 1 and 2 errors, respectively. The researchers observed that, when using very high-accuracy decoders, the bigger code led to slightly lower logical failure probabilities, as would be expected when operating sub-threshold. However, they reported simulations showing that there exists a very narrow parameter regime, just above the QEC threshold, where logical errors initially decrease with code size and then increase at much higher code sizes. The Google team has been cautious, claiming only that their device is operating in this ambiguous region around the QEC threshold. Even so, this was a world first.

What's next for superconducting qubits is a larger error suppression (ideally 10×) each time the surface code size is increased. This will require further qubit improvements and verification on a larger number of qubits. However, superconducting devices face scaling

Key Advances

- In superconducting qubits the suppression of logical error with increasing code size has been reported.
- In reconfigurable atom arrays fault-tolerant logic over hundreds of physical qubits has been demonstrated.
- Theory improvements to make QEC more hardware-efficient and first real-time decoders fast enough for all qubit types.

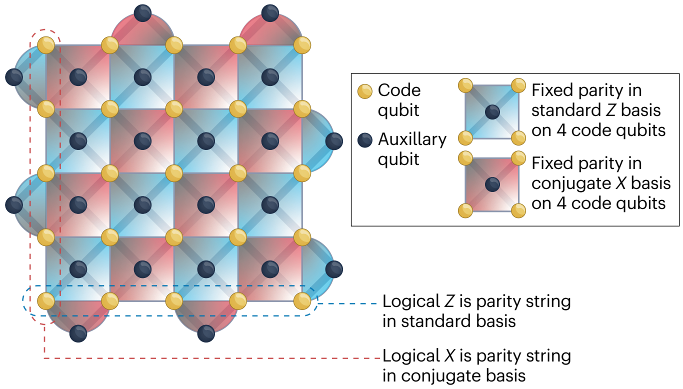

Fig. 1 | A surface code capable of correcting any two errors, using 49 qubits including auxiliary qubits. To detect the presence of bit-flip errors, one measures observables called stabilizers; these measure the parity of small subsets of qubits, shown in the blue shaded regions. To detect the presence of phase errors, one makes similar sets of measurements but on the conjugate (X) basis, shown in the pink shaded regions. Crucially, these measurements must commute with each other, and with the logical observables. Whereas a single qubit Z observable anti-commutes with an X observable, pairs of such observables commute, so it is possible to protect against both bit flips and phase errors at the same time. To achieve this, auxiliary qubits are used to measure products of Z or X observables without measuring the single qubit observables that anti-commute.

challenges: chip yield decreases rapidly with size, and overheating of dilution refrigerators (caused by current qubit control electronics) will likely become a bottleneck. From an optimistic perspective, different materials and cleaner fabrication processes have been shown to dramatically extend transmon qubit coherence lifetimes and improve chip yield. Additionally, an alternative hardware-efficient surface code has been recently discovered[6] that could quickly lead to a big performance boost.

The biggest surprise in 2023 came from a completely different type of qubit[4]. The Harvard-led team working with QuEra and MIT dramatically improved reconfigurable atom arrays, enabling several large QEC experiments involving up to 280 qubits in the largest demonstration. In these systems, rubidium atoms are trapped in a 2D array by optical tweezers realized with lasers. Unlike superconducting devices, the 2D array is not fixed, so that the grid of atoms can be rearranged by modulating the laser. Once appropriately rearranged, two-qubit gates can be realized by a global pulse affecting atoms forming nearby pairs. Since every atom is identical and pulses are applied globally, the complexity of qubit control is greatly simplified, easing scaling challenges. With this system, researchers implemented surface codes of three sizes, capable of correcting 1, 2 or 3 errors respectively. Furthermore, they demonstrated a pair of such surface codes in the same array, performing an error-corrected two-qubit logic gate between them. Measuring the success of this QEC logic experiment, researchers saw the sub-threshold hallmark of decreasing failure probability with increasing code size.

The impressive reconfigurability of these atom arrays opens exciting opportunities such as going beyond strictly 2D QEC codes like the surface code. For instance, the researchers implemented many copies of 'the smallest interesting color code', which is interesting because it supports an error-detected logic gate, a so-called non-Clifford gate, that is hard to simulate classically. Further opportunities include the possibility to realize good quantum low-density parity-check codes discovered in ref. 7, which promise fewer physical qubits per logical qubit. More results can be expected since scaling up to 10,000 atoms is widely believed to be feasible with the existing technology.

These atomic qubits in arrays do, however, have some drawbacks. Experiments are very slow, with QEC cycle times currently over 500× longer than in superconducting systems. Also, atomic qubits are essentially destroyed when measured, and atoms escaping the array is an ongoing and frequent process. This limited the feasible number of QEC rounds to a single round, with stabilizers measured only once; so the next step for this technology will be demonstrating that these results can be sustained when repeated over many QEC cycles. Mitigating atom loss by reloading and less destructive measurements will be crucial. Similar to neutral atoms, trapped ion qubits also have slow QEC cycles. In contrast to neutral atoms, ions are more robust against qubit loss, although so far trapped-ion devices have far fewer qubits.

Interestingly, the 2021 paper (ref. 1) also reported the first demonstration of 'real-time' decoding, where the decoding process is performed simultaneously with the QEC experiment. In other experiments, decoding has been undertaken as post-processing of recorded data, which is feasible for protected memory and classically simulatable (Clifford) logic gates. But for universal (non-Clifford) error-corrected logic, fast feedback is needed conditionally on the outcome of decoding. However, the real-time decoder in ref. 1 was a simple look-up table that was adequate for these very small demonstrations, but it is inherently not scalable.

2023 saw the development of the first real-time decoders that scale to ~1000 qubit surface codes[8,9] while operating fast enough to prevent an exponential decoding backlog[10] even for the current fastest qubit types (superconducting). As the missing element in all QEC experiments to date, scalable real-time decoding demonstrations are one of the next key milestones, alongside overcoming the unique challenges of each qubit platform.

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Published online: 16 February 2024

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Competing interests

The author declares no competing interests.