



News & Views

Entering the error-corrected quantum era

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In the past few decades, control and engineering technologies have experienced rapid development in various quantum computation platforms, from the realization of single-qubit gates to the implementation of high-quality two-qubit gates, and from the fabrication of a few physical qubits to the integration, calibration, and control of exceeding 50 physical qubits on a single chip. We have arrived at the noisy intermediate-scale quantum (NISQ) era [1], in which quantum systems with 50–100 noisy physical qubits can show superiority over classical systems in some applications, although the performance is limited by operation errors. In addition to finding valuable applications, another parallel and critical task is to scale up the system dimension and optimize the parameters to realize quantum error correction (QEC) to suppress errors. Recent experiments [2–5] on QEC reveal that we are entering the error-corrected quantum (ECQ) era. In this paper, we are going to introduce these advancements and summarize the challenges in this era as shown in Fig. 1.

Among various experimental NISQ platforms, the superconducting system is one of the leading quantum information processing platforms and allows scalable solid-state qubit fabrication, and high-fidelity single-qubit and two-qubit gates [6]. The key idea of QEC is to protect quantum information with redundant encoding in a large Hilbert space. From this perspective, two technical routes have been verified by experiments based on different physical architectures of the superconducting circuit. One route, called bosonic codes [7,8], is to encode a logical qubit into a bosonic oscillator that has an infinitely large Hilbert space. In a superconducting system, microwave resonators with ultralong coherence times are introduced as high-quality quantum memories for storing quantum information. The encoding, decoding, error syndrome measurement, and recovery operations are implemented by superconducting transmon qubits, which serve as ancillary nonlinear elements dispersively coupled with the cavity. This architecture is hardware efficient since a single logical qubit can be realized by a cavity and an ancillary transmon qubit, and it is possible to extend to more logical qubits and compatible with quantum network designs by using microwave photons for

transferring quantum information. Benefiting from the above advantages, the break-even point of QEC, i.e., the coherence time of a logical qubit exceeds that of the constituent elements of the system, has been achieved with several types of bosonic codes, including cat codes [3], binomial codes [4], and Gottesman-Kitaev-Preskill (GKP) codes [5].

The other route is a direct extension of the quantum systems by scaling up the number of physical qubits and encoding a logical qubit into a highly entangled state of many physical qubits. This route can be realized with transmon or fluxonium qubits, which can be directly coupled through capacitors or inductors, or indirectly coupled through auxiliary modes. For this qubit-array architecture, the most recognized QEC code is the surface codes [9] with a high threshold for localized errors, in which the physical qubits can be placed in a grid with only the nearest-neighbor interactions. A distance- d surface code can tolerate up to $\lfloor \frac{d-1}{2} \rfloor$ errors in a row or column, which requires d^2 data qubits to encode the logical state and $d^2 - 1$ ancillary qubits to implement the stabilizer measurement. Many research groups have used surface codes to implement QEC experiments, such as the recent progress led by the University of Science and Technology of China [10] and ETH Zurich [11]. However, these preliminary demonstrations of surface codes in a superconducting system are not able to exhibit the extension of the coherence time of the logical qubits protected by QEC.

Recently, reported in *Nature*, a milestone experiment was implemented by the Google Quantum AI team, and it demonstrated the advantage of QEC in the qubit-array architecture [2]. In particular, they have implemented both distance-3 and distance-5 surface codes in their expanded Sycamore device with 17 and 49 physical qubits, respectively. In the distance-3 surface codes, 9 data qubits are randomly initialized in $|0\rangle$ or $|1\rangle$, followed by 25 cycles of stabilizer measurement. In the last cycle, the data qubits are also measured in the Pauli Z basis. All the syndrome information is decoded and analyzed after the experiment to confirm the error rate; therefore, real-time feedback is not necessary for the experiment. Four distance-3 surface codes selected from the subset of the distance-5 surface code are implemented for better comparison. These results indicate that, for distance-3 surface codes, the logical error probability per cycle is 3.028% averaged over 25 cycles and four subsets. Excitingly, the logical error probability is effectively suppressed to 2.914% by extending the system

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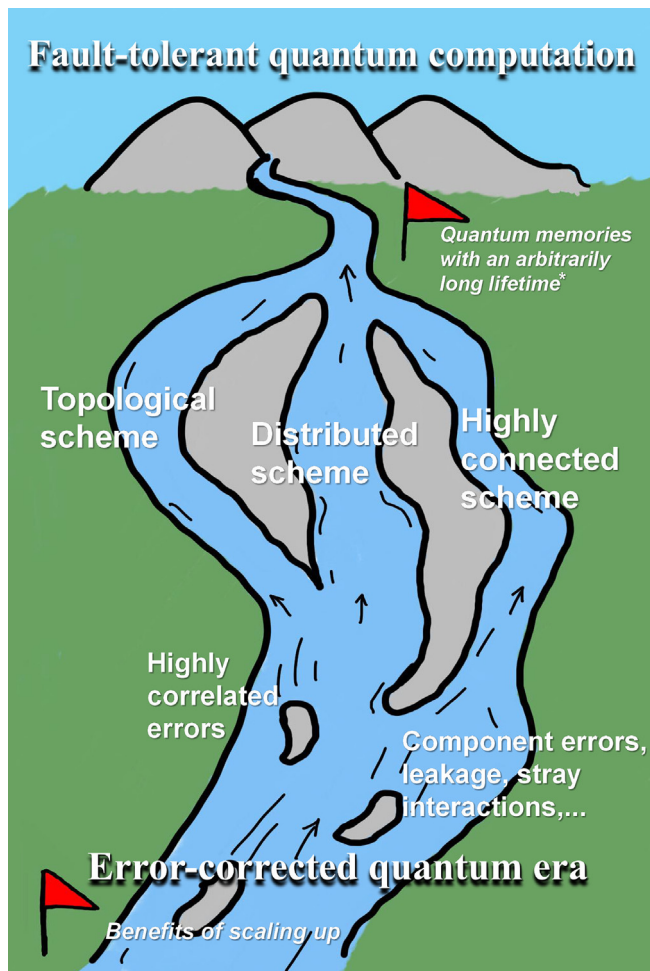


Fig. 1. (Color online) Recent experiments [2–5] show the benefits of scaling up the logical qubit and reveal that we are entering the error-corrected quantum era. The ultimate goal of this era is to realize fault-tolerant quantum computation. To achieve this goal, it is necessary to further suppress the localized errors such as component errors, leakage, and stray interactions, determine and mitigate highly correlated errors such as cosmic rays, and finally verify three scaling-up schemes: topological scheme, distributed scheme, and highly connected scheme. One feasible milestone in the near term is to realize quantum memories with an arbitrarily long lifetime, i.e., at least three orders of magnitude better than the break-even point of QEC.

to distance-5. For the first time, this experiment demonstrates the benefit of QEC when scaling up the surface code size.

In addition to unambiguously validating the advantage of QEC in surface codes, the exploration and analysis of the system performance in Google's experiment also identify two types of dominant errors in the QEC systems. The first type is localized errors including component errors, leakage of the code space, and stray interaction in the two-qubit gates. Here, component errors refer to the Pauli errors corresponding to different components in the circuits. These localized errors are the ones that have the most significant impact on the performance of QEC at the current stage. The second type is the highly correlated errors, such as cosmic rays. According to Google's experiment, these widespread correlated errors become apparent when the logical error per cycle decreases to about 10^{-6} . It is essential to determine and suppress these errors in the next stage. With regard to the QEC experiments based on the bosonic codes [3–5], the calibration of the localized errors is accurate while the calibration of highly correlated errors requires further exploration with more extensive physical systems.

Looking ahead, the achievement by the Google Quantum AI team and also the beating of break-even point demonstrated in bosonic codes indicate the arrival of the ECQ era. In this era, QEC is routinely used to protect and improve the performance of the systems. Although correlated errors increase as the system scales and thus limit the maximum gain that can be obtained from QEC, we are still optimistic about the future of superconducting quantum systems under the protection of QEC. From Google's QEC experiment, we learned that an improvement of all system imperfections by only 10%–20% could bring their system below the threshold. It is foreseeable that the error will be gradually suppressed, and any incremental improvement in any process, including design, fabrication, calibration, control, decoding, measurement, as well as reset of physical qubits, will bring a considerable improvement to the performances of logical qubits and will benefit quantum information processing and related applications.

An outlook of the ECQ era is shown in Fig. 1. In addition to the errors that need to be eliminated as mentioned above, there are many other obstacles ahead in realizing the ultimate goal of universal fault-tolerant quantum computation. There are three possible competitive extension routes with different connectivity to reach the final goal.

The first route is the topological scheme that integrates more transmon qubits while maintaining the planar structure of the superconducting circuits. This route is very friendly to near-term control technology since the planar-type architecture and the nearest-neighbor interactions of the physical qubits can be preserved. Although low connectivity may limit the choice of QEC codes and the extensions, more logical qubits can be encoded by introducing a defect into the lattice or splitting the lattice in the surface codes [9]. Single-qubit and two-qubit gates can be realized through lattice surgery or by deforming and braiding the defects [9]. The main challenge of this scheme is the design and fabrication of a large array of superconducting qubits with an acceptable yield and low cross-talk. In addition, as the number of physical qubits increases, it may be necessary to further develop on-chip integrated control components to overcome the limited volume of dilution refrigerators.

The second route is the distributed scheme utilizing the distributed architecture with modularized logical qubits [12]. Inside each module, the number and quality of physical qubits can be increased through an upgrade of today's technology to achieve one or a few logical qubits with larger code distances and better error correction quality. Between different modules, non-local operations can be performed through the interaction with entangled states that are distributed to corresponding modules [13] or auxiliary qubits that can be transmitted between modules (i.e., flying qubits). Since the fidelity of these non-local operations is lower than that within each module, purification or QEC is needed to enhance the entanglement [12]. The main challenge of this scheme is the construction of a transmission channel with high fidelity and low ancillary resources, and microwave-to-optics conversion technology may be necessary due to the advantages of telecom optical photons in long-distance transmission. Some critical technologies required for this scheme have been preliminarily validated, as demonstrated in Ref. [13].

The third route is the highly connected scheme that directly connects different transmon qubits or bosonic cavities with bosonic modes [7]. These couplings can realize higher connectivity between physical qubits, and thus break through the limitations of topologically planar structures. This route enables more types of optional QEC codes with higher encoding efficiencies or better fault-tolerant properties (for example, transversal T gate), such as high-dimensional color codes and quantum low-density parity-check codes [14]. Furthermore, a fault-tolerant scheme with flag

qubits [15] can also be achieved with high connectivity. The main challenge of this scheme is to realize strong coupling between different types of cavities and transmon qubits.

To be reminded, the schemes mentioned above can be extended to other platforms, such as cold atoms and trapped ions. The extension efficiency is severely limited by logical errors, making it necessary to first suppress the local errors inside each logical qubit to a certain extent. Therefore, the errors and the three schemes are placed in series in Fig. 1. Nevertheless, these two explorations should be carried out simultaneously in practice.

To achieve the ultimate goal of universal fault-tolerant quantum computing with arbitrarily high fidelity, it is most likely to optimize and combine the above three schemes and other potential schemes in a hybrid physical platform [7]. To this end, we need to further develop some key engineering technologies in the near future, including low-latency feedback control, parallel measurement, and fast reset. As the NISQ era will coexist with the ECQ era for a considerable period of time, the enhancement of these common technologies will also contribute to the NISQ application, and we can possibly achieve more substantial quantum advantages in these NISQ applications by devoting more resources to QEC. Therefore, we hope to have an attainable standard to help one make a trade-off between the width and the depth of the quantum circuits to obtain the optimal result. Lastly, a clear and appreciable target is required in the near term to better illustrate the advantage of QEC in this era, and we propose a feasible milestone that is to realize quantum memories with an arbitrarily long lifetime. In practice, it should be a thousand times longer than the break-even point of QEC.

Conflict of interest

The authors declare that they have no conflict of interest.

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