Plugging Leaks in Quantum Computing

A new strategy improves error correction in quantum computation by mitigating the effects of qubits escaping from their intended states.

By **Joseph Emerson**

Quantum computers operate in a high-dimensional space and leverage coherence, entanglement, and other exotic quantum effects. As a result, these systems are uniquely sensitive to errors in ways that their classical counterparts are not. Overcoming such errors is the central challenge for realizing successful large-scale quantum computation. Among the many error-removal methods, quantum error correction is the gold standard, but it is most effective when errors occur independently across qubits and over time—that is, when the errors have limited correlations. Now Jian-Wei Pan at the University of Science and Technology of China and his colleagues have demonstrated a novel way to suppress correlated errors caused by so-called leakage errors [**1**]. They have achieved this feat using a control scheme that is integrated efficiently within a single cycle of error correction. This demonstration greatly expands the class of physical error sources that can be curtailed within the architectural constraints of quantum error correction.

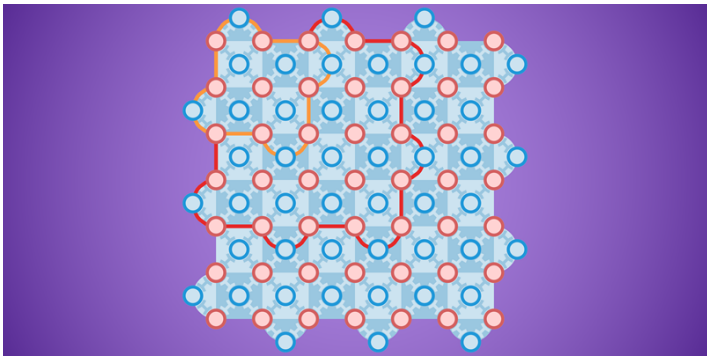

Figure 1: Pan and his colleagues demonstrated an error-corrected quantum memory on a platform of 97 superconducting qubits [**1**]. The red and blue circles are data and auxiliary qubits, respectively. The orange and red borders contain distance-3 and distance-5 subsets of qubits, respectively.
Credit: T. He *et al.* [**1**]

Error correction works best when both correlated errors and errors that preserve coherence are negligible. Coherent errors can emerge from general imperfections in qubit control, depending on the timescale of the imperfections' variations. Meanwhile, correlated errors across qubits can emerge from specific control imperfections, such as microwave crosstalk and residual, unintended couplings between qubits. Lastly, correlated errors across time steps can emerge from a wide variety of mechanisms.

Great effort has gone into developing methods to detect and mitigate coherent and correlated errors in qubit systems. The suppression of coherent errors is largely a solved problem, through techniques such as dynamical decoupling [**2**] and randomized compiling [**3**]. And the presence of correlations across both qubits and time (associated with so-called non-Markovian errors) can now be efficiently detected via a suite of approaches that use a strategy known as randomized benchmarking [**4**–**6**]. However, devising efficient methods to suppress error correlations has remained a substantial challenge, particularly within the timing and other architectural constraints of quantum error correction.

A significant source of error correlations in several leading quantum-computing platforms—including ion qubits and superconducting qubits—is a mechanism known as leakage. Leakage occurs when a qubit's quantum state escapes the two-dimensional subspace of physical energy levels defined as

the qubit's 0 and 1 states. Leakage errors on their own are easily detected [**7**, **8**] and can be managed by error-correction techniques. But one of the unique challenges that they present is that the quantum information is typically not lost; it remains present, adjacent to the qubit subspace, over a long timescale. The leakage problem is then compounded by the fact that the leaked information can later reenter the qubit subspace. This process can alter the quantum information on either that same qubit or an adjacent qubit and lead to correlated errors across the computation. That is, the reentry error occurs if and only if the leakage error also occurred, and these kinds of correlated errors are often beyond the scope of what error-correcting codes are designed to reliably detect and remove.

Pan and his colleagues tackled this issue in a superconducting-qubit platform set up to perform as a quantum memory, with both the data qubits and ancilla (auxiliary) qubits required for a full error-correction scheme (Fig. **1**). They enacted their scheme within the architecture of the so-called surface code, a leading approach to quantum error correction owing to its low qubit-connectivity requirements and high error-rate tolerance. In the new scheme, leakage of the data qubits is mitigated using integrated control circuits driven entirely by microwave pulses, and this mitigation is executed as a fast subroutine within each correction cycle. Meanwhile, a reset protocol for the ancilla qubits reduces leakage and other errors in these auxiliary qubits.

The team used an interleaved randomized benchmarking technique to estimate the additional errors introduced by the leakage-suppression circuits. But that approach can be subject to significant inaccuracies compared with state-of-the-art methods such as cycle benchmarking [**5**]. Nevertheless, Pan and his colleagues were still able to validate that their combination of elements, within the constraints of a correction cycle, achieved a net error-suppression factor of 1.4. This result means that making the surface code larger by one unit in distance reduces the logical-error rate by a factor of 1.4, a finding the researchers show would have been impossible without such leakage mitigation.

Pan and his colleagues demonstrated an error-corrected quantum memory with a distance-7 surface code that was executed across 97 physical qubits and that had a depth of 40 correction cycles. This demonstration was a large-scale implementation and an impressive feat by today's standards. But we must temper our expectations because it is still far from the goalposts set by utility-scale fault-tolerant quantum computing and its associated real-world impact. For example, the gold standard for showing quantum advantage—that quantum computing can surpass classical computing—is the implementation of Shor's algorithms for factoring large integers and solving the so-called discrete-logarithm problem. This feat would pose a threat to systems used for Internet transactions, bitcoin security, and so on, which depend on the difficulty of those tasks. Recent theoretical advances have brought down the requirements for factoring a 2048-bit integer from an estimated 20 million qubits to "only" one million qubits [**9**]. So the good news is that these requirements are moving closer to our experimental capabilities; the bad news is that they remain a long way off.

Joseph Emerson: Institute of Quantum Computing and Department of Applied Mathematics, University of Waterloo, Ontario, Canada

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