Radar / Quantum Computing

Quantum Error Correction Update 2024

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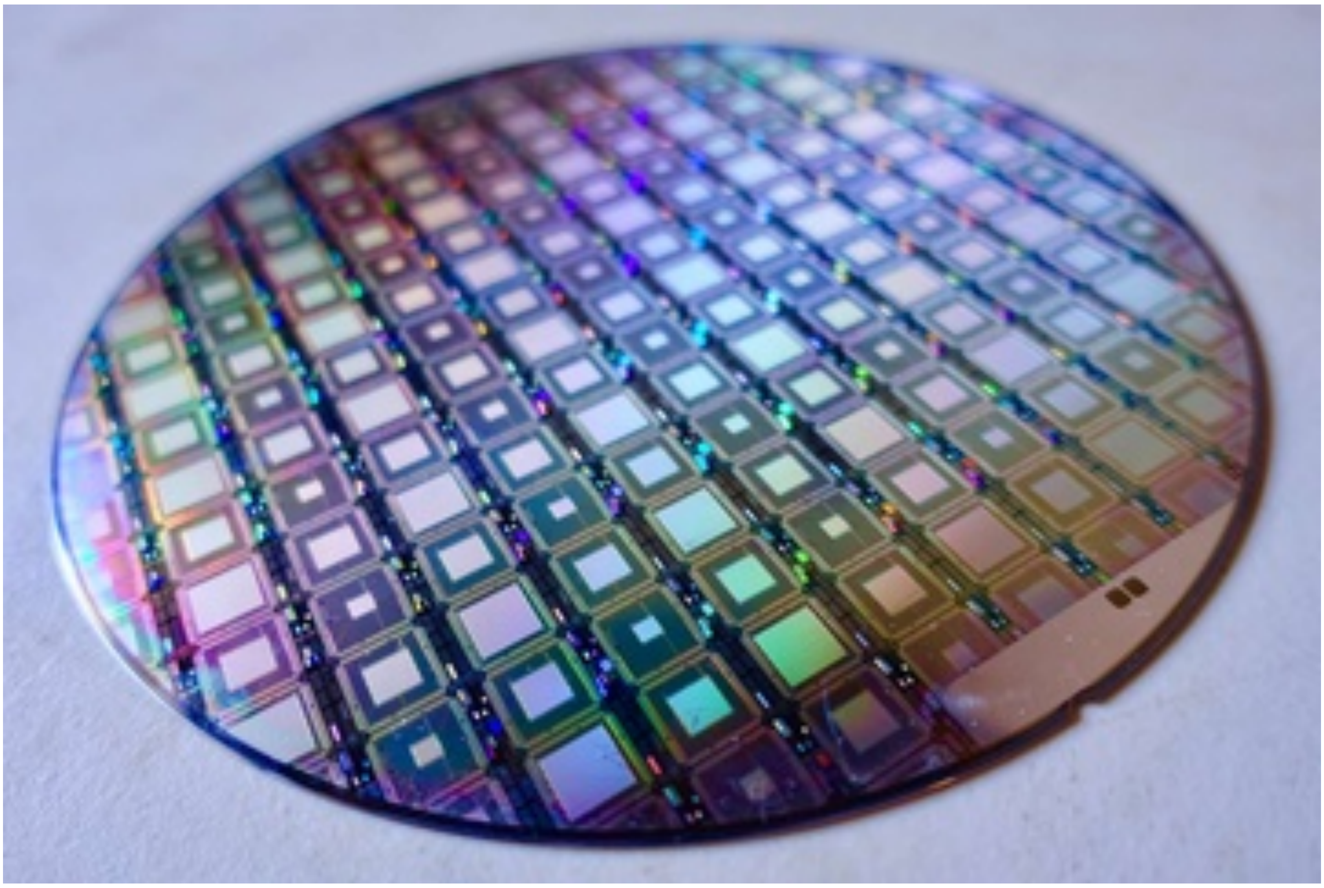
December 17, 2024



A Wafer of the Latest D-Wave Quantum Computers (source: Steve Jurvetson on Flickr) challenges of engineering at those extremes, there is the whole matter of the rest of the universe having a very strong inclination to reunite with the subatomic particles the physicists have cleaved off into isolation. While the quantum computer tries its best to keep the quasiparticle in the superconducting qubit or the atom in the laser tweezer stable, the entire universe keeps butting in with vibration and radiation, anomalous thermodynamic effects, and other mysterious influences. All those intrusions threaten the fragile computation with a collapse into undifferentiated chaos, the background noise of the universe.

For many people, quantum computing sprang into our awareness with the 2019 announcement of something Google called “quantum supremacy.” The blog post and the accompanying press coverage described a contrived task run on 50 superconducting qubits in their lab at UCSB, which they said would be impossible to replicate on classical hardware in a reasonable time. In the mild controversy and extreme confusion that followed, a fact that may have eluded those who had not previously been paying attention to the esoteric topic was that Google's machine had no capacity for detecting and correcting errors. The Google team programmed the digital gates run on their Sycamore system with minute variations in the control signals in an effort to minimize the inaccuracies and errors, but the greatest challenge to the experimental results was noise rather than the relatively small scale.

In the ensuing surge of interest in Google's device and other quantum computers from IBM, Rigetti, and IonQ, the limitations imposed by noise were not always directly addressed, which could at times be misleading to those just learning about quantum computing for the first time. In an effort to demystify, physicist John Preskill's talk at the Q2B conference in 2017 described the machines being built as “noisy, intermediate-scale quantum computers,” or NISQ. Preskill laid out his belief that NISQ computers were worth building for three reasons: first, to explore their shortcomings in hopes that future machines would work better; second, to exploit the current state of the art as exotic lab instruments capable of generating novel scientific results; and third, because of the slight chance that someone would find something useful for them to do.

The hope of finding useful applications with NISQ computers was always a long shot. It had long been an assumption that the problem of errors from noise would need a solution before any practical application was developed. When Peter Shor discovered the quantum factoring algorithm in 1995, the consensus that clever engineering could eventually create high-quality qubits, and the following 25 years would do much to bolster that pessimism. By 2019, the best error rate the Google team could manage on a single qubit was 0.16%, or 16 errors per 1,000 operations.[1]

Aside from mere engineering challenges, qubits are vulnerable to a type of error unique to quantum computing. They can suffer from bit flips just like classical computers, where a “0” becomes a “1,” or vice versa. Qubits can also suffer “phase flips,” where the value is unaffected but the phase is reversed from positive to negative. In effect it is as if the amplitude of a wave remains the same, but the peak turns into a trough or a trough into a wave, which is unique to a quantum computing context.

To compound all of these challenges are the intrinsically weird properties of quantum information that are the basis for the potential power of quantum computing. Qubits operate in a “coherent” state that includes superposition and entanglement to create massive multidimensional computational power. Measuring a qubit’s state to see if it has suffered a bit or phase flip collapses that state, and all the quantum information is irretrievably lost. Not only does that make it impossible to directly detect errors, but if an error occurs, there’s no way to reconstruct the correct quantum state.

Despite these challenges, and in defiance of prevailing beliefs, Peter Shor took on the problem himself, and in 1995, less than a year after his factoring algorithm breakthrough, he’d created the first error-correcting code for quantum computation. Classical error correction originated with the work of Richard Hamming, an American mathematician who was a colleague of Claude Shannon’s at Bell Labs and worked on the Manhattan Project. Hamming codes relied on repetition of information in ways that made errors easy to identify and correct. This strategy could not simply be ported to the quantum information regime, for the reasons stated above. Shor’s solution was to prepare a circuit that would “smear” a single quantum state out over nine physical qubits, which in aggregate would comprise a single logical qubit. This logical qubit is a concatenation of a three-qubit bit-flip code and a three-qubit phase-flip code, making it resistant to either, as seen in Figure 1. The circuit illustrated is simply the state preparation; actually making a fault-tolerant quantum algorithm run would require repeated cycles of measuring certain qubits in the middle of the circuit running, detecting errors, and taking steps to correct them. Those corrections can be carried out with additional gates, and finally the resulting qubit state is measured.

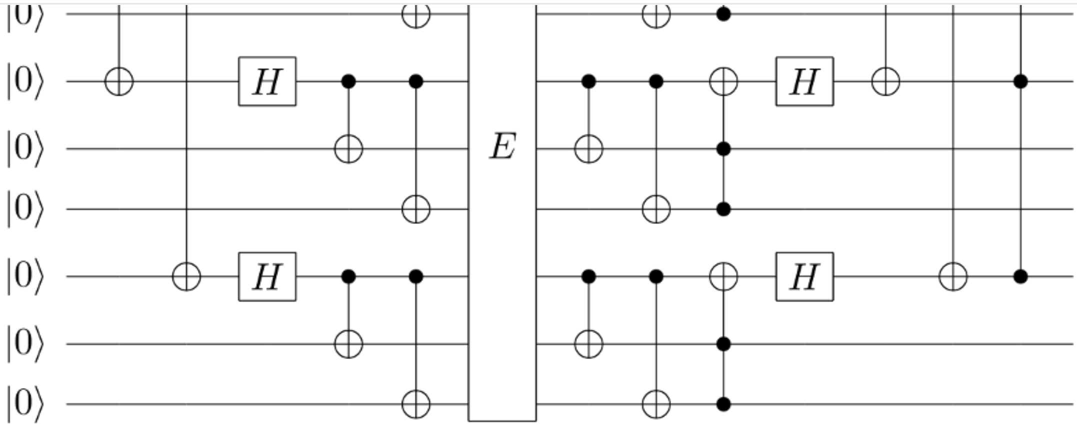


Figure 1 – The heart of Shor's error correcting code illustrated in a simple circuit diagram

While Shor's work proved the point that error correction was indeed possible, even for quantum information, it was limited to single qubit errors and, in practical terms, wasn't sufficient for long-running computation. Thankfully, as is almost always the case with difficult problems, Shor wasn't the only one working on the challenge of error correction. An alternative school of thought began to emerge in 1997, when Alexei Kitaev, a brilliant physicist then at the Landau Institute for Theoretical Physics in Russia, proposed a method for projecting qubits states onto a lattice, seen in Figure 2, whose edges wrap around to join one another, forming a torus.

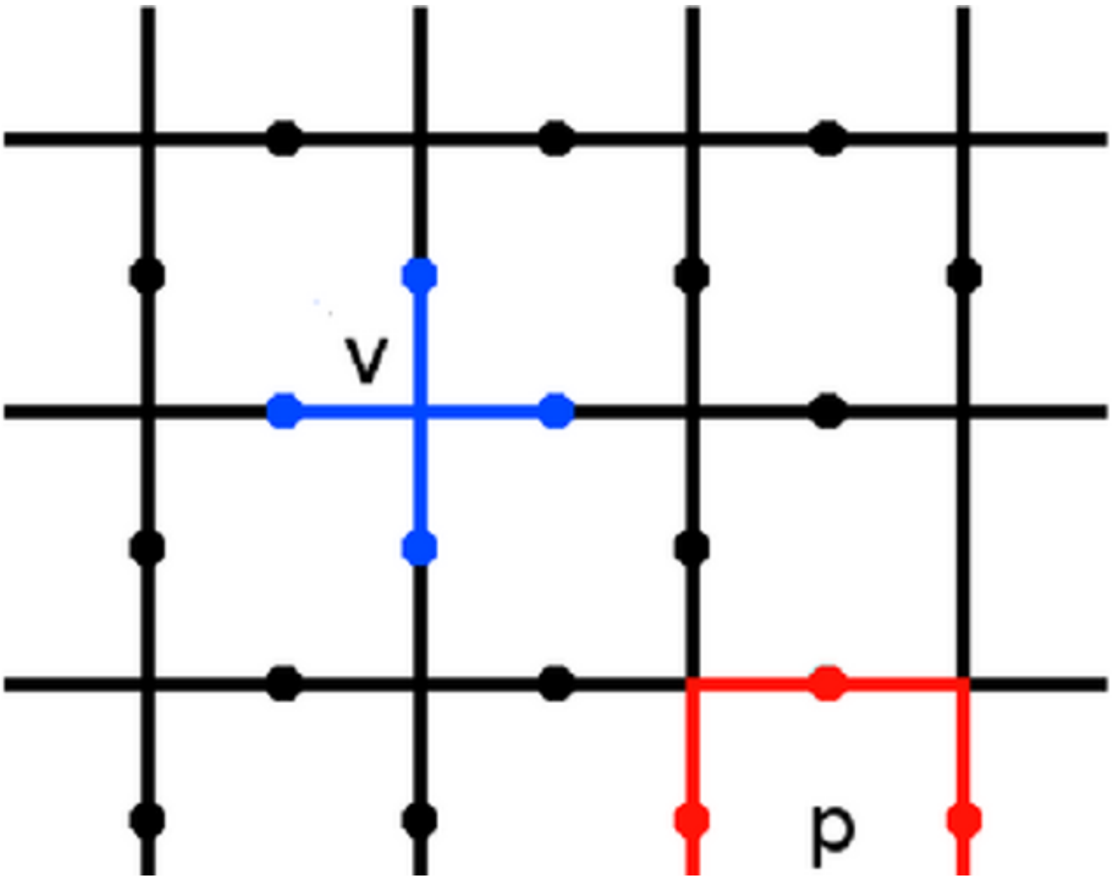


Figure 2 – The toric code's 2D lattice projection

Each intersection on the lattice is a vertex, one of which is labeled *v* in Figure 2, and each square in the lattice is known as a plaquette, labeled *p*. The logical qubit is encoded in such a way where each plaquette must have an even number of 1 states in the four qubits of the plaquette. The vertices also must have an even number of 1s surrounding them. In that way, midcircuit measurements can be made to detect any odd number of 1s, a so-called "syndrome" detection that reveals a bit or phase flip. Any bit flip will be detected by two neighboring plaquettes, giving the surface code a resiliency that increases with the size of the torus, seen in Figure 3. The toric code can be used to encode two logical qubits in a minimum of 21 physical qubits for resiliency to up to three correlated errors, referred to as "distance-3" code.

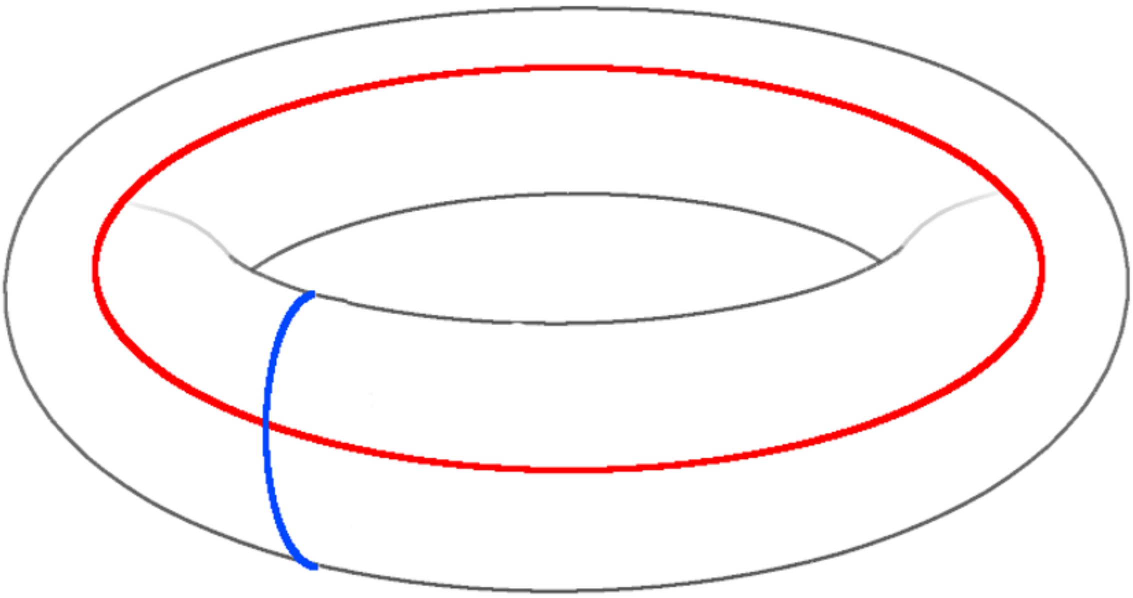


Figure 3 – Kitaev's code projected as a torus

Shor's and Kitaev's error correcting work in the late '90s established two broad categories that can be applied to quantum error correction generally. Shor's approach, often generalized as an "additive" technique, adapted classical error correction approaches to quantum information, while Kitaev's approach took advantage of the mathematics that is native to quantum systems. Approaches like Shor's, including the whole family known as Calderbank-Shor-Steane codes (or CSS), are considered theoretically easier to understand, with a lower ratio of diverse landscape of quantum error correction, of course, as the impressive taxonomy curated by the Quantum Error Correction Zoo can attest.

Both Shor's and Kitaev's codes and many of their variants and successors have been successfully demonstrated at small scale, but most of the focus and investment during the NISQ era has been on scale of systems, and physical quality. More recently, there are signs that the nascent technology is shifting from NISQ to focus on logical qubits. A joint effort between Microsoft and Quantinuum has resulted in a demonstration of tesseract codes producing logical qubits. Part of the CSS family of classically derived "color codes," the technique was used to create four logical qubits out of 16 physical qubits on the Quantinuum trapped ion device. They executed five rounds of operation with error correction, and, with 12 logical qubits, they measured a 0.11% error rate, more than 20 times better than the error rate of the physical qubits.

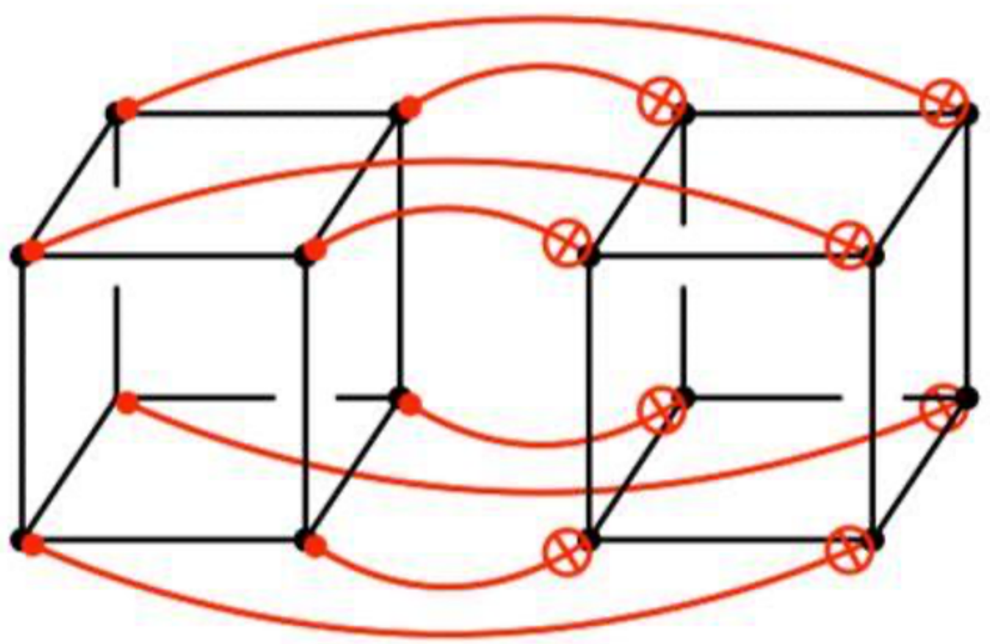


Figure 4 – Visualization of the Microsoft and Quantinuum code on 16 qubits, from "Demonstration of Quantum Computation and Error Correction with a Tesseract Code"

Meanwhile, in the topological quantum error correction field, Google has been hard at work implementing the surface code, and in August posted a remarkable paper to the arXiv. They described a full implementation of a from 3 to 5 to 7. In other words, as they added more qubits and made the logical qubits more robust, the error rate continued to drop below that of the physical qubits, proving some degree of practical scalability.

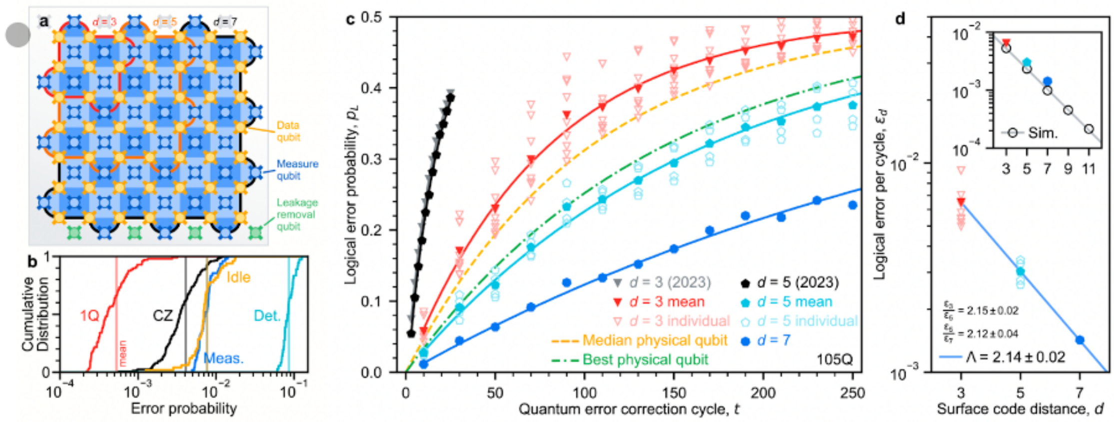


Figure 5 – Google surface code topology and performance, from "[Quantum Error Correction Below the Surface Code Threshold](#)"

Both experiments, though impressive, expose pitfalls in their respective paths ahead. The Quantinuum experiment benefited from the device's high-quality charged atom-based qubits, with two-qubit gate fidelities of 99.87% and effectively infinite coherence times, as well as its ability to connect any qubit to any other qubit, so-called "all-to-all connectivity." However, the H2 device, with 56 qubits, is the largest trapped ion system built to date, and larger systems will have significant physical constraints to overcome. One-dimensional traps are limited to about 30 qubits; Quantinuum has extended that by building what they call a "racetrack," a trap that curves around in an oval and connects back to itself that the ions physically shuttle around. An amazing engineering feat but not one that suggests systems with orders of magnitude more qubits whizzing around. Even if they do build much larger systems, ions make very slow qubits, both in gate operations and with all the physical shuttling to achieve the proximity required for two-qubit gates. Superconducting devices offer operations that are orders of magnitude faster, in terms of the wall clock time.

However, speed isn't everything. Google's result showed that the greater the distance of the surface code, the lower the error rate of the logical qubit. All well and good, but to achieve distance-7, they needed 105 qubits for 1 logical qubit. A logical qubit with an error rate of 10^{-6}, equivalent to one error for every million operations, would need distance-27, implemented on 1,457 ratio of almost 1,500:1 is going to require somehow bridging multiple smaller chips to deliver systems at scale. To factor a 1,024-bit number to its primes using Shor's algorithm, for example, is minimally estimated to require 2,000 logical qubits, which Google's surface code would need 3,000,000 physical qubits to produce. It would also take about a billion gate operations, which would mean, at a 10^{-6} error rate, you could expect 1,000 errors to slip through.

The basic math can cause despair among quantum computing enthusiasts, but an important aspect of both experiments is that the implementations are naive, in the sense that they are coding up the theoretical error correcting codes on hardware that has not been optimized specifically for carrying out a specific code implementation. In August of 2023, IBM posted a paper to the arXiv suggesting that chip designs might play a role in achieving better ratios for logical qubits. Their approach leveraged another classical error correction technique, low-density parity checks, or LDPC, which was developed in the early '60s and, when the computing resources developed that could support it, has since been popular in communications due to its high efficiency. The IBM team described a biplanar chip with 144 physical qubits on each surface interconnected in a fashion that yields 12 logical qubits, with quantum LDPC codes producing distance-12.

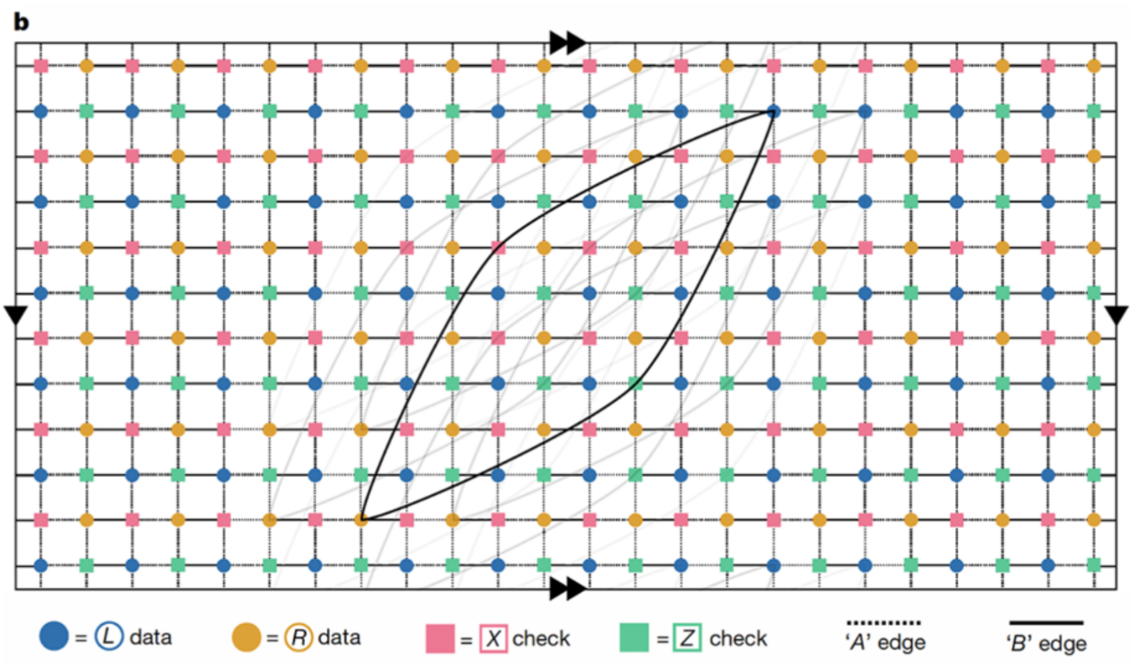


Figure 6 – IBM's LDPC error code, also known as Bivariate Bicycle, or "gross" code

To date, IBM's "gross code," its name derived from the dozen dozen physical at Harvard and MIT, respectively, came up with their own approach to LDPC and implemented it on a neutral atom device. The resulting paper, published in December 2023, demonstrated the flexibility of the optical lattice holding the atoms in place, and the ability to move atoms using optical tweezers allowed the team to realize a kind of Von Neumann architecture in their vacuum chamber, with separate areas for storage, entanglement, readout, and error correction, as seen in Figure 7. With 280 physical qubits and LDPC codes, the researchers produced 48 logical qubits with distance-7. The neutral atom implementation was a clear step ahead of IBM's paper on LDPC, as the team was able to not only encode the 48 logical qubits but also perform 200 transversal gate operations on them. Their results stopped short of a fully operational fault-tolerant device, however, as they did not go through a full operational cycle of gate operation, syndrome detection, and correction, and the system required manual intervention in order to operate.

Neutral atoms don't have the scaling issues of ions traps; they operate a two-dimensional optical lattice that holds hundreds of atoms acting as qubits in current hardware from QuEra and Pasqal, with another vendor, Atom Computing, promising a device with over a thousand qubits. As Lukin and Vuletic's experiment demonstrated, they also can experiment with error-correction optimized processor designs virtually, running rings around the design-fabricate-characterize lifecycle of a superconducting chip. Neutral atom systems do share a weakness with trapped ions, however, in that their operational pace is very slow. QuEra's current device, Aquila, which is an analog quantum simulator that doesn't have gate operations, can run about three jobs per second. It is unlikely that gates and error correction will make that any faster. With IBM measuring their systems in the hundreds of thousands of circuit layer operations per second, or CLOPS, it's clear where the advantage lies.

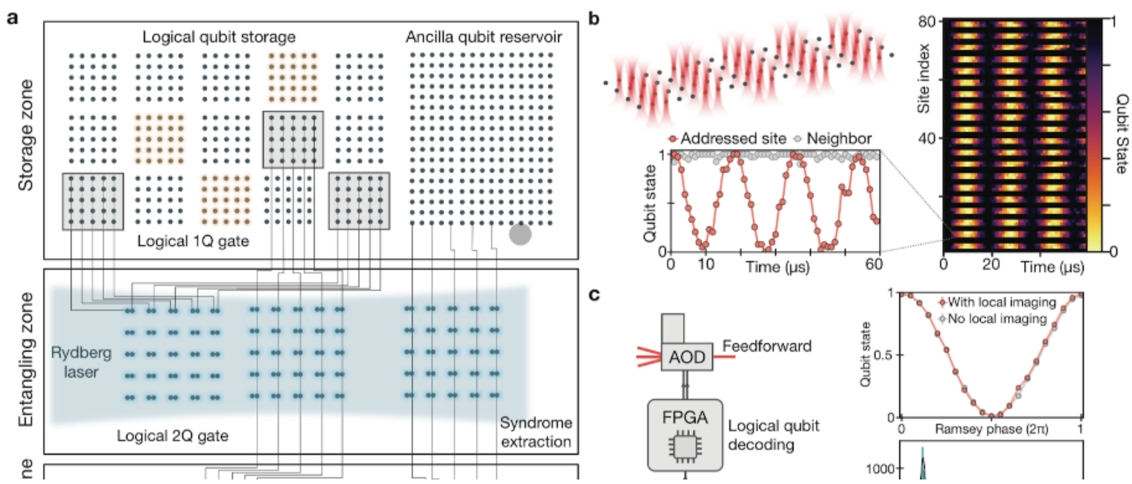


Figure 7 – Virtual Von Neumann-like architecture, from "Logical Quantum Processor Based on Reconfigurable Atom Arrays"

Even when IBM does bring a gross code chip to market, there's no guarantee that it will signal the beginning of the era of logical qubits. The LDPC codes used by IBM and the QuEra cofounders only protect Clifford gates, which are both efficiently simulated by classical means and not a universal set of gates. Toffoli gates are typically added to the Clifford set to attain universality, but Toffoli gates would not be protected by LDPC and so would be as vulnerable to error as they are on devices today. Both companies are planning workarounds: IBM will use z-rotations to get universality, while QuEra will rely on transversal gates, and both are likely to use what are called "magic states," which can be used to distill logical states from physical, noisy ones. If those are accurate enough to not degrade the overall system performance, the market may allow them to use the term "logical qubits" to describe their results, even with the slight cheating going on.

Other hardware-assisted approaches to fault tolerance are in development in newer, more exotic approaches to superconducting qubits with names like "cat qubits" and "dual-rail qubits," or using hardware-implemented bosonic codes. Vendors such as Alice & Bob, Nord Quantique, and Quantum Circuits Inc. plan to launch devices in 2025 that will provide the first opportunities to experience hardware-assisted logical qubits in operation. On an entirely different note, Google Quantum AI announced they had used DeepMind's machine learning technology to create AlphaQubit, a GPU-powered "AI decoder" for quantum states that reduces error rates by 6% over existing methods. Certainly, it has been widely anticipated that machine learning models will play a role in programming logical qubits, however they end up being implemented, as the gate operations needed for logical quantum gates are much more complex than those for physical qubits.

Despite all the positive news about quantum error correction this year, it remains far from clear just what path to fault tolerance will eventually triumph. What does seem certain is that the predictions that NISQ devices would be unable to produce commercial value were on the mark. Prominent leaders of software companies once bullish on hybrid algorithms combining noisy qubits with classical computations have expressed increasing skepticism, with the CEO of QunaSys, Tennin Yan, saying on stage at Q2B Paris in 2023 that approach is "dead."[2] It is also quite certain that devices with various types of error

However, advances undeniably continue to be made, and the bar for quantum advantage is now not that far off. Simulating entangled qubit states numbering 50 or more is considered impossible to accomplish with all the existing computational power in the entire world. If IBM delivers five of their 12 logical qubit chips in a cluster, or QuEra ships a device with 300 neutral atoms encoding logical qubits, or we see milestones along those lines from other vendors, we will have arrived at a new era of quantum computing.

Footnotes

1. Frank Arute, Kunal Arya, Ryan Babbush, et al., "Quantum Supremacy Using a Programmable Superconducting Processor," *Nature* 574 (2019): 505–510, https://doi.org/10.1038/s41586-019-1666-5.
2. Tennin Yan, "Beyond VQE: Advancing Quantum Computing Applicability" (presentation at Q2B, Paris, 4 May 2023), https://q2b.qcware.com/session/q2b23-paris-beyond-vqe-advancing-quantum-computing-applicability/.

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