

A study on Qubit Stability, Quantum Error Correction and Performance Limitations

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Abstract:

Practical quantum computation requires logical operations whose error rates lie many orders of magnitude below those of any physical qubit. Quantum error correction (QEC) only closes that gap if physical noise is weak enough, uncorrelated enough and decoded fast enough. We provide a critical, structured review of the physical mechanisms limiting the stability of qubits, the mathematical foundations of QEC, the main code families, and the experimental record on superconducting, trapped-ion, neutral-atom, semiconductor-spin, photonic, bosonic and topological platforms. Reproducible circuit-level simulation of rotated surface-code memories (Stim and PyMatching, fixed seeds, uniform depolarizing noise) places the threshold crossing near 0.75% and yields a suppression factor consistent with a slope-based parameter near 1%. We find that the logical failure probability changes by at most 16 % for a decoder-calibration study with a global mismatch between assumed and true error rates, while discarding noise information increases it by a factor 1.5-2.0. Published experiments analyzed include distance-7 superconducting memories with a suppression factor of 2.14 ± 0.02 per distance step, neutral-atom logical-processor demonstrations and bosonic memories beyond break-even. We enumerate seven testable research proposals and gaps in correlated noise, leakage, real-time decoding, non-Clifford cost, and cross-platform benchmarking. We intentionally do not include commercial timelines.

Keywords: decoherence, fault-tolerant quantum computing, logical qubits, quantum error correction, qubit stability, quantum LDPC codes, surface code.

1. INTRODUCTION

Quantum processors store information in physical systems that interact with their surroundings. Energy relaxation, dephasing, photon loss, leakage out of the computational subspace, imperfect control and imperfect readout each corrupt stored amplitudes and phases, and the no-cloning theorem forbids the classical remedy of copying and majority voting [1]. Quantum error correction (QEC) gets around the obstacle by spreading one logical state over many physical degrees of freedom and measuring only parity-like quantities, called syndromes, which reveal errors without revealing the encoded information [2]–[4]. Nearly every scheme follows the pipeline in Fig. 1. A logical state is prepared and the physical array suffers noise during gates and idling. Ancilla qubits extract syndromes round after round, a classical decoder turns the syndrome history into a correction, and that correction is either applied physically or tracked in a Pauli frame while logical computation continues.

Literature often slides between three notions of stability, and they need to be kept apart. *Physical qubit stability* concerns a single device element and is quantified by relaxation and coherence times, gate and measurement fidelities, and leakage probabilities, all of which depend on materials, fabrication, temperature, control hardware and calibration. *Logical qubit stability* concerns encoded information under repeated correction and is quantified by the logical error probability per correction cycle, the logical memory lifetime relative to the best physical qubit, and the suppression factor obtained when the code distance grows. A logical qubit is a property of a code, a syndrome-extraction circuit, a

decoder and a noise environment taken together, so the same hardware can show different logical stability under different decoders. *System-level fault tolerance* concerns whether arbitrarily long computations can be executed with a controlled resource overhead: logical gates (including non-Clifford operations), logical measurement, real-time classical processing, control electronics and cryogenic infrastructure all enter, and the threshold theorems guarantee the property only when physical noise is below a model-dependent threshold [5]–[7]. High physical fidelity is thus necessary but not sufficient for logical reliability, and a below-threshold memory is necessary but not sufficient for fault-tolerant computation.

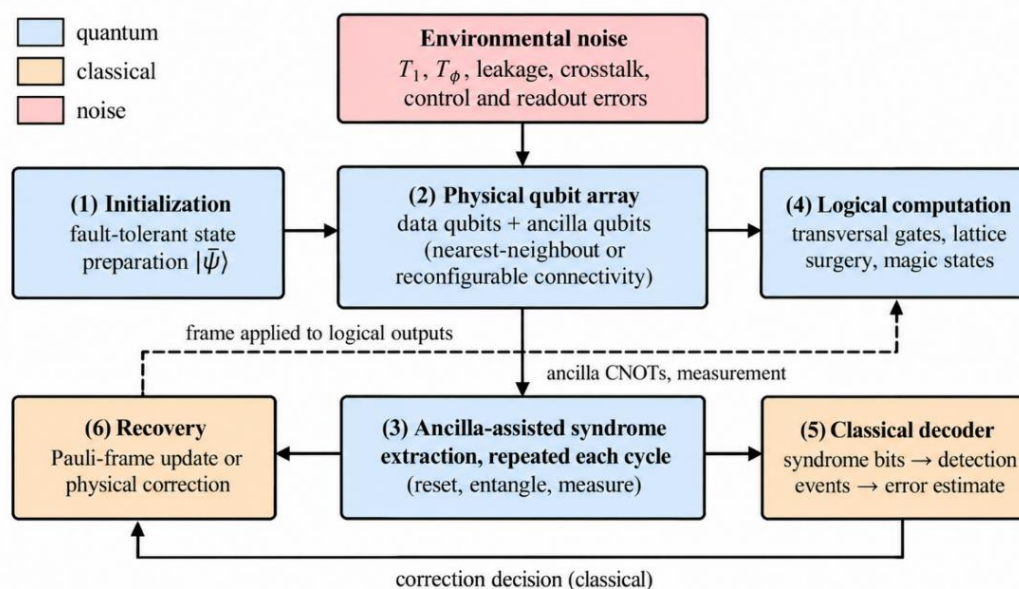


Fig. 1. Fundamental architecture of a fault-tolerant quantum computer. Logical information is initialized (1) into a physical qubit array (2) that is exposed to environmental noise. Ancilla-assisted syndrome extraction (3) produces classical syndrome bits, a classical decoder (5) infers the most likely error, and a recovery step (6) is applied either physically or as a Pauli-frame update in software, which is later folded into the logical computation (4) and its readout. Schematic; no data. Original figure prepared for this review.

The article is a critical, structured review that (i) traces the development of qubit stability and QEC from the foundations of quantum information theory, (ii) sets out the noise models and code-theoretic conditions together with their assumptions, (iii) compares code families and hardware platforms on stated metrics using primary sources only, (iv) reports a small reproducible simulation that supplies explicit baselines, and (v) identifies research gaps and offers testable proposals. It is not a systematic review, and it carries no PRISMA flow diagram, because screening counts were not recorded at that level of detail (Section 2). It claims no methodological novelty. The remaining sections run as follows: historical analysis (3), physical mechanisms and noise models (4), mathematical foundations (5), code comparison (6), surface-code architecture (7), platform comparison (8), metrics and benchmarking (9), quantitative results (10), research gaps and proposals (11 and 12), and discussion and conclusion (13 and 14).

2. REVIEW METHODOLOGY

The review follows the protocol in Table 1. Searches used a general web search engine, publisher and arXiv pages, Crossref records and the Semantic Scholar and RePEc indexes. The subscription indexes (IEEE Xplore, Web of Science, Scopus) were not queried, so the search strings in Table 1 should be re-run there before submission to confirm that no major primary result has been missed. Screening counts were not tallied at each stage, which is why the work is classed as a critical structured review and why no PRISMA diagram is shown.

Table 1: Literature-identification and evidence-synthesis protocol

Element	Protocol applied
Sources	Publisher pages (Nature Portfolio, APS Physical Review journals, Quantum), arXiv records, Crossref, Semantic Scholar and RePEc indexes; IEEE Xplore, Web of Science and Scopus not queried (see text)
Search terms	(“quantum error correction” OR “fault-tolerant quantum computation” OR “logical qubit”) AND (threshold OR “surface code” OR “color code” OR qLDPC OR bosonic OR GKP OR cat); (decoherence OR “T1” OR “T2” OR “coherence time”) AND (superconducting OR ion OR “neutral atom” OR spin OR photonic OR Majorana); (“randomized benchmarking” OR “cycle benchmarking” OR “quantum volume”)
Date limits	1982 to 17 October 2026; the verified primary record reaches online publication in November 2025 and print issues dated January 2026
Inclusion	Peer-reviewed primary experimental or theoretical papers; foundational theory; authoritative reviews; software papers for tools used in Section 10
Exclusion	Press releases, vendor blogs and secondary web summaries as sources of numbers; commercial claims without a primary publication; reports from 2026 located only through secondary sources and not verified against the primary record
Evidence tiers	A: peer-reviewed primary; B: peer-reviewed review; C: thesis or preprint (identified in the reference list); D: commercial or press (never cited for numbers)
Preprints	One doctoral thesis, available as an arXiv preprint, is cited for the stabilizer formalism; no numerical result rests on a preprint
Duplicates	Preprint and journal versions merged; the journal version cited
Data extraction	Numbers transcribed from abstracts, main text or supplementary tables of primary papers, with device, gate type and decoder recorded; transcription from preprint text is noted where the published supplement was not consulted
Reference verification	Title, authors, journal, volume, pages and date of every entry were cross-checked against at least one independent record (publisher page, Crossref, or the Semantic Scholar, RePEc or arXiv indexes); DOI strings were taken from those records, and resolution through doi.org itself was not possible from the working environment; the Gottesman thesis was checked through arXiv only

3. HISTORICAL EVOLUTION

The conceptual groundwork dates to the early 1980s, when the no-cloning theorem was established [1]. Decoherence theory later explained why superpositions of macroscopic objects are so fragile [8]. Error correction became a credible prospect in 1995 and 1996. Shor and Steane showed that arbitrary single-qubit errors can be corrected by encoding one qubit into nine or seven qubits [2], [3], and Calderbank, Shor and Steane built CSS codes from classical codes [9]. The stabilizer formalism [4], [10] and the necessary-and-sufficient correction conditions [11] gave the subject its algebraic and geometric language. Threshold theorems for concatenated codes came next [5]. The surface and toric codes, first studied as topological memories [12], [13], became the leading candidate for planar hardware once their resource costs had been worked out [14]. Magic-state distillation showed how to add a non-Clifford resource to the Clifford operations [15]. Bosonic encodings arrived with cat codes, Gottesman–Kitaev–Preskill (GKP) codes and binomial codes [16]–[18]. On the qLDPC side, theory reached asymptotically good codes [19] and concrete bivariate-bicycle codes sized for near-term devices [20].

Experiments moved from break-even attempts on bosonic modes [21], through repeated detection and correction on small surface codes [22], [23], to below-threshold exponential suppression [24] and integrated logical-processor demonstrations on atom arrays [25], [26]. Table 2 lists milestones with the nature of each entry (theory, peer-reviewed experiment, architecture study or software). Commercial roadmaps are left out because they are not primary evidence. The last entries are the most recent peer-reviewed records that could be verified, and later reports that could not be checked against the primary record are not listed.

Table 2: Chronological milestones in qubit stability and QEC (T: theory; E: peer-reviewed experiment; A: architecture or resource study; S: software). Years follow the journal record.

Year	Milestone	Type	Ref.
1982	No-cloning theorem	T	[1]
1995	Nine-qubit code correcting arbitrary single-qubit errors	T	[2]
1996	Seven-qubit code; CSS construction from classical codes	T	[3], [9]
1997	Stabilizer formalism (thesis); error-correction conditions	T	[4], [11]

Year	Milestone	Type	Ref.
1997/ 2008	Threshold theorem for concatenated codes (conference version 1997, journal 2008)	T	[5]
1998	Quantum codes over GF (4), including the five-qubit code in the stabilizer framework	T	[10]
1999	Cat-state bosonic code for amplitude damping	T	[16]
2001	GKP code (oscillator grid states)	T	[17]
2002–03	Topological memory and anyonic fault tolerance (toric code)	T	[12], [13]
2005	Magic-state distillation	T	[15]
2006	Subsystem (Bacon–Shor type) and color codes	T	[27], [28]
2012	Surface-code architecture and resource analysis	A	[14]
2016	Binomial codes proposed; cat-code memory with gain near 1.1	T, E	[18], [21]
2019	Surface-code computation by lattice surgery	A	[29]
2020	GKP error correction in a superconducting circuit	E	[30]
2021	Real-time fault-tolerant QEC on trapped ions; Stim simulator; RSA-2048 resource estimate	E, S, A	[31]–[33]
2021–22	Cosmic-ray error bursts resolved in superconducting arrays	E	[34]
2022	Repeated QEC in a distance-3 surface code; fault-tolerant universal gate set on ions; asymptotically good qLDPC codes	E, E, T	[19], [22], [35]
2023	Distance-3 to 5 surface code; GKP memory beyond break-even; leakage removal	E	[23], [36], [37]
2023–24	Logical processor on reconfigurable atom arrays	E	[25]
2024	Bivariate-bicycle qLDPC memory design; neural-network decoder; constant-overhead atom-array proposal	T, E, T	[20], [38], [39]
2024–25	Distance-7 surface-code memory below threshold, real-time decoding at distance 5	E	[24]
2025	Color code from distance 3 to 5; concatenated cat-qubit repetition code; logical magic-state distillation; transversal fault tolerance; sparse-blossom decoder	E, E, E, T, S	[40]–[44]
2025	Interferometric parity measurement in hybrid devices (not a qubit demonstration)	E	[45]
2025–26	Integrated fault-tolerant neutral-atom architecture, up to 448 atoms	E	[26]

4. PHYSICAL MECHANISMS OF QUBIT INSTABILITY AND NOISE MODELS

A. Relaxation and coherence times

For a two-level system, the diagonal element of the density matrix relaxes toward equilibrium with time constant T_1 , and the off-diagonal element decays with time constant T_2 . Under the usual Bloch-type assumptions (Markovian, time-independent rates),

$$\begin{aligned}\rho_{11}(t) - \rho_{11}^{\text{eq}} &= [\rho_{11}(0) - \rho_{11}^{\text{eq}}] e^{-t/T_1}, & \rho_{01}(t) \\ &= \rho_{01}(0) e^{-i\omega_q t} e^{-t/T_2}\end{aligned}\quad (1)$$

and the coherence time decomposes into a relaxation contribution and a pure-dephasing time T_ϕ ,

$$\frac{1}{T_2} = \frac{1}{2T_1} + \frac{1}{T_\phi}, \quad T_2 \leq 2T_1 \quad (2)$$

If the detuning is static or slowly varying but differs from one repetition to the next, the signal acquires an additional Gaussian envelope. For a quasi-static detuning distribution of standard deviation σ_δ , a Ramsey experiment returns ρ_{01} multiplied by $e^{-t/T_2} e^{-\sigma_\delta^2 t^2/2}$, and the inhomogeneous dephasing time T_2^* is conventionally the $1/e$ time of the envelope, so that $T_2^* \leq T_2$. A Hahn echo [46] refocuses the static component and returns a time $T_{2,\text{echo}}$ that lies between T_2^* and the intrinsic T_2 whenever the noise has appreciable low-frequency weight. The relations depend on the model, and they assume exponential decay, a single noise bath and no leakage, and a T_2 measured with a dynamical-decoupling sequence (CPMG, for example) is a filtered quantity that depends on the sequence used. For gate durations t much shorter than T_1 and T_2 , idling alone contributes an average infidelity

$$1 - \bar{F} \approx \frac{t}{6T_1} + \frac{t}{3T_2} \quad (3)$$

which reduces to $t/(3T_1)$ at the $T_2 = 2T_1$ limit. The expression gives a floor, not a prediction of gate error, since it leaves out control errors, leakage, crosstalk and coherent miscalibration.

B. Mechanisms limiting stability

Energy relaxation and dielectric loss. In superconducting circuits, spontaneous emission into control lines, Purcell decay through the readout resonator, two-level-system defects in oxides and interfaces, and quasiparticle tunneling determine T_1 . Two-level-system defects also make T_1 fluctuate slowly over hours, tying physical stability to calibration drift. *Phase decoherence.* Flux noise, charge noise and thermal photons in readout resonators contribute to T_ϕ ; the low-frequency spectrum of many solid-state noise sources is approximately $1/f$, which yields non-exponential decay and strongly sequence-dependent coherence [47]. *Thermal fluctuations* populate excited states and resonator photons, which sets a floor on the effective temperature. *Magnetic-field and charge noise* dominate spin-based devices and trapped-ion hyperfine or optical qubits, where laser phase noise, motional heating and magnetic-field fluctuations play analogous roles [48], [49]. *Photon loss* is the dominant error of bosonic and photonic encodings and is the physical origin of the displacement errors that GKP codes correct [17], [36]. *Leakage* moves population outside the computational subspace, for example into higher transmon levels, and leaked qubits corrupt neighbouring syndrome measurements for many cycles unless actively removed [37]. *Imperfect control pulses, readout errors and crosstalk* add coherent and incoherent errors that depend on calibration. *Fabrication variability* spreads frequency, coherence and coupling from qubit to qubit, which complicates uniform operation across large arrays.

Correlated errors break the independence assumed by most threshold analyses. Ionizing radiation and cosmic rays deposit energy in the substrate and generate quasiparticles that raise error rates simultaneously over many qubits [34]. In a recent superconducting experiment, repetition codes up to distance 29 were limited by rare correlated events that occurred about once every 3×10^9 cycles, whereas high-energy impact events had earlier been recorded roughly every 10 s before the device was modified [24]. *Non-Markovian effects* arise when the environment retains memory of past system states, so that errors in successive cycles are correlated in time and the semigroup (Lindblad) description fails [50].

C. Noise models

Table 3 lists the channels used below, with their typical uses and main limitations.

A general physical operation on a density matrix ρ is a completely positive trace-preserving (CPTP) map with Kraus operators $\{K_k\}$,

$$\mathcal{E}(\rho) = \sum_k K_k \rho K_k^\dagger, \quad \sum_k K_k^\dagger K_k = I \quad (4)$$

Amplitude damping with decay probability $\gamma = 1 - e^{-t/T_1}$ has $K_0 = |0\rangle\langle 0| + \sqrt{1-\gamma} |1\rangle\langle 1|$ and $K_1 = \sqrt{\gamma} |0\rangle\langle 1|$. *Phase damping* is the Pauli-Z channel

$$\mathcal{E}_\phi(\rho) = (1 - p_\phi)\rho + p_\phi Z\rho Z, \quad p_\phi = 1/2 (1 - e^{-t/T_\phi}) \quad (5)$$

which multiplies ρ_{01} by e^{-t/T_ϕ} . The general *Pauli channel* and its symmetric special case, *depolarizing noise*, are

$$\mathcal{E}(\rho) = \sum_{P \in \{I, X, Y, Z\}} p_P P\rho P, \quad p_X = p_Y = p_Z = \frac{p}{3} \text{ (depolarizing)} \quad (6)$$

Applying a Pauli twirl to amplitude damping yields a Pauli channel with

$$p_X = p_Y = \frac{\gamma}{4}, \quad p_Z = \frac{2 - \gamma - 2\sqrt{1-\gamma}}{4} \quad (7)$$

and the twirled model is what stabilizer simulators sample. Twirling throws away the coherent part of the error, and coherent errors can add up quadratically rather than linearly in the number of cycles. Pauli models can therefore understate the logical error caused by coherent miscalibration. *Leakage* is

modeled on a qutrit with $K_0 = |0\rangle\langle 0| + \sqrt{1-p_L} |1\rangle\langle 1| + |2\rangle\langle 2|$ and $K_1 = \sqrt{p_L} |2\rangle\langle 1|$, and a *heralded erasure* channel $\mathcal{E}(\rho) = (1-p_e)\rho + p_e |e\rangle\langle e|$ flags the location of the failure, which makes erasure considerably easier to correct than an unlocated Pauli error. *Correlated multi-qubit errors* are captured by a Pauli channel on n qubits with a joint distribution over error patterns E , for example a burst model

$$\mathcal{E}_{\text{burst}}(\rho) = (1-q)\rho + q \sum_{E \in \mathcal{B}} w_E E \rho E^\dagger, \quad \sum_{E \in \mathcal{B}} w_E = 1 \quad (8)$$

where q is the burst probability per cycle and $\mathcal{B}$ is a set of patterns supported on a spatial region. For slow classical noise a *stochastic Hamiltonian* $H(t) = 1/2 [\omega_q + \xi(t)]Z$ gives a dephasing factor $\exp[-1/2 \langle \varphi^2(t) \rangle]$ for Gaussian noise, with

$$\langle \varphi^2(t) \rangle = \int_{-\infty}^{\infty} \frac{d\omega}{2\pi} S_\xi(\omega) \frac{4\sin^2(\omega t/2)}{\omega^2} \quad (9)$$

which for $1/f$ spectra produces approximately Gaussian decay [47]. The *Lindblad master equation*,

$$\frac{d\rho}{dt} = -i[H, \rho] + \sum_k \gamma_k (L_k \rho L_k^\dagger - 1/2 \{L_k^\dagger L_k, \rho\}) \quad (10)$$

reproduces the exponential model with $L_1 = \sigma_-$, $\gamma_1 = 1/T_1$ and $L_2 = Z$, $\gamma_2 = 1/(2T_\phi)$.

As a consistency check, the Pauli-twirl probabilities of (7), the idle-infidelity expression (3), the Kraus completeness of the leakage channel and the rates of (10) were verified numerically against the corresponding channels for sample values of T_1 , T_2 and t . The expression (3) agrees with the exact average gate fidelity to first order in t .

Table 3: Noise models, typical use and principal limitations

Model	Typical use	Principal assumptions and limitations
Kraus / CPTP map	General single-cycle error description	Requires full process characterization; exponential parameter count in n
Amplitude and phase damping	Relating T_1 , T_ϕ to gate error	Markovian, single bath, no leakage; coherent errors absent
Depolarizing and Pauli	Stabilizer and threshold simulation	Obtained by twirling; hides coherent and leakage errors
Erasure and leakage	Atom loss, photon loss, transmon level excursion	Leakage needs a qutrit or larger model; propagation through gates is hardware specific
Correlated Pauli (burst)	Cosmic-ray and shared-bath events	Pattern set $\mathcal{B}$ and rate q must be measured; breaks independence assumptions of thresholds
Stochastic Hamiltonian	Low-frequency flux, charge and magnetic noise	Gaussian, classical noise; sequence-dependent decay
Lindblad master equation	Open-system dynamics, bosonic modes	Markovian and weak-coupling; fails when bath memory is significant [50]

5. MATHEMATICAL FOUNDATIONS OF QUANTUM ERROR CORRECTION

A. Conditions for correction

The no-cloning theorem [1] excludes redundancy by copying. A code is a subspace $\mathcal{C}$ with projector P spanned by codewords $|i\rangle$. A set of error operators $\{E_a\}$ is correctable if and only if

$$\langle i | E_a^\dagger E_b | j \rangle = C_{ab} \delta_{ij} \quad \text{for all codewords } |i\rangle, |j\rangle \quad (11)$$

equivalently $PE_a^\dagger E_b P = C_{ab} P$, with a Hermitian matrix C that does not depend on the codeword [11]. The condition has two parts. Orthogonal codewords must stay orthogonal after any pair of errors (the $i \neq j$ terms vanish), and the errors must not reveal which codeword was stored (the diagonal term does not depend on i). When C has full rank the code is nondegenerate, and when C is rank deficient distinct errors act identically on the code space (degeneracy). For a stabilizer code of distance d , all errors of weight at most

$$t = \left\lfloor \frac{d-1}{2} \right\rfloor \quad (12)$$

form a correctable set, and the code detects up to $d-1$ errors and corrects up to $d-1$ erasures at known locations. Two qualifications apply. First, the statement covers arbitrary errors on at most t qubits. It says nothing about correlated errors spread over more qubits, and it assumes perfect syndrome extraction and recovery. Second, many codes correct particular error patterns of weight greater than t (a topological code with a good decoder resolves numerous such patterns), so t is a worst-case guarantee and not a measure of average-case capability. Under circuit-level noise the effective distance can also change, because faults in ancilla preparation, gates and readout alter which combinations of faults are harmful [14].

B. Stabilizer codes

A stabilizer code is defined by an abelian subgroup $\mathcal{S}$ of the Pauli group that does not contain $-I$, and the code space is the joint $+1$ eigenspace [4], [10],

$$\mathcal{C}(\mathcal{S}) = \{|\psi\rangle: g|\psi\rangle = |\psi\rangle \quad \forall g \in \mathcal{S}\} \quad (13)$$

With $n-k$ independent generators the code encodes k logical qubits in n physical qubits. The syndrome bit of a generator g_i is the outcome of measuring g_i , and a Pauli error E flips syndrome bit i if and only if E anticommutes with g_i . Logical operators lie in the normalizer, $N(\mathcal{S}) \setminus \mathcal{S}$, and the distance is the minimum weight of such an operator, giving the notation $[[n, k, d]]$. CSS codes are built from two classical parity-check matrices that satisfy

$$H_X H_Z^T = 0 \pmod{2}, \quad k = n - \text{rank } H_X - \text{rank } H_Z \quad (14)$$

so that X -type and Z -type stabilizers commute [3], [9]. The three-qubit repetition code against bit flips has stabilizers $Z_1 Z_2$ and $Z_2 Z_3$, and the Shor code concatenates a bit-flip and a phase-flip repetition code to correct arbitrary single-qubit errors [2]. A Pauli error E is the product of a bit flip (X) and a phase flip (Z), and a correct decoder identifies E up to multiplication by a stabilizer element.

C. Fault-tolerant operation

Ancilla qubits measure stabilizers without measuring logical information, but the measurement circuit is itself noisy and propagates errors. Through a CNOT with control c and target t ,

$$X_c \rightarrow X_c X_t, \quad Z_t \rightarrow Z_c Z_t \quad (15)$$

so one fault in an ancilla can spread to several data qubits (a hook error). A circuit is fault-tolerant when any single fault produces at most one error per code block [6], [7]. Practical remedies include extraction schedules that align hook errors perpendicular to the logical operator, flag qubits, transversal gates (which act qubit by qubit and so cannot spread errors within a block), fault-tolerant state preparation and measurement, and repeated syndrome measurement so that measurement errors can be told apart from data errors. No code admits a universal set of transversal gates, which motivates magic-state distillation and injection for non-Clifford operations [7], [15]. Recovery need not be applied physically. Tracking a Pauli frame F in software, with the update

$$F \leftarrow F \cdot \hat{E}, \quad F \leftarrow U F U^\dagger \text{ under a Clifford gate } U \quad (16)$$

defers correction to the logical measurement, and the frame has to be resolved only before a non-Clifford gate is applied.

D. Logical error scaling and threshold

Below a threshold p_{th} , increasing the code distance suppresses the logical error exponentially [5], [13]. A commonly used approximate relation for a code with odd distance d is

$$p_L \approx A \left(\frac{p}{p_{\text{th}}} \right)^{(d+1)/2} \quad (17)$$

where p_L is the logical error probability for a specified operation (here, one correction cycle of a memory), p is the single physical error parameter of a specified noise model, p_{th} is the threshold of that noise model, circuit and decoder, and A is a prefactor that depends on the code, noise model, circuit schedule, decoder and the number of fault paths. The relation is an approximate scaling law, not a universal formula. It holds only well below threshold, only for noise models that reduce to one parameter p , and only when errors are sufficiently uncorrelated. Experiments and numerical studies therefore report the measured suppression factor

$$\Lambda = \frac{\varepsilon_d}{\varepsilon_{d+2}} \quad (18)$$

the ratio of logical errors per cycle at consecutive odd distances, which equals p_{th}/p under (17). When a memory experiment of R rounds yields a failure probability P_L , the error per round is extracted by assuming independent, symmetric flips in each round,

$$\varepsilon_L = \frac{1}{2} [1 - (1 - 2P_L)^{1/R}] \quad (19)$$

Every quantitative comparison in this review names the noise model, correction cycle and operation behind a number, since values obtained under different assumptions cannot be exchanged.

6. COMPARISON OF QUANTUM ERROR-CORRECTING CODES

Table 4 compares fourteen code families on the requested axes. Entries on physical resources, distance and syndrome weight follow from the code definitions; entries on experimental maturity are limited to results in the cited primary sources. Where no verified primary demonstration was retrieved, the table says so instead of extrapolating.

Four trade-offs organize the table. First, locality against rate: the surface code has a constant encoding rate of one logical qubit per patch and needs only nearest-neighbour two-dimensional connectivity, whereas qLDPC codes encode many logical qubits per block at the cost of non-local checks. Bivariate-bicycle codes were reported to offer an order-of-magnitude reduction in encoding overhead relative to the surface code at a similar circuit-level threshold, and their Tanner graph can be split into two planar layers [20]. Asymptotically good qLDPC codes exist [19], and reconfigurable atom arrays are a natural hardware match for the required connectivity [39]. No qLDPC memory with verified experimental results was found in the sources used here. Second, logical gate support: the colour code supports transversal Clifford gates, which was exploited in a superconducting experiment with distance-3 and distance-5 codes where logical randomized benchmarking showed transversal Cliffords adding an error of 0.0027(3) and the suppression factor from distance 3 to 5 was 1.56(4) [40]. The surface code instead relies on lattice surgery and magic states [15], [29]. Third, noise bias: cat qubits suppress bit flips exponentially in mean photon number and hand the remaining phase flips to an outer repetition code, and a distance-5 concatenated memory showed logical phase-flip error decreasing from distance 3 to 5 with a minimum logical error per cycle of 1.65(3)% for the distance-5 code [41]. Fourth, analog versus digital encoding: GKP codes correct small displacements in phase space and a superconducting-cavity memory reached a gain of $G = 2.27 \pm 0.07$ over its best constituent component [36], while an earlier cat-code memory reached about 1.1 [21], [36].

Table 4: Comparison of quantum error-correcting codes.

Code	Parameters, resources	Correction and decoding	Connectivity and logical gates	Correlated noise, leakage	Maturity*
Repetition	$[[n,1]]$ against one error type; n data, $n-1$ ancilla	Corrects only X (or Z) errors; majority or matching decoding	1D chain; no logical gate set	Burst events set an error floor	Up to distance 29 as a probe of correlated errors [24]
Shor	$[[9,1,3]]$; 9 data qubits	Single error; arbitrary syndrome lookup	Non-local, weight up to 6 checks; limited gates	Not designed for correlated or leakage errors	Historical proposal [2]
Steane	$[[7,1,3]]$ CSS from the classical Hamming code; 7 data	Single error; arbitrary lookup decoding	Weight-4 checks; transversal Clifford gates	Single-fault assumption	Trapped-ion fault-tolerant gate sets [31], [35]
Five-qubit perfect	$[[5,1,3]]$; saturates the quantum Hamming bound	Single error; lookup	Weight-4 non-CSS checks; few transversal gates	Single-fault assumption	Small demonstrations only (none retrieved here) [10]
Bacon–Shor	$[[m^2,1,m]]$ subsystem code	Weight-2 gauge measurements; matching-type decoding	Local gauge operators; weight- $2m$ stabilizers inferred	Subsystem structure tolerates some gauge noise	Proposal [27]; none retrieved

Code	Parameters, resources	Correction and decoding	and	Connectivity and logical gates	and	Correlated noise, leakage	Maturity*
Surface (planar)	$[[d^2+(d-1)^2, 1, d]]$	Weight-4 and weight-2 checks; MWPM, neural decoders		2D nearest neighbour; lattice surgery, magic states		Threshold sensitive to correlated bursts and leakage	Distance 7, $\Lambda = 2.14 \pm 0.02$ [24]
Rotated surface	$[[d^2, 1, d]]$; $2d^2 - 1$ qubits in total	Same checks, fewer qubits; MWPM		2D nearest neighbour		As planar surface code	Distance 7, 101 qubits reported [24]
Toric	$[[2L^2, 2, L]]$ on a torus	Same as surface; optimal-decoder threshold from a statistical-mechanics mapping		Periodic boundaries; non-planar		As surface code	Theory [12], [13]
Colour	2D $[[n, 1, d]]$ on a 3-colourable lattice; weight-6 checks in the hexagonal layout	Matching-type or restriction decoders		Transversal Clifford gates (H, S)		Higher check weight raises circuit-level sensitivity	Distance 3 to 5, $\Lambda_{3/5} = 1.56(4)$ [40]; logical distillation on atoms [42]
Concatenated	n^L qubits at L levels	Hierarchical decoding; threshold proof [5]		Transversal gates at low levels		Threshold proven for local stochastic noise	Small codes only
qLDPC (bivariate bicycle)	$[[144, 12, 12]]$ gross code uses 144 data and 144 check qubits [20]	BP with post-processing; high rate		Two-layer (thickness 2) connectivity		Studied at circuit level; correlated noise open	None retrieved; atom-array proposal [39]
Cat	One bosonic mode per qubit; mean photon number $\bar{n}$	Passive bit-flip suppression; phase-flip outer code		Bias-preserving gates required		Ancilla transmon dephasing and photon loss	Distance-5 concatenated memory [41]
Binomial	One bosonic mode; truncated Fock encoding	Photon-number parity checks		Cavity-transmon control		Photon loss and dephasing	Proposal [18]; none retrieved
GKP	One bosonic mode with grid states; finite squeezing	Displacement error correction, often by reinforcement-learned control		Ancilla-assisted gates		Loss and dephasing limit lifetime	$G = 2.27 \pm 0.07$ [30], [36]

* Maturity refers to the strongest verified experimental result in the cited sources; “none retrieved” means that no verified primary demonstration was found. n : data qubits or modes.

7. SURFACE-CODE ARCHITECTURE

A. Layout and stabilizer circuits

The rotated surface code of distance d places d^2 data qubits on a square grid with $d^2 - 1$ measurement (ancilla) qubits at plaquette centres, giving $2d^2 - 1$ qubits in total, as drawn for $d = 3$ in Fig. 2. Interior plaquettes carry weight-4 stabilizers and alternate between X and Z type, while boundary plaquettes carry weight-2 stabilizers. A syndrome cycle resets the ancillas, applies four entangling layers, and measures the ancillas. For an X -type check the ancilla starts in $|+\rangle$ and acts as a CNOT control on four data qubits, and for a Z -type check the data qubits control a CNOT on the ancilla. The ordering of the four entangling layers is chosen so that a single ancilla fault produces a hook error aligned perpendicular to the logical operator it could damage, preserving the circuit-level distance [14]. Logical operators are strings of Pauli operators crossing the patch. In the experimental device of Ref. [24] the distance-7 code used 101 qubits, more than the 97 of the minimal layout; the additional qubits reflect device-specific implementation details that are not interpreted here.

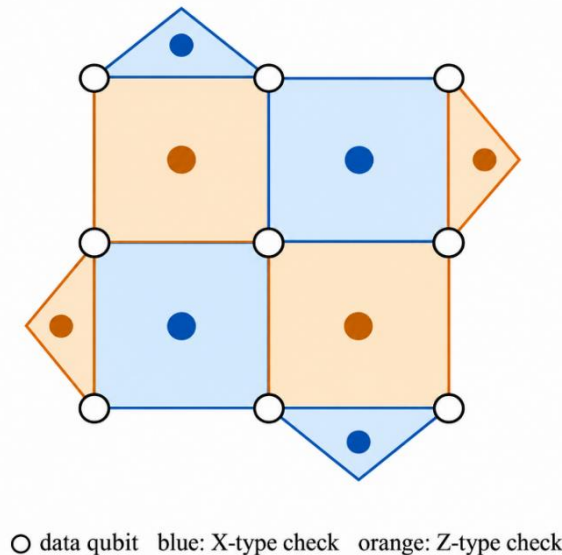


Fig. 2. Rotated surface code at distance $d = 3$: nine data qubits (circles) and eight check qubits, four of weight 4 in the interior and four of weight 2 on the boundary, with blue and orange denoting X-type and Z-type checks respectively. Schematic prepared for this review.

B. Syndrome processing and decoding

Fig. 3 summarizes the classical workflow. Ancilla outcomes form a syndrome record s_r each round, detection events are $D_r = s_r \oplus s_{r-1}$, and fault mechanisms define the edges of a detector graph. Minimum-weight perfect matching (MWPM) pairs detection events by the lowest-weight path, which maps to the most likely error under independent faults, and an optimized implementation corrects on the order of a million errors per core-second [44]. Alternatives include neural-network decoders, which outperformed matching on experimental data from a superconducting processor [38] and were used for the headline logical error rates of Ref. [24], as well as belief-propagation-based decoders for qLDPC codes [20]. Real-time decoding is a separate requirement: in Ref. [24] a distance-5 memory was decoded in real time with an average latency of $63 \mu\text{s}$ against a correction-cycle time of $1.1 \mu\text{s}$, and the logical error per cycle at distance 5 was $0.35\% \pm 0.01\%$ for the real-time decoder.

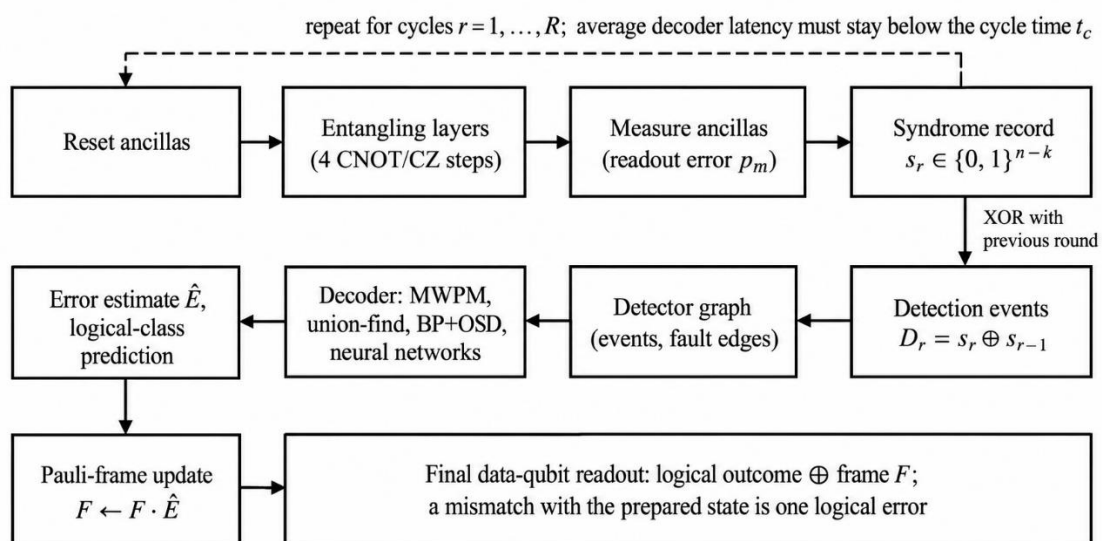


Fig. 3. Syndrome-measurement and decoding workflow for a memory experiment. Quantum operations (blue) feed a classical processing chain (orange) whose output is a Pauli-frame update. Schematic; no data. Original figure prepared for this review.

C. Logical operations, leakage and correlated errors

Logical Clifford operations between surface-code patches are performed by lattice surgery, which merges and splits patches by measuring joint logical operators and is the basis of large-scale compilation schemes [29]. Non-Clifford gates require magic states, whose distillation was demonstrated at the logical level on neutral atoms with distance-3 and distance-5 colour codes, where output logical fidelity improved over inputs [42]. Logical state preparation and readout use transversal initialization and measurement of data qubits followed by decoding of the final round. Leakage is mitigated by removing leaked population after each cycle. In a superconducting study, doing so on every qubit cut steady-state data-qubit leakage about tenfold and held the device-average leakage below 10^{-3} [37]. Correlated error bursts are mitigated by materials and junction engineering, and their residual rate sets a floor that, in repetition codes at distance 29, was of order 10^{-10} per cycle [24], [34]. An earlier distance-25 repetition code showed a floor of 1.7×10^{-6} per round determined by a single high-energy event, falling to 1.6×10^{-7} when that event was excluded [23].

8. COMPARISON OF QUBIT PLATFORMS

Table 5 compares platforms using values from primary sources only. Each number refers to the device and condition named in its cell, and comparing across rows requires accounting for gate type, benchmarking method and device generation. A cell that says “none retrieved” means that no verified primary value was available for that claim.

Three observations follow from the table. First, several platforms have reached high two-qubit fidelity: trapped ions at 99.9(1)% [49], and neutral atoms and silicon spins at 99.5% [51], [52]. Among the sources retrieved, however, the logical memories that improve with distance below threshold are superconducting [24] or neutral-atom characterization circuits [26]. Fidelity alone does not predict the logical outcome, because cycle time, leakage, correlated errors and decoder latency all intervene. Second, connectivity trades against parallelism: reconfigurable atom arrays and ion shuttling allow non-local operations, whereas fixed superconducting and spin arrays offer fast parallel local gates. Third, topological and photonic approaches are architecturally distinct, and the strongest verified results in the cited sources are a measurement primitive [45] and an architectural blueprint [53], not logical memories.

Table 5: Qubit-platform comparison from primary sources. SC: superconducting; NN: nearest neighbour; “none retrieved”: no verified primary value was available.

Platform	Verified performance (device, condition)	Dominant noise sources	Connectivity, parallelism	QEC maturity	Bottlenecks
SC transmon	Mean $T_1 = 68 \mu\text{s}$, $T_{2,\text{CPMG}} = 89 \mu\text{s}$ on a 105-qubit processor; XY gate 25 ns, CZ 42 ns; cycle time 1.1 μs [24]. Component errors listed for a 72-qubit processor: single-qubit 6.2×10^{-4} , CZ 2.8×10^{-3} (excluding crosstalk and leakage), readout 0.8×10^{-2} , reset 1.5×10^{-3} [24]	Dielectric loss, leakage, correlated bursts [34], [37]	2D NN, parallel gates	Distance 7, $\Lambda = 2.14 \pm 0.02$, memory 2.4 ± 0.3 times beyond best physical qubit lifetime [24]; colour code $\Lambda_{3/5} = 1.56(4)$ [40]	Correlated error floor, wiring and cryogenic load, decoder throughput
Trapped ion	Two-qubit 99.9(1)%, single-qubit 99.9934(3)% for $^{43}\text{Ca}^+$ hyperfine qubits in a room-temperature trap [49]; average two-qubit infidelity $1.84(5) \times 10^{-3}$ on a 32-qubit race-track system [54]	Laser and magnetic-field noise, motional heating	All-to-all within a zone; transport between zones	Real-time fault-tolerant QEC [31]; fault-tolerant universal gate set [35]	Gate speed relative to superconductors, transport overhead, optical control scaling

Platform	Verified performance (device, condition)	Dominant noise sources	Connectivity, parallelism	QEC maturity	Bottlenecks
Neutral atom	Two-qubit 99.5% on up to 60 atoms in parallel [51]; up to 48 logical qubits on 280 atoms [25]; up to 448 atoms, $2.14(13) \times$ below-threshold performance in a four-round characterization circuit [26]	Rydberg-state decay, atom loss, laser phase noise	Reconfigurable by tweezer motion; highly parallel	Logical processors, logical magic-state distillation with colour codes [42], transversal fault tolerance [43]	Cycle rate (mid-circuit reuse raised experimental rates by two orders of magnitude [26]), atom loss, entropy removal
Spin (silicon)	Single-qubit and two-qubit fidelities above 99.5% by gate set tomography [55]; single-qubit 99.8%, two-qubit 99.5% [52]	Charge noise, residual nuclear spins, crosstalk [48]	NN arrays	None retrieved	Variability across devices, control wiring, scale of arrays
Photonic	None retrieved; architecture-level blueprint for a scalable fault-tolerant machine [53]	Loss, probabilistic sources	Mode-based, fusion or measurement driven	None retrieved	Loss budget, source and detector performance
Bosonic modes	GKP memory gain $G = 2.27 \pm 0.07$ [36]; concatenated cat repetition code of distance 5, 1.65(3)% logical error per cycle [41]	Photon loss, ancilla-induced dephasing	Modes coupled through ancilla transmons	Beyond break-even memories [30], [36]	Scaling the number of modes, bias-preserving gates
Topological (Majorana)	Parity-measurement error of 1%, signal-to-noise ratio 1 in $3.7 \mu\text{s}$ [45]	Quasiparticle poisoning, disorder [56]	Not applicable at present	No qubit demonstrated in the cited source	Demonstrating a coherent topological qubit

9. PERFORMANCE METRICS AND BENCHMARKING

Physical metrics. The times T_1 , T_2 and T_2^* (Section 4) describe memory, whereas the average gate fidelity $\bar{F}$ and the error per gate describe operations. State-preparation and measurement (SPAM) errors affect syndrome extraction every cycle and are often comparable to or larger than gate errors. Leakage probability per gate or per cycle measures excursions out of the computational subspace.

Logical metrics. The logical error per correction cycle ε_L ((19)), the suppression factor Λ ((18)), the logical memory lifetime relative to the best physical qubit (for example, 2.4 ± 0.3 in [24]), the logical error per logical gate (for example, 0.0027(3) added by a transversal Clifford in [40]), and the physical-to-logical qubit overhead describe encoded performance. For bosonic memories the gain G is the ratio of logical lifetime to that of the best physical component, so $G > 1$ marks break-even [36]. Decoder latency determines whether a real-time decoder can keep pace with the cycle time, as measured in [24].

System metrics. Quantum volume measures the largest square random circuit that a device runs successfully under a heavy-output criterion [57]. The metric folds together connectivity, gate error and compilation quality, but it was not designed to reflect syndrome-extraction quality, decoder performance or logical scaling.

Why the metrics are not interchangeable. Coherence times and gate fidelities do not determine ε_L , because the logical error depends on the circuit schedule, on correlated and leaked errors that RB does not capture, on measurement errors, on the decoder, and on cycle time. A device with high $\bar{F}$ and slow cycles can have a worse logical error per unit time than one with lower $\bar{F}$ and fast cycles. Quantum volume also rewards connectivity that a surface-code memory never uses. A suppression factor is meaningful only at a stated noise operating point and decoder, and ε_L depends on the basis, the number of rounds and the initial state.

Benchmarking protocols. Randomized benchmarking applies random Clifford sequences of length m and fits the survival probability to $F(m) = A\alpha^m + B$, from which the error per Clifford is $r = (1 - \alpha)(D - 1)/D$ with $D = 2^n$ [58]. Interleaved RB inserts a target gate and bounds its error through

the ratio of the interleaved and reference decay constants, approximately $r_g \approx (D - 1)(1 - \alpha_{\text{int}}/\alpha_{\text{ref}})/D$ [59]. Cycle benchmarking estimates Pauli error rates of multi-qubit gate cycles and exposes crosstalk and correlated errors that single-gate RB averages away [60]. Ramsey experiments measure T_2^* and the detuning, spin-echo and dynamical-decoupling sequences measure $T_{2,\text{echo}}$ and filtered coherence [46], and logical benchmarking applies RB to encoded gates [40]. RB assumes gate-independent, Markovian noise and measures an average over a gate set, so it can understate worst-case or coherent errors.

10. QUANTITATIVE RESULTS

A. Computational study design

Two simulation studies provide reproducible baselines. Both use Stim [32] to generate rotated surface-code memory circuits in the Z basis and PyMatching [44] to decode with MWPM. *Noise model.* Uniform circuit-level depolarizing noise with a single parameter p applied (i) after every Clifford gate, (ii) to data qubits before each round, (iii) as a flip before every measurement, and (iv) as a flip after every reset. *Code parameters.* Distances $d = 3, 5, 7, 9, 11$ with $R = d$ rounds. *Decoder.* MWPM with edge weights derived from the detector error model of the assumed noise. *Statistics.* Failures are counted per shot with 95% Wilson confidence intervals. Study A used 400,000 shots per point for $p \leq 0.003$ and 150,000 otherwise (80,000 for $d \geq 9$ above $p = 0.003$) across eleven values of p from 0.1% to 1.2%. Study B used 120,000 to 200,000 shots per point with the same syndromes shared by all decoders in a comparison (paired sampling). *Seeds.* A base seed of 20261017 plus a deterministic offset per point. *Environment.* Python 3.13, Stim 1.16.0, PyMatching 2.4.0, NumPy 2.5.3 on Linux. The scripts and raw counts accompany the manuscript as supplementary material. The simulations are computational results from a simplified noise model, and they are not experimental measurements.

B. Threshold behaviour and suppression with distance

Fig. 4 shows the logical error per round against distance for p between 0.1% and 0.5%, together with published experimental values, and Fig. 5 shows the logical failure probability against p for all distances. Curves for neighbouring distances cross between $p = 0.7\%$ and 0.8% , with pairwise crossings at 0.64% (3 to 5), 0.74% (5 to 7), 0.75% (7 to 9) and 0.76% (9 to 11) estimated by linear interpolation between grid points. The crossing drifts upward and levels off as d grows, as expected from finite-size effects, and the grid spacing leaves each estimate uncertain by roughly ± 0.05 percentage points. Below the crossing, P_L falls with d (below-threshold regime), and above it P_L rises with d (above-threshold regime). At $p = 0.1\%$, P_L falls from 8.1×10^{-4} at $d = 3$ to 2.5×10^{-6} at $d = 9$, and no failures were observed at $d = 11$ in 400,000 shots.

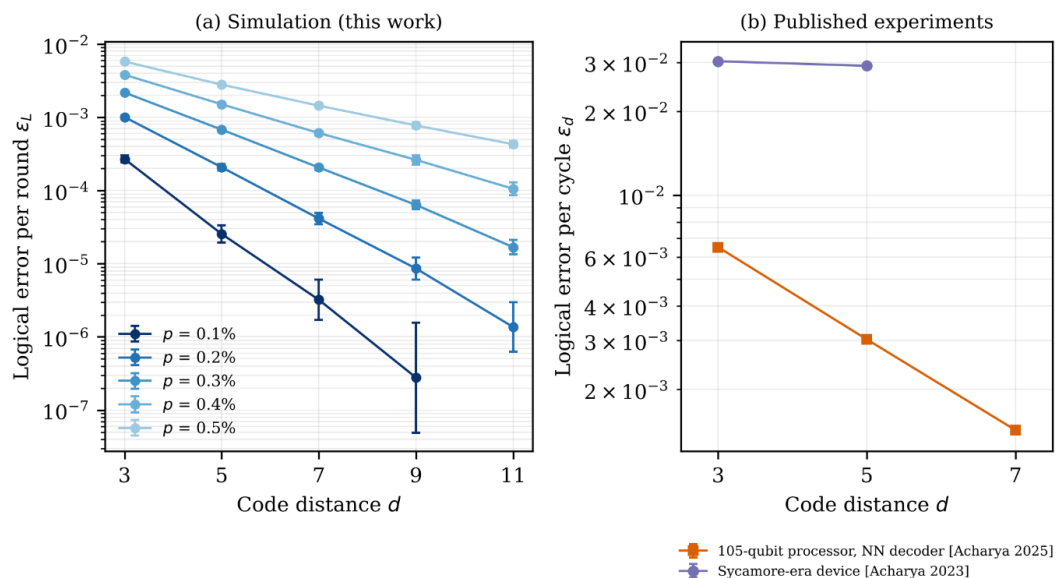


Fig. 4. Logical error per round versus code distance. (a) Simulation by this work (Stim and PyMatching, uniform circuit-level depolarizing noise, $R = d$ rounds, 95% Wilson intervals, points without observed failures omitted). (b) Published experiments: values transcribed from Ref. [24] (105-qubit processor, neural-network decoder: 6.50×10^{-3} , 3.03×10^{-3}

and 1.43×10^{-3} at $d = 3, 5, 7$, with the quoted uncertainties) and from Ref. [23] ($3.028 \pm 0.023\%$ at $d = 3$ and $2.914 \pm 0.016\%$ at $d = 5$). Panels are not directly comparable because the noise models, decoders and devices differ.

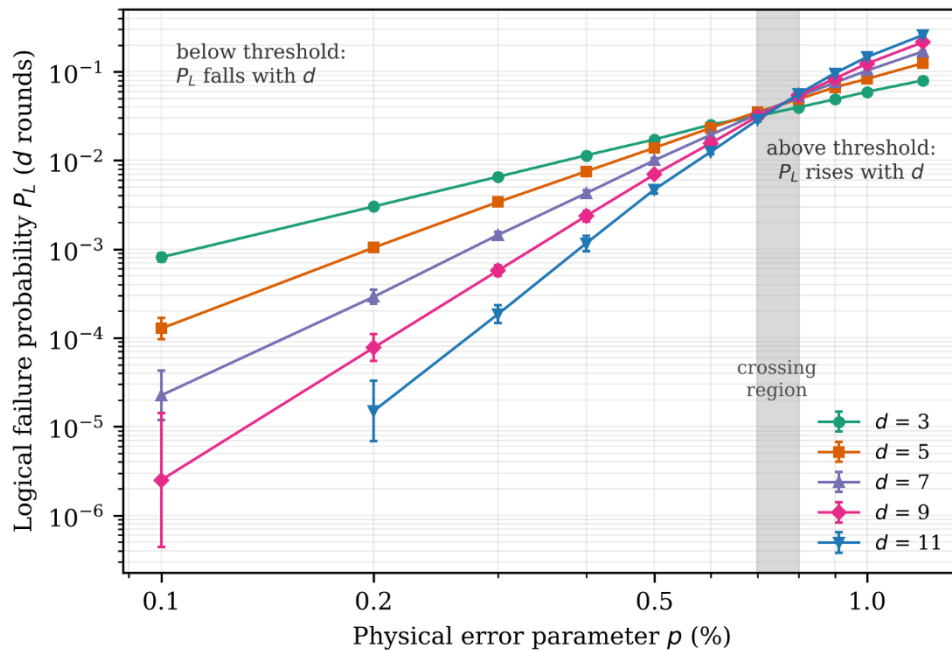


Fig. 5. Logical failure probability over d rounds versus the physical error parameter p for distances 3 to 11 (simulation by this work; same model and statistics as the previous figure). The grey band marks the region 0.7% to 0.8% in which neighbouring-distance curves cross.

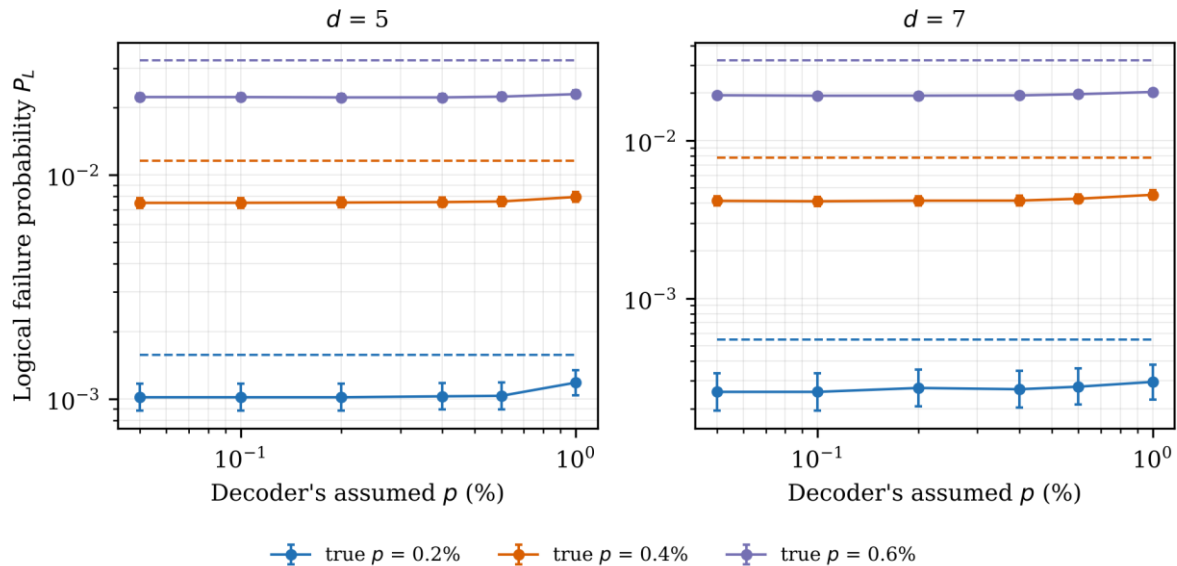
Fitting $\ln \varepsilon_L$ against $(d + 1)/2$ at fixed p gives the suppression factors in Table 6. The product $p\Lambda$ is nearly constant at 0.97% to 1.0%, consistent with the scaling law (17) and a slope-based threshold parameter near 1%. The slope-based value exceeds the crossing-based threshold of about 0.75%, a gap that shows why (17) is only approximate. The relation describes the slope at low p , whereas the threshold proper is the crossing point in the large- d limit, and the two coincide only asymptotically and for idealized noise. For comparison, the experimental suppression factor of 2.14 ± 0.02 [24] corresponds in this simulated model to $p \approx 0.46\%$, but the match is only illustrative, since real devices have non-uniform and partly correlated noise.

Table 6: Fitted suppression factor Λ per distance step from the simulation (weighted fit of $\ln \varepsilon_L$ against $(d + 1)/2$ using distances with at least one observed failure; $\pm$ is the 1σ statistical range of the fit and excludes model error)

p (%)	Distances used	Λ	Range	$p\Lambda$ (%)
0.1	4	9.93	8.91 to 11.06	0.99
0.2	5	4.93	4.77 to 5.10	0.99
0.3	5	3.28	3.23 to 3.33	0.98
0.4	5	2.47	2.43 to 2.51	0.99
0.5	5	1.95	1.93 to 1.97	0.97
0.6	5	1.67	1.66 to 1.69	1.00

C. Decoder calibration study (baseline for adaptive QEC)

Study B asks how much the logical failure probability depends on the accuracy of the error rates assumed by the decoder. For $d = 5$ and $d = 7$ and true $p = 0.2\%$, 0.4% , 0.6% , the decoder was built from the detector error model of an assumed p_{dec} between 0.05% and 1.0%, and a uniform-weight baseline ignored noise information entirely. Fig. 6 and Table 7 show that assumed rates differing from the true rate by factors between 0.08 and 5 change P_L by at most 16% (largest at $d = 5$, $p = 0.2\%$, $p_{\text{dec}} = 1.0\%$), whereas the uniform-weight decoder raised P_L by 1.46 to 2.02 times. Two points follow. A purely scalar drift in the overall error rate barely harms MWPM under this noise model, so the case for adaptive correction rests on non-uniform or correlated drift, which was not simulated here. Weights that carry even approximate noise information are also valuable, so a decoder that estimates spatial structure online has measurable headroom.



Solid: MWPM with weights from assumed p . Dashed: uniform-weight MWPM baseline (same syndromes).

Fig. 6. Decoder-calibration study (simulation by this work). Solid lines: logical failure probability of MWPM with weights computed for an assumed p_{dec} at three true values of p . Dashed lines: uniform-weight MWPM on identical syndromes. Error bars: 95% Wilson intervals; paired sampling shares syndromes across decoders.

Table 7: Decoder-calibration study (simulation): logical failure probability with matched weights, ratio for the uniform-weight baseline, and ratio for the most mismatched weighted decoder ($p_{\text{dec}} = 1.0\%$)

d	True p (%)	Matched P_L (failures / shots)	Uniform / matched	Mismatched / matched
5	0.2	1.02e-03 (203 / 200000)	1.54	1.16
5	0.4	7.56e-03 (1511 / 200000)	1.53	1.05
5	0.6	2.23e-02 (2682 / 120000)	1.46	1.03
7	0.2	2.70e-04 (54 / 200000)	2.02	1.09
7	0.4	4.16e-03 (832 / 200000)	1.88	1.09
7	0.6	1.97e-02 (2359 / 120000)	1.64	1.03

11. CRITICAL RESEARCH GAPS

Table 8 pairs each gap with the available evidence and a proposed solution that has a measurable outcome. Gaps are framed by what the verified sources show, and any statement of absence refers only to the sources retrieved for this review.

Table 8: Research gaps, supporting evidence and proposed solutions

Gap	Evidence in the reviewed sources	Proposed solution and metric
Physical fidelity to logical reliability	Gate fidelities of 99.5% to 99.9% exist in several platforms (Table 5) but scaling logical memories were found only on superconducting and neutral-atom devices [24], [26]	Cross-platform logical benchmark with fixed reporting fields (P7); Λ , ϵ_L per cycle and per microsecond
Correlated noise	Error bursts limit repetition codes at about one event per 3×10^9 cycles [24]; cosmic-ray bursts [34]	Burst-aware decoding and device mitigation (P3); logical floor versus burst rate
Leakage accumulation	Leakage removal reduced steady-state data-qubit leakage about tenfold in one study [37]	Leakage-aware detector models (P5); Λ with leakage flags
Real-time decoding	Average latency of 63 μs against a 1.1 μs cycle at distance 5 [24]; neural decoders need latency evidence [38]	Reliability-guaranteed fast decoders (P2); latency and logical error jointly
Qubit overhead	Surface code needs $2d^2-1$ qubits per logical qubit; qLDPC codes report about tenfold lower overhead at similar threshold [20]	Hardware-aware qLDPC co-design (P6); qubits per logical qubit-cycle
Non-Clifford cost and magic states	Logical distillation has been demonstrated at small distance [42]; injected magic states exceed 99% fidelity only with post-selection that retains about 75% of the data [40]	Cultivation and transversal-gate co-design; space-time volume per T state

Gap	Evidence in the reviewed sources	Proposed solution and metric
Calibration drift	T_1 fluctuates over time in solid-state devices (Section 4); no verified primary drift-versus-logical-error study was retrieved	Online noise estimation and weight adaptation (P1); logical error under drift
Non-Markovian noise	Lindblad models fail when baths have memory [50]; $1/f$ noise is sequence dependent [47]	Memory-aware noise tomography within QEC data; model-selection accuracy
Inconsistent benchmarking	Fidelities, cycle times and decoders differ across reports; quantum volume does not reflect logical performance [57]	Standard logical metrics and disclosure checklist (P7)
Cooling and control electronics	Large arrays require wiring and classical processing; not quantified by the retrieved primary sources	Co-design studies reporting power and latency per logical qubit
Fabrication yield and integration	Device-to-device variability is documented for spin qubits [48]	Yield-aware code layout; logical performance versus defect rate
Compiler and control integration	Lattice-surgery compilation exists [29]; experimental control integration is limited	Decoder-in-the-loop compilation; logical gate error versus schedule

12. FUTURE RESEARCH PROPOSALS

Each proposal gives a hypothesis, motivation, methodology, model, baselines, metrics, expected outcome, risks and a validation strategy. The proposals are hypotheses to be tested, and the expected outcomes are predictions, not results.

P1. Adaptive QEC from measured device noise. *Hypothesis:* online estimation of detector-graph edge weights from syndrome statistics lowers the logical error under drifting, spatially non-uniform noise relative to static weights. *Motivation:* the baseline in Section 10 shows that uniform weights cost a factor of 1.5 to 2.0 while scalar drift is nearly harmless, so what matters is structure. *Methodology:* estimate pairwise detection-event correlations each batch of cycles and re-weight the matching graph. *Model:* circuit-level Pauli noise with qubit-dependent rates $p_q(t)$ following a bounded random walk. *Baselines:* static weights from the initial calibration, uniform weights, oracle weights. *Metrics:* ε_L , estimator error, adaptation lag. *Expected outcome:* recovery of most of the gap between static and oracle decoders. *Risks:* estimator variance and non-stationarity faster than the averaging window. *Validation:* Stim and PyMatching with seeded drift models, followed by replay of experimental syndrome data where released.

P2. Machine-learning-assisted decoding with reliability guarantees. *Hypothesis:* a neural decoder with calibrated confidence and abstention rules achieves lower logical error than matching while bounding the conditional failure probability. *Motivation:* neural decoders have outperformed matching on experimental data [38] but offer no worst-case guarantee. *Methodology:* train on simulated and experimental syndromes, apply conformal calibration, and fall back to matching when confidence is low. *Model:* detector-event sequences with labels from known logical outcomes. *Baselines:* MWPM [44], published neural decoder [38]. *Metrics:* ε_L , calibration error, latency, fallback rate. *Expected outcome:* guaranteed error bounds at small cost in average accuracy. *Risks:* distribution shift between training and operation. *Validation:* held-out devices and noise settings.

P3. Correlated-noise-aware code design. *Hypothesis:* adding burst-pattern hyperedges to the detector graph and choosing layouts that spatially separate burst footprints lowers the logical floor. *Motivation:* bursts set the repetition-code floor [24], [34]. *Methodology:* extend the model of (8) to circuit level, decode with hypergraph-aware matching. *Baselines:* independent-noise decoding. *Metrics:* logical error versus burst rate q and footprint size. *Expected outcome:* an improved floor when the burst model is accurate. *Risks:* burst patterns vary with hardware. *Validation:* simulation sweeps and comparison with reported burst statistics.

P4. Hybrid bosonic and discrete-variable correction. *Hypothesis:* concatenating a biased-noise bosonic inner code with a qLDPC or surface outer code reduces the physical-qubit overhead at a fixed target logical error. *Motivation:* cat qubits suppress bit flips and reached a distance-5 repetition memory [41]. *Methodology:* compute thresholds of biased-noise outer codes with measured bias ratios. *Model:* Pauli channel with $p_Z \gg p_X$. *Baselines:* surface code with unbiased noise. *Metrics:* qubits per logical qubit at $\varepsilon_L = 10^{-6}$. *Expected outcome:* overhead reduction growing with bias. *Risks:* bias-

preserving gate imperfections. *Validation*: simulation with experimentally reported bias and error rates.

P5. Leakage-aware real-time decoding. *Hypothesis*: feeding leakage flags into the detector model lowers logical error beyond removal alone. *Motivation*: removal cut steady-state data-qubit leakage about tenfold [37], leaving residual leakage unmodelled. *Methodology*: qutrit-level circuit simulation with leakage transport, decoder with flag-dependent weights. *Baselines*: removal with leakage-blind decoding. *Metrics*: Λ , residual leakage population. *Expected outcome*: measurable gain in Λ at fixed leakage rate. *Risks*: additional readout fidelity demands. *Validation*: qutrit simulations validated against published leakage rates.

P6. Resource-efficient qLDPC architectures. *Hypothesis*: bivariate-bicycle codes with two-layer connectivity reach a given logical error with fewer qubits than rotated surface codes under circuit noise including realistic connectivity penalties. *Motivation*: reported tenfold overhead reduction [20] and atom-array suitability [39]. *Methodology*: circuit-level simulation with routing overhead. *Baselines*: rotated surface code. *Metrics*: qubits and cycles per logical qubit-cycle. *Expected outcome*: advantage that shrinks with routing cost. *Risks*: decoder complexity and gate support. *Validation*: open simulators and fixed code instances.

P7. Cross-platform logical-qubit benchmarking. *Hypothesis*: a fixed disclosure standard (noise operating point, cycle time, rounds, decoder, leakage handling, post-selection fraction) makes logical results comparable across platforms. *Motivation*: Section 9 shows that metrics are not interchangeable. *Methodology*: define normalized quantities ε_L per cycle, per microsecond and per physical qubit, with post-selection reported separately. *Baselines*: existing reports re-expressed in the standard. *Metrics*: rank stability across disclosure fields. *Expected outcome*: identification of results that depend on post-selection or decoder choice. *Risks*: community adoption. *Validation*: retrospective application to published papers.

Novelty statement. The comparison with the literature in Sections 3 and 4 shows that each technique named above already exists in some form. What this article offers is limited to the synthesis, the explicit baselines of Section 10 and the proposed combinations, which must be tested before any claim of novelty can be made.

13. DISCUSSION

Dominant stability mechanisms by platform. In superconducting devices, dielectric loss, leakage and correlated bursts dominate the distance-scaling limit [24], [34], [37]. In trapped ions and neutral atoms the demonstrations point to control quality, speed and (for atoms) loss and entropy removal [26], [54]. In silicon spins, charge noise and device variability limit scaling [48]. In bosonic modes, photon loss and ancilla-induced dephasing limit memory gain [36], [41]. In topological approaches the open problem is demonstrating a qubit at all [45], [56].

When increasing distance helps. Distance helps when the physical error parameter lies below the threshold of the relevant circuit, noise is weakly correlated, leakage does not accumulate, and the decoder keeps pace with the cycle time. In simulation with uniform depolarizing noise the crossing lies near 0.75% and the slope-based parameter near 1% (Section 10); experiments show a suppression factor of 2.14 ± 0.02 over distances 3 to 7 [24]. A suppression factor near 2 means that each increase of distance by two halves the error but raises the qubit count by roughly 1.5 to 3 times over the distances considered here, so the benefit is real but costly in qubits. Reaching a logical error of 10^{-12} from 10^{-3} at $\Lambda = 2$ would require many distance increments, so lowering physical error to raise Λ matters as much as scaling up.

Correlated noise and thresholds. Threshold theorems assume local stochastic noise. Bursts instead correlate errors across many qubits and set floors that a larger distance cannot lower unless the burst footprint is smaller than the code. Repetition-code experiments exposed such a floor at the 10^{-10} level per cycle [24]. Threshold values quoted for independent noise should therefore be read as upper bounds on what correlated environments allow.

Code-family trade-offs. Surface codes offer locality and an experimentally validated path but high overhead, colour codes offer transversal Clifford gates but heavier checks [40], qLDPC codes offer low overhead with non-local connectivity [20], [39], and bosonic codes offer hardware efficiency with

bias or analog requirements [36], [41]. No family wins on every axis, and the best choice depends on the platform.

Fair cross-platform comparison. A fair comparison must state the noise operating point, cycle time, number of rounds, decoder, leakage treatment, post-selection, and whether the figure is a memory or a gate result. Wall-clock logical error rates and qubit footprint matter as much as per-cycle numbers because platforms differ by orders of magnitude in cycle time. Post-selection can improve a reported fidelity at the cost of throughput, as the magic-state result with 75% retention illustrates [40].

Milestones for large-scale fault tolerance. Verified milestones to date are below-threshold memories, real-time decoding at modest distance, logical magic-state distillation at small distance and integrated logical processors on atom arrays [24], [26], [42]. Open milestones include logical error rates near the 10^{-6} to 10^{-12} per operation range needed by long algorithms, large-scale non-Clifford throughput, and sustained operation with real-time decoding. Resource estimates for cryptographically relevant tasks depend strongly on assumed physical error, cycle time and overhead [33].

Limitations. The review rests on verified primary sources and leaves out 2026 reports that could not be verified. Subscription indexes were not searched, and some numerical values were transcribed from article text without checking the published supplements. The simulations use a simplified uniform noise model with no leakage or correlated noise.

14. CONCLUSION AND ROADMAP

Four findings stand out. First, physical fidelity, logical stability and system-level fault tolerance are distinct properties, and the first does not imply the others. Second, exponential suppression of logical errors with distance has been demonstrated below threshold, with a suppression factor of 2.14 ± 0.02 and a memory 2.4 ± 0.3 times beyond the best physical qubit [24]. Third, correlated errors, leakage, decoder latency and non-Clifford cost are the engineering limits that determine whether larger codes keep paying off. Fourth, a simple simulation shows that noise-informed decoding is worth a factor of 1.5 to 2.0 and that scalar calibration drift alone is benign, which points adaptive-QEC research toward structured and correlated drift.

Near-term experimental priorities: report logical metrics in the standard of P7; reduce correlated bursts and leakage; demonstrate real-time decoding at larger distance; and measure Λ at several operating points on each platform. *Medium-term architectural objectives:* logical gates below the memory error rate with transversal or lattice-surgery operations; demonstrations of qLDPC memories with realistic connectivity; and integrated decoders in the control stack. *Long-term requirements:* logical operation rates and error levels sufficient for long algorithms, high-throughput magic-state production, manufacturable yields, and cooling and control budgets compatible with large arrays. No commercial timeline is asserted, because the primary literature reviewed here does not support one.

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