

QUANTUM RESILIENCE: CANADIAN INNOVATIONS IN QUANTUM ERROR CORRECTION AND QUANTUM ERROR MITIGATION

SUMMARY: We review how quantum error correction and mitigation combat noise in quantum processes, highlighting Canadian contributions within the field's historical evolution.



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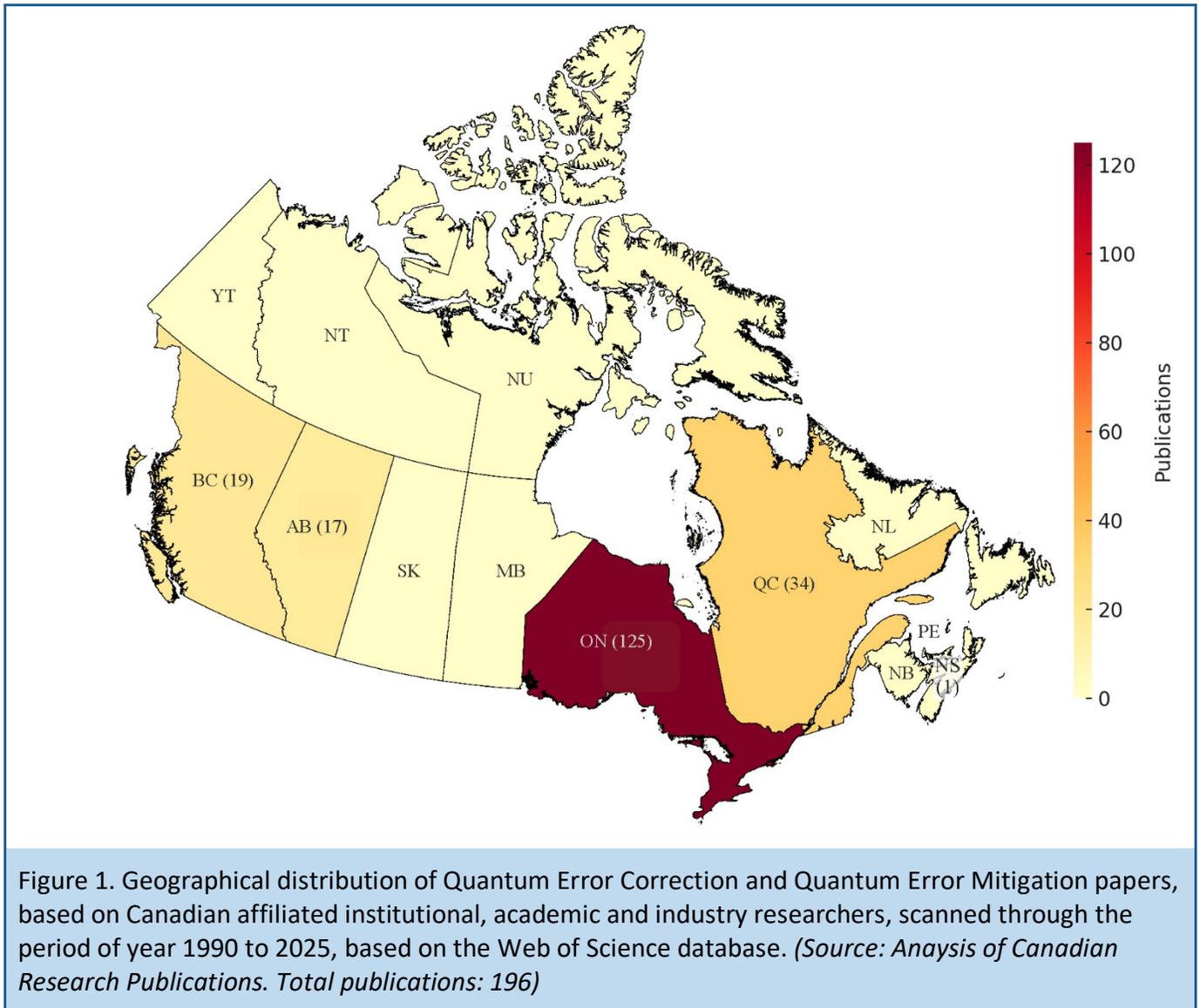
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Quantum computers promise to solve problems that are intractable even for the fastest supercomputers, from designing new materials to cracking complex optimization problems. Researchers across the globe are tirelessly developing quantum solutions to tackle complex problems, and Canada is at the forefront of these efforts. Notably, Canada is home to both the first quantum hardware company (D-Wave) and the first quantum software company (1QBit) in the world. Xanadu is another leading Canadian photonic quantum computing company driving innovation in both quantum hardware and software development. And, of course, there are so many other companies in Canada and worldwide that we do not have enough space to list them all here. Interested readers can refer to [Canadian Quantum Directory](#) and the University of Waterloo's [website](#) which are two excellent resources that offer an extensive list of many (though not all) startups and companies working on quantum technologies in Canada. Yet, despite these tremendous concerted efforts, significant challenges still stand in the way of deploying quantum computers for real-world applications.

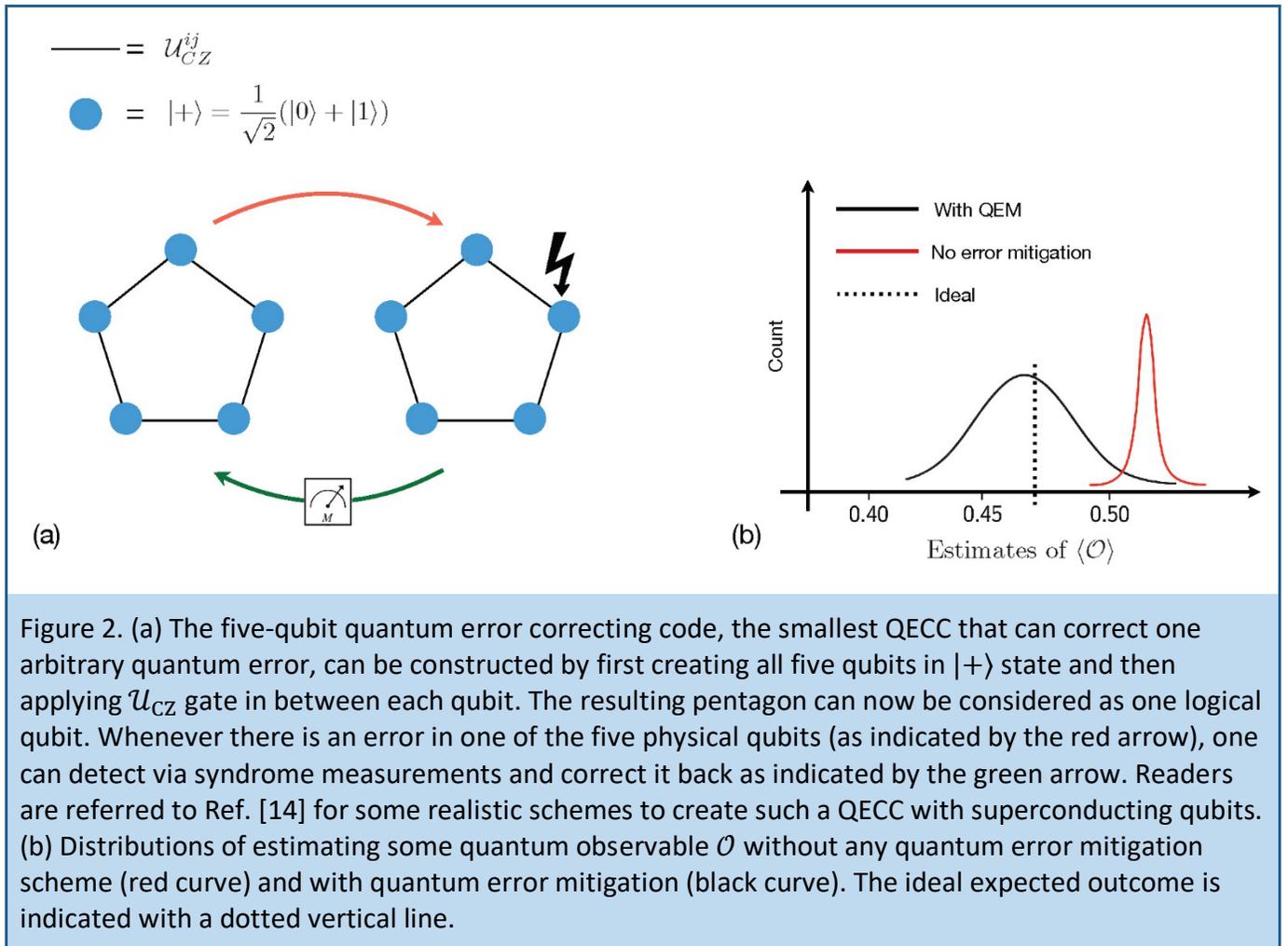
One such challenge is the extreme fragility of quantum bits (qubits). The slightest interaction with the environment or tiny imperfections in hardware can introduce errors that spoil a calculation, complicating both information storage and the scaling of quantum processing units. Even cosmic rays can deter the fate of qubits [1]! Overcoming this "noise" is essential to unlock useful quantum computing [2]. Researchers worldwide, including many in Canada, are developing two complementary strategies to tackle errors in quantum information processing. One approach is quantum error

correction (QEC): encoding information in clever ways so that errors can be detected and fixed on the fly [3,4]. The other is quantum error mitigation (QEM): finding ways to reduce or cancel errors in today’s small to intermediate-scale quantum devices without the full overhead of error correction [5]. This article briefly reviews these strategies and highlights the pivotal contributions of Canadian institutions and researchers, from pioneering theoretical codes to cutting-edge experiments and collaborations (see geographical distribution in Fig. 1).



BRIEF HISTORY OF QUANTUM ERROR CORRECTION

In 1996, Laflamme, *et al.* unveiled the five-qubit “perfect” code, the smallest possible scheme that corrects any single-qubit error [6,7] (see Fig. 2(a)). Their work produced the Knill–Laflamme conditions [8], standard criteria for deciding whether a set of states forms a valid quantum code.



Two years later, Laflamme, nuclear magnetic resonance pioneer David Cory, and collaborators delivered the first laboratory proof-of-principle demonstration of QEC, encoding information into the nuclear spins of a liquid molecule and successfully reversing an induced error [9]. Daniel Gottesman, who was affiliated with the Perimeter Institute, formalized stabilizer codes [10] and co-invented the Gottesman–Kitaev–Preskill (GKP) code for continuous-variable quantum systems [11]. This was one of the significant developments in this field and is now the main driving force behind many of the initiatives in qumode quantum information processing [12]. David Poulin (originally from Sherbrooke) developed efficient decoding algorithms and showed, via threshold theorems, that if each physical qubit’s error drops below $\sim 1\%$, scaling up will actually make logical errors rarer [13]. With the development of the theory of quantum error correction codes and the stabilizer formalism, Canadian and Canada-affiliated researchers played a pivotal role in advancing this field during the first decade of the 21st century.

This synergy between elegant theoretical insights and rigorous experimental work has catalyzed a global push toward realizing surface-code architectures—two-dimensional lattices in which local parity checks suppress the spread of error “ripples.” In 2023, Google demonstrated this principle at scale,

constructing a distance-5 surface code from 49 superconducting qubits. Crucially, the resulting logical error rate outperformed that of a smaller code, offering the first empirical confirmation of long-standing predictions about surface-code behavior [2].

BRIDGING QUBITS AND CODES: ADVANCES IN QUANTUM ERROR CORRECTION AND DETECTION

Building on its early foundational breakthroughs, Canada has quickly emerged as a global center for innovation in quantum error correction. Across industry, academia, and government laboratories, teams are advancing both the theoretical design of new codes and the engineering of hardware capable of supporting them. A common thread uniting these efforts is the pursuit of dramatically lower resource overheads compared to conventional QEC approaches such as the surface code—without compromising, and in some cases improving, error-suppression performance. Canadian researchers are contributing everything from novel error-correcting codes and advanced software toolchains to experimental milestones that bring fault-tolerant hardware closer to reality. Below is a curated, though not exhaustive, selection of these developments:

TOWARDS FAULT-TOLERANT QC

Xanadu has focused on bosonic encoding strategies, notably using GKP photonic qubits, to simplify quantum error correction requirements. In recent work, they demonstrated how universal quantum error correction could be implemented with significantly reduced qubit overhead using linear optical operations [15]. Supported by government investment, Xanadu is actively working toward a fully fault-tolerant photonic quantum computing platform, highlighting the strong integration of theoretical and hardware efforts within Canada.

ADVANCEMENTS IN QUANTUM LOW-DENSITY PARITY-CHECK CODES

One notable recent advancement from the startup Photonic Inc. in Vancouver, which introduced a new family of quantum low-density parity-check (QLDPC) codes called Subsystem Hypergraph Product Simplex codes (SHYPS) [16]. These codes can significantly reduce the number of physical qubits required for fault-tolerant quantum computing compared to conventional codes such as the surface code. Photonic Inc. further complemented their theoretical work with a specialized hardware architecture optimized for these highly connected QLDPC codes, leveraging photonic technology for efficient entanglement distribution. Such codes are optimized for use with Photonic Inc.'s hybrid photonic spin-qubit chips. In fact, local and global connectivity of physical qubits define the resulting quantum codes [17].

BOSONIC CODES ON SUPERCONDUCTING HARDWARE

In superconducting circuits, Sherbrooke-based startup Nord Quantique has made remarkable strides by experimentally demonstrating a hardware-efficient quantum error correction approach using (beyond GKP) bosonic grid states. Their pioneering experiments have shown that this method can actively extend qubit coherence times without excessive redundancy, an essential step towards

scalable quantum computing [18,19]. These developments were strongly supported by collaborations within the Sherbrooke quantum ecosystem, including the Institut Quantique and IBM Quantum Hub.

SURFACE CODES

Researchers at the University of Waterloo's Institute for Quantum Computing (IQC) and the Perimeter Institute have introduced groundbreaking QEC codes like the three-dimensional subsystem toric code. This code notably allows single-shot quantum error correction, significantly simplifying the correction process and reducing the overhead needed for practical fault-tolerant quantum computing [20]. An experimental realization of distance-three surface code using 17 physical qubits can also be found in [21].

ERROR DETECTION FOR EARLY-TERM FAULT TOLERANCE

Researchers from the BEIT group have proposed a resource-efficient framework for quantum error detection (QED) tailored to near-term quantum devices [22]. Through simulations of Grover's algorithm under a circuit-level noise model, they demonstrate that optimizing syndrome measurement schedules can enhance algorithm success probabilities. Additionally, they introduce a data-driven method to predict optimal compilation parameters based on circuit and noise characteristics. This work provides actionable guidelines for implementing QED in early-term quantum experiments and underscores its potential as a pragmatic error mitigation strategy for shallow quantum algorithms.

NEUTRAL DECODERS FOR TOPOLOGICAL CODES

Researchers at the University of Waterloo and the Perimeter Institute have pioneered the use of machine learning for quantum error correction by developing a neural network-based decoder. It was demonstrated that a restricted Boltzmann machine could efficiently decode syndrome data from topological quantum codes without requiring explicit algorithmic construction, adapting flexibly to the error distributions encountered. This method has opened a significant new avenue for scalable, adaptive decoding algorithms [23].

FLAG FAULT-TOLERANT ERROR CORRECTION

A new fault-tolerant error correction method applicable to arbitrary-distance quantum codes through the innovative use of flag qubits was introduced. By strategically employing flag qubits to signal problematic syndrome measurements, their approach effectively manages high-weight errors while significantly reducing resource overhead compared to traditional fault-tolerant ancilla techniques [24].

Collectively, these initiatives, ranging from innovative new codes and sophisticated decoding algorithms to cutting-edge hardware implementations, represent a comprehensive and cohesive approach to quantum error correction on Canadian soil. By closely aligning theoretical breakthroughs with practical experimental demonstrations, Canada is playing a crucial role in paving the way for fault-tolerant quantum computing.

FROM CODES TO QUICK FIXES: CANADIAN LEADERSHIP IN QUANTUM ERROR MITIGATION

Full quantum error correction demands thousands of physical qubits per logical qubit, a resource requirement beyond near-term capabilities. This limitation has led to *quantum error mitigation*, a technique designed to extract greater accuracy from noisy quantum devices with minimal additional resources (see Fig. 2(b)). Canadian research teams have played a key role in advancing several prominent error mitigation methods:

ZERO-NOISE EXTRAPOLATION (ZNE)

ZNE is a popular method that consists of running the same quantum circuit at different noise levels (using techniques such as stretching gate durations) and mathematically extrapolating to the zero-noise limit. Canadian researchers have been instrumental in developing and improving many error mitigation protocols based on ZNE. Digital ZNE provides a practical framework where unitary folding and parameterized noise scaling can be applied using only gate-level access common to most quantum instruction sets [25]. Another scheme, called variable-noise Clifford data regression (vnCDR), developed with the participation of the University of Waterloo, combines ZNE with Clifford data regression to mitigate errors, was shown to be more powerful than the individual methods of ZNE and CDR [26]. QEM protocols for quantum annealing using ZNE were introduced by a team comprising of researchers from D-Wave, the University of British Columbia, and Simon-Fraser University [27]. A recent study comprising of researchers from the University of Waterloo and the Vector Institute has also shown that ZNE is not the best option for mitigating errors in quantum sensing [28].

RANDOMIZED COMPILING (RC)

Conceived by researchers at the University of Waterloo, RC inserts randomly chosen gate twirls that convert coherent, bias-inducing errors into easier-to-model stochastic noise [29]. Their spin-off, Quantum Benchmark—later acquired by Keysight—made RC diagnostics widely available [30-32].

SYMMETRY-BASED POST-SELECTION AND SUPERPOSED MITIGATION

When a physical system obeys a conservation law—such as fixed particle number—any measurement outcomes that violate that constraint can simply be rejected. Extending this principle, a research team from Waterloo introduced a technique in which multiple noisy circuit executions are combined so that their quantum interference cancels specific error contributions. This idea is now advancing from theory to experiment, with early investigations exploring its practical viability [33].

QUASI-PROBABILISTIC METHODS

Error mitigation strategies such as Probabilistic Error Cancellation (PEC) based on quasi-probabilistic methods are among methods that are widely utilized and promise an unbiased result, albeit at the cost of an exponential runtime. Canadian researchers have developed quasi-probabilistic EM techniques that outperform PEC. *Pauli Error Cancellation* [34] was introduced by researchers from Keysight technologies and the University of Waterloo, and it was shown to mitigate non-local and gate-

dependent noise. A constant runtime quasi-probabilistic EM protocol, called *Error Mitigation by Restricted Evolution (EMRE)*, was recently introduced which works by restricting the evolution of the input state [35]. This constant runtime comes at the cost of a small finite bias. Another scheme called Hybrid EMRE or HEMRE was also proposed by combining EMRE with PEC. It was shown that when using HEMRE, a user can fix the maximum tolerable bias and achieve the mitigated result with a runtime not greater than that of PEC. The EMRE framework was subsequently extended to the design of a resource-efficient mitigation protocol based on noise amplification and robust extrapolation to the zero noise limit and is termed as the *Physics-Inspired Extrapolation (PIE)* method [36]. Unlike typical ZNE methods, PIE analytically justifies the extrapolation function and assigns operational meaning to the fitting parameters. The method demonstrates good accuracy and robustness in simulating quantum dynamics up to 84 qubits.

NEURAL ERROR MITIGATION

A team of researchers from 1QBit, the University of Waterloo, the Vector Institute, and the Perimeter Institute for Theoretical Physics introduced a machine learning-based framework for error mitigation in quantum simulations. By leveraging neural networks, the method achieves improved accuracy in quantum chemistry and lattice gauge theory simulations on noisy quantum devices [37]. In another work, researchers introduce a neural model that achieves quantum error mitigation without any prior knowledge of the noise and without training on noise-free data [38].

OTHER EM STRATEGIES

Other error mitigation schemes and analysis have been introduced by a team of researchers comprising of researchers from Canada. A benchmarking study to understand the application of quantum error mitigation in quantum chemistry was studied in [39]. Another work [40] introduced an error detection scheme by using the Bravyi-Kitaev superfast encoding and showed that it can be used to mitigate errors in quantum chemistry simulations. Schemes to reduce the logical error rate of Clifford circuits without the exponential sampling overhead of error mitigation were also developed with the involvement of Canadian researchers [41]. Researchers from Canadian institutions have also been involved in correctly characterizing state preparation and measurement (SPAM) errors which helped both in mitigating such errors and in designing reliable quantum processing units [42]. Lastly, *Mitiq*---a Python package, widely used in the quantum community to implement and deploy error mitigation protocols---was also developed in collaboration with Canadian researchers [43].

Thanks to these techniques, small quantum processors have already produced chemically and physically meaningful results, despite raw error rates that would otherwise swamp useful signals.

REMARKS AND WELL-WISHES

Since the late 1990s, quantum error correction has been a foundational pillar in the pursuit of building reliable quantum computers. While significant strides continue toward the ultimate goal of fault-tolerant quantum computing involving millions of physical qubits, quantum error mitigation has emerged as an invaluable complementary tool, enabling researchers to obtain trustworthy results from

today's noisy quantum hardware. In this brief review, we have highlighted notable contributions from Canadian and Canada-affiliated researchers in academia and industry in both quantum error correction and mitigation. The selected references presented here represent only a curated subset of Canada's extensive contributions to the field -- see Fig. 1.

Looking ahead, Canadian researchers are poised to play a pivotal role in achieving two key milestones. The first is the long-term goal of experimentally demonstrating quantum error correction beyond the fault-tolerance threshold *at useful scales*. While beyond-threshold computation has now been performed at small scales [2], we estimate that useful simulations in chemistry, for example, will require thousands of logical qubits to demonstrate practical usefulness. The second is a more immediate milestone in the noisy intermediate-scale quantum and early fault-tolerant quantum computing era, involving the integration of quantum error mitigation techniques with error-correcting codes on existing hardware to enable utility-scale quantum computations [44].

We find ourselves in a remarkable era, achieving a level of quantum system control and manipulation unimaginable to the pioneers of quantum mechanics, including the ability to remotely operate quantum systems from across the globe. While substantial work remains to elevate noisy quantum devices to practical, industry-relevant applications, the significant progress already made provides ample reason for optimism. To continue to be a leader in the future quantum technologies, Canada needs greater resources and top global talent committed to long-term breakthroughs. As we celebrate the 2025 International Year of Quantum Science and Technology (IYQ), it is fitting to reflect on these achievements and recognize the promising journey ahead.

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DATA AVAILABILITY

The data used to generate the Canada heatmap (Fig. 1) is available upon request.

REFERENCES

1. J. M. Martinis, Saving superconducting quantum processors from decay and correlated errors generated by gamma and cosmic rays, *npj Quantum Inf.* **7**, 1 (2021).
2. Google Quantum AI, Suppressing quantum errors by scaling a surface code logical qubit, *Nature* **614**, 676 (2023).
3. T. A. Brun, *Quantum Error Correction* (Cambridge University Press, Cambridge UK, 2013) 10.1017/CBO9781139034807.
4. P. Kaye, R. Laflamme, and M. Mosca, *An Introduction to Quantum Computing* (Oxford University Press, Oxford UK, 2007).
5. Z. Cai, *et al.*, Quantum error mitigation, *Rev. Mod. Phys.* **95**, 045005 (2023).
6. R. Laflamme, C. Miquel, J. P. Paz, and W. H. Zurek, Perfect quantum error correcting code, *Phys. Rev. Lett.* **77**, 198 (1996).

7. C. H. Bennett, D. P. DiVincenzo, J. A. Smolin, and W. K. Wootters, Mixed-state entanglement and quantum error correction, *Phys. Rev. A* **54**, 3824 (1996).
8. E. Knill and R. Laflamme, A theory of quantum error correcting codes, *Phys. Rev. Lett.* **84**, 2525 (1996).
9. D. G. Cory, *et al.*, Experimental quantum error correction, *Phys. Rev. Lett.* **81**, 2152 (1998).
10. D. E. Gottesman, Ph.D. thesis, Caltech, 1997. Stabilizer codes and quantum error correction.
11. D. E. Gottesman, A. Kitaev, and J. Preskill, Encoding a qubit in an oscillator, *Phys. Rev. A* **64**, 012310 (2001).
12. S. Konno, *et al.*, Logical states for fault-tolerant quantum computation with propagating light, *Science* **383**, 289 (2024).
13. D. Poulin, Optimal and efficient decoding of concatenated quantum block codes, *Phys. Rev. A* **74**, 052333 (2006).
14. T. H. Kyaw, D. A. Herrera-Martí, E. Solano, G. Romero, and L.-C. Kwek, Creation of quantum error correcting codes in the ultrastrong coupling regime, *Phys. Rev. B* **91**, 064503 (2015).
15. B. W. Walshe, *et al.*, Linear-optical quantum computation with arbitrary error-correcting codes, *Phys. Rev. Lett.* **134**, 100602 (2025).
16. A. J. Malcolm, *et al.*, Computing efficiently in qLDPC codes, arXiv:2502.07150 (2025).
17. N. Baspin and A. Krishna, Connectivity constrains quantum codes, *Quantum* **6**, 711 (2022).
18. M.-A. Lemonde, *et al.*, Hardware-efficient fault tolerant quantum computing with bosonic grid states in superconducting circuits, arXiv:2409.05813 (2024).
19. D. Lachance-Quirion, *et al.*, Autonomous quantum error correction of Gottesman–Kitaev–Preskill states, arXiv.2310.11400 (2023).
20. A. Kubica and M. Vasmer, Single-shot quantum error correction with the three-dimensional subsystem toric code, *Nat. Commun.* **13**, 6272 (2022).
21. S. Krinner, *et al.*, Realizing repeated quantum error correction in a distance-three surface code, *Nature* **605**, 669 (2022).
22. T. Ginsberg and V. Patel, Quantum error detection for early term fault-tolerant quantum algorithms, arXiv:2503.10790 (2025).
23. G. Torlai and R. G. Melko, Neural decoder for topological codes, *Phys. Rev. Lett.* **119**, 030501 (2017).
24. C. Chamberland and M. E. Beverland, Flag fault-tolerant error correction with arbitrary distance codes, *Quantum* **2**, 53 (2018).
25. T. Giurgica-Tiron, Y. Hindy, R. LaRose, A. Mari, and W. J. Zeng, Digital zero noise extrapolation for quantum error mitigation, *IEEE International Conference on Quantum Computing and Engineering (QCE)*, 306 (2020).
26. A. Lowe, *et al.*, Unified approach to data-driven quantum error mitigation, *Phys. Rev. Res.* **3**, 033098 (2021).
27. J. Raymond, *et al.*, Quantum error mitigation in quantum annealing, *npj Quantum Inf.* **11**, 1 (2025).
28. A. Ijaz, *et al.*, More buck-per-shot: Why learning trumps mitigation in noisy quantum sensing, *Materials Today Quantum* **6**, 100042 (2025).
29. J. J. Wallman and J. Emerson, Noise tailoring for scalable quantum computation via randomized compiling, *Phys. Rev. A* **94**, 052325 (2016).

30. A. Hashim, *et al.*, Randomized compiling for scalable quantum computing on a noisy superconducting quantum processor, *Phys. Rev. X* **11**, 041039 (2021).
31. A. Winick, *et al.*, Concepts and conditions for error suppression through randomized compiling, *arXiv:2212.07500* (2022).
32. S. J. Beale and J. J. Wallman, Randomized compiling for subsystem measurements, *arXiv:2304.06599* (2023).
33. J. Miguel-Ramiro, *et al.*, Superposed quantum error mitigation, *Phys. Rev. Lett.* **131**, 230601 (2023).
34. S. Ferracin, *et al.*, Efficiently improving the performance of noisy quantum computers, *Quantum* **8**, 1410 (2024).
35. G. Saxena and T. H. Kyaw, Error mitigation by restricted evolution, *arXiv:2409.06636* (2024).
36. P. Díez-Valle, G. Saxena, J. S. Baker, J.-H. Lee, and T. H. Kyaw, Physically motivated extrapolation for quantum error mitigation, *arXiv:2505.07977* (2025).
37. E. R. Bennewitz, F. Hopfmueller, B. Kulchytskyy, J. Carrasquilla, and P. Ronagh, Neural error mitigation of near-term quantum simulations, *Nat. Mach. Intell.* **4**, 618–624 (2022).
38. M. Liao, Y. Zhu, G. Chiribella, and Y. Yang, Noise-agnostic quantum error mitigation with data augmented neural models, *npj Quantum Inf.* **11**, 1 (2025).
39. V. K. Prasad, F. Cheng, U. Fekl, and H.-A. Jacobsen, Applications of noisy quantum computing and quantum error mitigation to “adamantaneland”: A benchmarking study for quantum chemistry, *Phys. Chem. Chem. Phys.* **26**, 4071 (2024).
40. T. Hagge and N. Wiebe, Error mitigation via error detection using generalized superfast encodings, *arXiv:2309.11673* (2023).
41. N. Delfosse and E. Tham, Low-cost noise reduction for Clifford circuits, *arXiv:2407.06583* (2024).
42. J. Lin, J. J. Wallman, I. Hincks, and R. Laflamme, Independent state and measurement characterization for quantum computers, *Phys. Rev. Res.* **3**, 033285 (2021).
43. R. LaRose, *et al.*, *Mitiq*: A software package for error mitigation on noisy quantum computers, *Quantum* **6**, 774 (2022).
44. Y. Suzuki, S. Endo, K. Fujii, and Y. Tokunaga, Quantum error mitigation as a universal error reduction technique: Applications from the NISQ to the fault-tolerant quantum computing eras, *PRX Quantum* **3**, 010345 (2022).