■論文読み

[Suppressing quantum errors by scaling a surface code logical qubit]()

参考文献の逆引き.

- [1] Shor, P. W. Scheme for reducing decoherence in quantum computer memory. Phys. Rev. A 52, R2493 (1995).
  - Quantum error correction
- [2] Gottesman, D. Stabilizer Codes and Quantum Error Correction. PhD thesis, California Institute of Technology (1997).
  - Quantum error correction
- [3] Feynman, R. P. Simulating physics with computers. Int. J. Theor. Phys. 21, 467-488 (1982).
  - Since Feynman ’ s proposal to compute using quantum mechanic
- [4] Shor, P. W. Polynomial-time algorithms for prime factorization and discrete logarithms on a quantum computer. SIAM Rev. 41, 303-332 (1999).
  - many potential applications have emerged, including factoring
- [5] Farhi, E. et al. A quantum adiabatic evolution algorithm applied to random instances of an NP-complete problem. Science 292, 472-475 (2001).
  - many potential applications have emerged, including ..., optimization
- [6] Biamonte, J. et al. Quantum machine learning. Nature 549, 195-202 (2017).
  - many potential applications have emerged, including ..., machine learning
- [7] Lloyd, S. Universal quantum simulators. Science 273, 1073-1078 (1996).
  - many potential applications have emerged, including ..., quantum simulation
- [8] Aspuru-Guzik, A., Dutoi, A. D., Love, P. J. & Head-Gordon, M. Simulated quantum computation of molecular energies. Science 309, 1704-1707 (2005).
  - many potential applications have emerged, including ..., quantum chemistry
- [9] Reiher, M., Wiebe, N., Svore, K. M., Wecker, D. & Troyer, M. Elucidating reaction mechanisms on quantum computers. Proc. Natl Acad. Sci. USA 114, 7555-7560 (2017).
  - These applications often require billions of quantum operations
- [10] Gidney, C. & Ekera, M. How to factor 2048 bit RSA integers in 8 hours using 20 million noisy qubits. Quantum 5, 433 (2021).
  - These applications often require billions of quantum operations
- [11] Kivlichan, I. D. et al. Improved fault-tolerant quantum simulation of condensed-phase correlated electrons via trotterization. Quantum 4, 296 (2020).
  - These applications often require billions of quantum operations
- [12] Ballance, C., Harty, T., Linke, N., Sepiol, M. & Lucas, D. High-fidelity quantum logic gates using trapped-ion hyperfine qubits. Phys. Rev. Lett. 117, 060504 (2016).
  - state-of-the-art quantum processors typically have error rates around 10 ー 3 per gate
- [13] Huang, W. et al. Fidelity benchmarks for two-qubit gates in silicon. Nature 569, 532-536 (2019).
  - state-of-the-art quantum processors typically have error rates around 10 ー 3 per gate
- [14] Rol, M. et al. Fast, high-fidelity conditional-phase gate exploiting leakage interference in weakly anharmonic superconducting qubits. Phys. Rev. Lett. 123, 120502 (2019).
  - state-of-the-art quantum processors typically have error rates around 10 ー 3 per gate
- [15] Jurcevic, P. et al. Demonstration of quantum volume 64 on a superconducting quantum computing system. Quantum Sci. Technol. 6, 025020 (2021).
  - state-of-the-art quantum processors typically have error rates around 10 ー 3 per gate
- [16] Foxen, B. et al. Demonstrating a continuous set of two-qubit gates for near-term quantum algorithms. Phys. Rev. Lett. 125, 120504 (2020).
  - state-of-the-art quantum processors typically have error rates around 10 ー 3 per gate
- [17] Wu, Y. et al. Strong quantum computational advantage using a superconducting quantum processor. Phys. Rev. Lett. 127, 180501 (2021).
  - state-of-the-art quantum processors typically have error rates around 10 ー 3 per gate
- [18] Knill, E., Laflamme, R. & Zurek, W. H. Resilient quantum computation. Science 279, 342-345 (1998).

  - quantum error correction can exponentially suppress the operational error rates in a quantum processor, at the expense of temporal and qubit overhead
- [19] Aharonov, D. & Ben-Or, M. Fault-tolerant quantum computation with constant error rate. SIAM J. Comput. 38, 1207-1282 (2008).
  - quantum error correction can exponentially suppress the operational error rates in a quantum processor, at the expense of temporal and qubit overhead
- [20] Egan, L. et al. Fault-tolerant control of an error-corrected qubit. Nature 598, 281-286 (2021).
  - quantum error correction on codes able to correct a single error, including the distance-3 Bacon-Shor
- [21] Ryan-Anderson, C. et al. Realization of real-time fault-tolerant quantum error correction. Phys. Rev. X 11, 041058 (2021).
  - quantum error correction on codes able to correct a single error, including ..., colour
- [22] Abobeih, M. et al. Fault-tolerant operation of a logical qubit in a diamond quantum processor. Nature 606, 884-889 (2022).
  - quantum error correction on codes able to correct a single error, including ..., five-qubit
- [23] Sundaresan, N. et al. Matching and maximum likelihood decoding of a multi-round subsystem quantum error correction experiment. Preprint at https://arXiv.org/abs/2203.07205 (2022).
  - quantum error correction on codes able to correct a single error, including ..., heavy-hexagon
- [24] Krinner, S. et al. Realizing repeated quantum error correction in a distance-three surface code. Nature 605, 669-674 (2022).
  - quantum error correction on codes able to correct a single error, including ..., surface
- [25] Zhao, Y. et al. Realization of an error-correcting surface code with superconducting qubits. Phys. Rev. Lett. 129, 030501 (2022).
  - quantum error correction on codes able to correct a single error, including ..., as well as continuous variable codes
- [26] Ofek, N. et al. Extending the lifetime of a quantum bit with error correction in superconducting circuits. Nature 536, 441-445 (2016).
  - quantum error correction on codes able to correct a single error, including ..., as well as continuous variable codes
- [27] Fl hmann, C. et al. Encoding a qubit in a trapped-ion mechanical oscillator. Nature 566, 513 -517 (2019).
  - quantum error correction on codes able to correct a single error, including ..., as well as continuous variable codes
- [28] Campagne-Ibarcq, P. et al. Quantum error correction of a qubit encoded in grid states of an oscillator. Nature 584, 368-372 (2020).
  - quantum error correction on codes able to correct a single error, including ..., as well as continuous variable codes
- [29] Grimm, A. et al. Stabilization and operation of a Kerr-cat qubit. Nature 584, 205-209 (2020).
  - quantum error correction on codes able to correct a single error, including ..., as well as continuous variable codes
- [30] Kitaev, A. Y. Fault-tolerant quantum computation by anyons. Ann. Phys. 303, 2-30 (2003).
  - Surface codes
- [31] Dennis, E., Kitaev, A., Landahl, A. & Preskill, J. Topological quantum memory. J. Math. Phys. 43, 4452-4505 (2002).
  - Surface codes
  - The updated error hypergraph is then decomposed into a pair of disjoint error graphs, one each for X and Z errors
  - the higher effective threshold caused by the confinement of errors to thin time slices in few-cycle experiments
- [32] Raussendorf, R. & Harrington, J. Fault-tolerant quantum computation with high threshold in two dimensions. Phys. Rev. Lett. 98, 190504 (2007).
  - Surface codes
- [33] Fowler, A. G., Mariantoni, M., Martinis, J. M. & Cleland, A. N. Surface codes: towards practical large-scale quantum computation. Phys. Rev. A 86, 032324 (2012).
  - Surface codes
  - the logical performance of a distance-5 code should improve faster than that of a distance-3 code as physical error rates decrease
- [34] Satzinger, K. et al. Realizing topologically ordered states on a quantum processor. Science 374 , 1237-1241 (2021).

- Surface codes

- [35] Horsman, C., Fowler, A. G., Devitt, S. & Meter, R. V. Surface code quantum computing by lattice surgery. New J. Phys. 14, 123011 (2012).
    - Most surface code logical gates can be implemented by maintaining logical memory and executing different sequences of measurements on the code boundary
- [36] Fowler, A. G. & Gidney, C. Low overhead quantum computation using lattice surgery. Preprint at https://arXiv.org/abs/1808.06709 (2018).
    - Most surface code logical gates can be implemented by maintaining logical memory and executing different sequences of measurements on the code boundary
- [37] Litinski, D. A game of surface codes: large-scale quantum computing with lattice surgery. Quantum 3, 128 (2019).
    - Most surface code logical gates can be implemented by maintaining logical memory and executing different sequences of measurements on the code boundary
- [38] Arute, F. et al. Quantum supremacy using a programmable superconducting processor. Nature 574, 505-510 (2019).
    - Sycamore devic
    - The circuits were benchmarked in simultaneous operation using random circuit techniques, on the 49 qubits used in distance-5 and the 4 CZ layers from the stabilizer circuit
- [39] Koch, J. et al. Charge-insensitive qubit design derived from the Cooper pair box. Phys. Rev. A 76, 042319 (2007).
    - transmon qubits
- [40] Neill, C. A Path towards Quantum Supremacy with Superconducting Qubits. PhD thesis, Univ. California Santa Barbara (2017).
    - tunable couplers
- [41] Yan, F. et al. Tunable coupling scheme for implementing high-fidelity two-qubit gates. Phys. Rev. Appl. 10, 054062 (2018).
    - tunable couplers
- [42] Chen, Z. et al. Exponential suppression of bit or phase errors with cyclic error correction. Nature 595, 383-387 (2021).
    - we implement single-qubit rotations, controlled-Z (CZ) gates, reset and measurement, demonstrating similar or improved simultaneous performance
    - We attribute this rise to data qubits leaking into non-computational excited states and anticipate that the inclusion of leakage-removal techniques on data qubits would help to mitigate this rise
    - we compute an appropriately normalized correlation pij between detection events occurring on any two detectors i and j
    - We use a generalization of pij to determine these probabilities
    - To understand the contributions of individual components to our logical error performance, we follow
    - These events may be identified by spikes in detection event counts
- [43] Kelly, J. et al. Scalable in situ qubit calibration during repetitive error detection. Phys. Rev. A 94, 032321 (2016).
    - Our stabilizer circuits contain a few modifications to the standard gate sequence described above, including phase corrections to correct for unintended qubit frequency shifts and dynamical decoupling gates during qubit idles
- [44] Wen, X.-G. Quantum orders in an exact soluble model. Phys. Rev. Lett. 90, 016803 (2003).
    - We also remove certain Hadamard gates to implement the ZXXZ variant of the surface code
- [45] Bonilla Ataides, J. P., Tuckett, D. K., Bartlett, S. D., Flammia, S. T. & Brown, B. J. The XZZX surface code. Nat. Commun. 12, 2172 (2021).
    - We also remove certain Hadamard gates to implement the ZXXZ variant of the surface code
- [46] Aliferis, P. & Terhal, B. M. Fault-tolerant quantum computation for local leakage faults. Quantum Inf. Comput. 7, 139-156 (2007).
    - We attribute this rise to data qubits leaking into non-computational excited states and anticipate that the inclusion of leakage-removal techniques on data qubits would help to mitigate this rise
- [47] Suchara, M., Cross, A. W. & Gambetta, J. M. Leakage suppression in the toric code. Proc. 2015 IEEE International Symposium on Information Theory (ISIT) 1119-1123 (2015).
    - We attribute this rise to data qubits leaking into non-computational excited states and anticipate that the inclusion of leakage-removal techniques on data qubits would help to mitigate this rise

- Further improvements could come from a more accurate prior, or by incorporating more fine-grained measurement information
- [48] McEwen, M. et al. Removing leakage-induced correlated errors in superconducting quantum error correction. Nat. Commun. 12, 1761 (2021).
  - We attribute this rise to data qubits leaking into non-computational excited states and anticipate that the inclusion of leakage-removal techniques on data qubits would help to mitigate this rise
- [49] Spitz, S. T., Tarasinski, B., Beenakker, C. W. & O ’ Brien, T. E. Adaptive weight estimator for quantum error correction in a time-dependent environment. Adv. Quantum Technol. 1, 1800012 (2018).
  - we compute an appropriately normalized correlation pij between detection events occurring on any two detectors i and j
- [50] Chen, E. H. et al. Calibrated decoders for experimental quantum error correction. Phys. Rev. Lett. 128, 110504 (2022).
  - We use a generalization of pij to determine these probabilities
- [51] Higgott, O., Bohdanowicz, T. C., Kubica, A., Flammia, S. T. & Campbell, E. T. Fragile boundaries of tailored surface codes and improved decoding of circuit-level noise. Preprint at https://arXiv.org/abs/2203.04948 (2022).
  - an efficient combination of belief propagation and minimum-weight perfect matching
  - The belief-matching decoder first runs belief propagation on the error hypergraph to update hyperedge error probabilities based on nearby detection events
  - The two likelihoods are each expressed as a tensor network contraction
- [52] Criger, B. & Ashraf, I. Multi-path summation for decoding 2D topological codes. Quantum 2, 102 (2018).
  - The belief-matching decoder first runs belief propagation on the error hypergraph to update hyperedge error probabilities based on nearby detection events
- [53] Fowler, A. G., Whiteside, A. C. & Hollenberg, L. C. Towards practical classical processing for the surface code. Phys. Rev. Lett. 108, 180501 (2012).
  - These graphs are decoded efficiently using minimum-weight perfect matching
- [54] Bravyi, S., Suchara, M. & Vargo, A. Efficient algorithms for maximum likelihood decoding in the surface code. Phys. Rev. A 90, 032326 (2014).
  - The two likelihoods are each expressed as a tensor network contraction
- [55] Chubb, C. T. & Flammia, S. T. Statistical mechanical models for quantum codes with correlated noise. Ann. Inst. Henri Poincar D 8, 269-321 (2021).
  - The two likelihoods are each expressed as a tensor network contraction
- [56] Pattison, C. A., Beverland, M. E., da Silva, M. P. & Delfosse, N. Improved quantum error correction using soft information. Preprint at https://arXiv.org/abs/2107.13589 (2021).
  - Further improvements could come from a more accurate prior, or by incorporating more fine-grained measurement information
- [57] McEwen, M. et al. Resolving catastrophic error bursts from cosmic rays in large arrays of superconducting qubits. Nat. Phys. 18, 107-111 (2022).
  - We attribute many of these logical errors in the higher-distance codes to a high-energy impact, which can temporarily impart widespread correlated errors to the system
- [58] Stephens, A. M. Fault-tolerant thresholds for quantum error correction with the surface code. Phys. Rev. A 89, 022321 (2014).
  - This threshold behaviour can be subtle
- [59] Emerson, J., Alicki, R. & yczkowski, K. Scalable noise estimation with random unitary operators. J. Opt. B 7, S347 (2005).
  - The circuits were benchmarked in simultaneous operation using random circuit techniques, on the 49 qubits used in distance-5 and the 4 CZ layers from the stabilizer circuit