# QuantumACES.jl: design noise characterisation experiments for quantum computers

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Summary

QuantumACES.jl is a Julia (Bezanson et al., 2017) package for designing, simulating, and performing scalable Pauli noise characterisation experiments for quantum computers. Noise in quantum devices is the key obstacle to large-scale quantum computation. Consequently, quantum computers will require fault-tolerant architectures that replace physical qubits and operations with redundantly-encoded logical equivalents, which entails regularly measuring the parity checks of quantum error correcting codes (Aliferis, 2013; Gottesman, 2010; Shor, 1996). Detailed characterisation of the noise in prototype quantum computers can demonstrate correct device performance and identify poorly functioning qubits and operations. It can also enable noise-aware decoding of quantum error correcting codes by calibrating the decoder prior on which physical configurations of errors are more and less likely (Chen et al., 2022; Higgott et al., 2023; Sundaresan et al., 2023; Tiurev et al., 2023; Tuckett et al., 2020).

QuantumACES.jl uses the framework of averaged circuit eigenvalue sampling (ACES) (Flammia, 2022) to design experiments that characterise Pauli noise in stabiliser circuits, following the theory and protocol outlined in (Hockings et al., 2024). Stabiliser circuits are a restricted class of quantum circuits that admit efficient classical simulation (Aaronson & Gottesman, 2004; Gottesman, 1997), including with Pauli noise. Quantum noise is tailored into Pauli noise by techniques such as Pauli frame randomisation (Knill, 2005), randomised compiling (Wallman & Emerson, 2016), or quantum error correction itself (Beale et al., 2018), and the theory of quantum error correction and fault tolerance generally relies on modelling noise as Pauli noise (Terhal, 2015).

QuantumACES.jl contains routines for designing optimised designs for noise characterisation experiments, given an arbitrary stabiliser circuit and Pauli noise model, using functions that precisely predict the performance of these experimental designs. It has built-in circuits and noise models and also allows users to define their own. These noise characterisation experiments are simulated with the open-source Python package Stim (Gidney, 2021), a fast simulator for stabiliser circuits with Pauli noise.

In a typical fault-tolerant quantum computing architecture, the bulk of the physical qubits and gate operations are dedicated to performing the syndrome extraction circuits that measure the parity checks of quantum error correcting codes. These syndrome extraction circuits, which are stabiliser circuits, are therefore the key target for noise characterisation experiments. QuantumACES.jl is tailored to characterising Pauli noise in syndrome extraction circuits, particularly for topological quantum error correcting codes such as the surface code (Bravyi & Kitaev, 1998; Dennis et al., 2002; Fowler et al., 2012; Kitaev, 2003). It leverages the fact that the simple structures of the syndrome extraction circuits of topological quantum codes remain similar across code sizes, enabling the optimised experimental design for the syndrome extraction circuit of a small-scale code to be transferred to syndrome extraction circuits of larger-scale versions of the same code. QuantumACES.jl is capable of calculating and precisely

⁴⁴ fitting the performance scaling of these experimental designs as a function of the code size,
⁴⁵ enabling performance predictions at scales where explicit calculation becomes intractable.

⁴⁶ Moreover, QuantumACES.jl makes it easy to simulate memory experiments for its syndrome
⁴⁷ extraction circuits with Stim, and supports decoding these experiments with the open-source
⁴⁸ Python packages PyMatching (Higgott, 2022; Higgott & Gidney, 2025) and BeliefMatch-
⁴⁹ ing (Higgott et al., 2023). It also contains an interface with the open-source Python package
⁵⁰ Qiskit (Javadi-Abhari et al., 2024), enabling the export of experimental designs and circuits to
⁵¹ Qiskit circuits which can then be implemented on quantum devices to characterise noise in
⁵² real quantum hardware.

Statement of need

⁵⁴ The utility of detailed and scalable Pauli noise characterisation methods grows as experimental
⁵⁵ progress pushes quantum devices towards scales of hundreds of qubits and initial demon-
⁵⁶ strations of fault tolerance. QuantumACES.jl enables noise characterisation in this context,
⁵⁷ as demonstrated in (Hockings et al., 2024). While there are several software packages for
⁵⁸ benchmarking and noise characterisation, there are no open-source packages capable of detailed
⁵⁹ and scalable Pauli noise characterisation of quantum devices. Forest-Benchmarking (Combes et
⁶⁰ al., 2019), is an open-source Python package containing many routines for quantum character-
⁶¹ isation, verification, and validation (QCVV), but its detailed noise characterisation techniques
⁶² are not scalable. Gate set tomography (GST) (Nielsen et al., 2021), is a principled and
⁶³ extremely detailed noise characterisation protocol implemented by the open-source Python
⁶⁴ package pyGSTi (Nielsen et al., 2022), but it is limited to characterising extremely small
⁶⁵ numbers of qubits. Cycle error reconstruction (CER) (Carignan-Dugas et al., 2023) is the noise
⁶⁶ characterisation protocol whose capabilities are most similar to ACES, but it is implemented
⁶⁷ by the commercial software True-Q (Beale et al., 2020).

Acknowledgements

References

⁷³ Aaronson, S., & Gottesman, D. (2004). Improved simulation of stabilizer circuits. *Physical*
⁷⁴ *Review A*, *70*(5), 052328. https://doi.org/10.1103/PhysRevA.70.052328

⁷⁵ Aliferis, P. (2013). Introduction to quantum fault tolerance. In D. A. Lidar & T. A. Brun
⁷⁶ (Eds.), *Quantum Error Correction* (pp. 126–160). Cambridge University Press. https:
⁷⁷ //doi.org/10.1017/CBO9781139034807.007

⁷⁸ Beale, S. J., Boone, K., Carignan-Dugas, A., Chytros, A., Dahlen, D., Dawkins, H., Emerson,
⁷⁹ J., Ferracin, S., Frey, V., Hincks, I., Hufnagel, D., Iyer, P., Jain, A., Kolbush, J., Ospadov,
⁸⁰ E., Pino, J. L., Qassim, H., Saunders, J., Skanes-Norman, J., … Wright, E. (2020). *True-Q*.
⁸¹ Zenodo. https://doi.org/10.5281/zenodo.3945249

⁸² Beale, S. J., Wallman, J. J., Gutiérrez, M., Brown, K. R., & Laflamme, R. (2018). Coherence
⁸³ in quantum error-correcting codes. *Physical Review Letters*, *121*(19), 190501. https:
⁸⁴ //doi.org/10.1103/PhysRevLett.121.190501

⁸⁵ Bezanson, J., Edelman, A., Karpinski, S., & Shah, V. B. (2017). Julia: A fresh approach to
⁸⁶ numerical computing. *SIAM Review*, *59*(1), 65–98. https://doi.org/10.1137/141000671

Bravyi, S. B., & Kitaev, A. Y. (1998). Quantum codes on a lattice with boundary. *arXiv Preprint*. https://arxiv.org/abs/quant-ph/9811052

Carignan-Dugas, A., Dahlen, D., Hincks, I., Ospadov, E., Beale, S. J., Ferracin, S., Skanes-Norman, J., Emerson, J., & Wallman, J. J. (2023). The error reconstruction and compiled calibration of quantum computing cycles. *arXiv Preprint*. https://arxiv.org/abs/2303.17714

Chen, E. H., Yoder, T. J., Kim, Y., Sundaresan, N., Srinivasan, S., Li, M., Córcoles, A. D., Cross, A. W., & Takita, M. (2022). Calibrated decoders for experimental quantum error correction. *Physical Review Letters*, *128*(11), 110504. https://doi.org/10.1103/PhysRevLett.128.110504

Combes, J., Gulshen, K. V., Harrigan, M. P., Karalekas, P. J., Silva, M. P. da, Alam, M. S., Brown, A. F., Caldwell, S., Capelluto, L. C., Crooks, G. E., Girshovich, D., Johnson, B. R., Peterson, E. C., Polloreno, A. M., Rubin, N. C., Ryan, C. A., Staley, A. N., Tezak, N. A., & Valery, J. A. (2019). *Forest benchmarking: QCVV using PyQuil*. Zenodo. https://doi.org/10.5281/zenodo.3455848

Dennis, E., Kitaev, A., Landahl, A., & Preskill, J. (2002). Topological quantum memory. *Journal of Mathematical Physics*, *43*(9), 4452–4505. https://doi.org/10.1063/1.1499754

Flammia, S. T. (2022). Averaged circuit eigenvalue sampling. *17th Conference on the Theory of Quantum Computation, Communication and Cryptography (TQC 2022)*, *232*, 4:1–4:10. https://doi.org/10.4230/LIPIcs.TQC.2022.4

Fowler, A. G., Mariantoni, M., Martinis, J. M., & Cleland, A. N. (2012). Surface codes: Towards practical large-scale quantum computation. *Physical Review A*, *86*(3), 032324. https://doi.org/10.1103/PhysRevA.86.032324

Gidney, C. (2021). Stim: A fast stabilizer circuit simulator. *Quantum*, *5*, 497. https://doi.org/10.22331/q-2021-07-06-497

Gottesman, D. (1997). *Stabilizer codes and quantum error correction* [PhD thesis, California Institute of Technology]. https://doi.org/10.7907/rzr7-dt72

Gottesman, D. (2010). An introduction to quantum error correction and fault-tolerant quantum computation. In S. Lomonaco (Ed.), *Quantum information science and its contributions to mathematics* (Vol. 68, pp. 13–58). American Mathematical Society. https://doi.org/10.1090/psapm/068

Higgott, O. (2022). PyMatching: A Python package for decoding quantum codes with minimum-weight perfect matching. *ACM Transactions on Quantum Computing*, *3*(3), 16:1–16:16. https://doi.org/10.1145/3505637

Higgott, O., Bohdanowicz, T. C., Kubica, A., Flammia, S. T., & Campbell, E. T. (2023). Improved decoding of circuit noise and fragile boundaries of tailored surface codes. *Physical Review X*, *13*(3), 031007. https://doi.org/10.1103/PhysRevX.13.031007

Higgott, O., & Gidney, C. (2025). Sparse blossom: Correcting a million errors per core second with minimum-weight matching. *Quantum*, *9*, 1600. https://doi.org/10.22331/q-2025-01-20-1600

Hockings, E. T., Doherty, A. C., & Harper, R. (2024). Scalable noise characterisation of syndrome extraction circuits with averaged circuit eigenvalue sampling. *arXiv Preprint*. https://arxiv.org/abs/2404.06545

Javadi-Abhari, A., Treinish, M., Krsulich, K., Wood, C. J., Lishman, J., Gacon, J., Martiel, S., Nation, P. D., Bishop, L. S., Cross, A. W., Johnson, B. R., & Gambetta, J. M. (2024). Quantum computing with Qiskit. *arXiv Preprint*. https://arxiv.org/abs/2405.08810

Kitaev, A. Y. (2003). Fault-tolerant quantum computation by anyons. *Annals of Physics*, *303*(1), 2–30. https://doi.org/10.1016/S0003-4916(02)00018-0

134 Knill, E. (2005). Quantum computing with realistically noisy devices. *Nature*, *434*(7029),
135 39–44. https://doi.org/10.1038/nature03350

136 Nielsen, E., Gamble, J. K., Rudinger, K., Scholten, T., Young, K., & Blume-Kohout, R. (2021).
137 Gate set tomography. *Quantum*, *5*, 557. https://doi.org/10.22331/q-2021-10-05-557

138 Nielsen, E., Seritan, S., Proctor, T., Rudinger, K., Young, K., Russo, A., Blume-Kohout, R.,
139 Kelly, R. P., Gamble, J. K., & Saldyt, L. (2022). *pyGSTi*. Zenodo. https://doi.org/10.
140 5281/zenodo.594712

141 Shor, P. W. (1996). Fault-tolerant quantum computation. *Proceedings of 37th Conference on*
142 *Foundations of Computer Science*, 56–65. https://doi.org/10.1109/SFCS.1996.548464

143 Sundaresan, N., Yoder, T. J., Kim, Y., Li, M., Chen, E. H., Harper, G., Thorbeck, T., Cross, A.
144 W., Córcoles, A. D., & Takita, M. (2023). Demonstrating multi-round subsystem quantum
145 error correction using matching and maximum likelihood decoders. *Nature Communications*,
146 *14*(1), 2852. https://doi.org/10.1038/s41467-023-38247-5

147 Terhal, B. M. (2015). Quantum error correction for quantum memories. *Reviews of Modern*
148 *Physics*, *87*(2), 307–346. https://doi.org/10.1103/RevModPhys.87.307

149 Tiurev, K., Derks, P.-J. H. S., Roffe, J., Eisert, J., & Reiner, J.-M. (2023). Correcting
150 non-independent and non-identically distributed errors with surface codes. *Quantum*, *7*,
151 1123. https://doi.org/10.22331/q-2023-09-26-1123

152 Tuckett, D. K., Bartlett, S. D., Flammia, S. T., & Brown, B. J. (2020). Fault-tolerant
153 thresholds for the surface code in excess of 5% under biased noise. *Physical Review Letters*,
154 *124*(13), 130501. https://doi.org/10.1103/PhysRevLett.124.130501

155 Wallman, J. J., & Emerson, J. (2016). Noise tailoring for scalable quantum computation
156 via randomized compiling. *Physical Review A*, *94*(5), 052325. https://doi.org/10.1103/
157 PhysRevA.94.052325