

# Bibliography

- [1] Tzvetan S. Metodi, Arvin I. Faruque, and Frederic T. Chong. *Quantum Computing for Computer Architects*. Morgan & Claypool Publishers, 2011. DOI: [10.2200/s00066ed1v01y200610cac001\\_xvi](https://doi.org/10.2200/s00066ed1v01y200610cac001_xvi)
- [2] Paul Benioff. The computer as a physical system: A microscopic quantum mechanical Hamiltonian model of computers as represented by turing machines. *Journal of Statistical Physics*, 22:563–591, May 1980. DOI: [10.1007/bf01011339](https://doi.org/10.1007/bf01011339) 3, 16
- [3] Charles H. Bennett. Logical reversibility of computation. *IBM J. Res. Dev.*, 17(6):525–532, November 1973. DOI: [10.1147/rd.176.0525](https://doi.org/10.1147/rd.176.0525) 3
- [4] Richard P. Feynman. Simulating physics with computers. *International Journal of Theoretical Physics*, 21(6–7):467–488, June 1982. DOI: [10.1201/9780429500459-11](https://doi.org/10.1201/9780429500459-11) 3, 9
- [5] Seth Lloyd. Universal quantum simulators. *Science*, pages 1073–1078, 1996. DOI: [10.1126/science.273.5278.1073](https://doi.org/10.1126/science.273.5278.1073) 3
- [6] David Deutsch. Quantum theory, the church-turing principle and the universal quantum computer. *Proc. of the Royal Society of London. A. Mathematical and Physical Sciences*, 400(1818):97–117, 1985. DOI: [10.1098/rspa.1985.0070](https://doi.org/10.1098/rspa.1985.0070) 4, 63
- [7] David Elieser Deutsch. Quantum computational networks. *Proc. of the Royal Society of London. A. Mathematical and Physical Sciences*, 425(1868):73–90, 1989. DOI: [10.1098/rspa.1989.0099](https://doi.org/10.1098/rspa.1989.0099) 4
- [8] David Z. Albert. On quantum-mechanical automata. *Physics Letters A*, 98(5–6):249–252, 1983. DOI: [10.1016/0375-9601\(83\)90863-0](https://doi.org/10.1016/0375-9601(83)90863-0) 4
- [9] Ethan Bernstein and Umesh Vazirani. Quantum complexity theory. *SIAM Journal on Computing*, 26(5):1411–1473, 1997. DOI: [10.1145/167088.167097](https://doi.org/10.1145/167088.167097) 4, 62, 65, 103
- [10] Daniel R. Simon. On the power of quantum computation. *SIAM Journal on Computing*, 26(5):1474–1483, 1997. DOI: [10.1137/s0097539796298637](https://doi.org/10.1137/s0097539796298637) 4
- [11] Peter W. Shor. Algorithms for quantum computation: Discrete logarithms and factoring. In *Proc. 35th Annual Symposium on Foundations of Computer Science*, pages 124–134, IEEE, 1994. DOI: [10.1109/sfcs.1994.365700](https://doi.org/10.1109/sfcs.1994.365700) 4, 69, 121

- [12] Peter W. Shor. Polynomial-time algorithms for prime factorization and discrete logarithms on a quantum computer. *SIAM Review*, 41(2):303–332, 1999. DOI: [10.1137/s0097539795293172](https://doi.org/10.1137/s0097539795293172) 4, 11, 57, 69, 99
- [13] Lov K. Grover. A fast quantum mechanical algorithm for database search. *ArXiv Preprint quant-ph/9605043*, 1996. DOI: [10.1145/237814.237866](https://doi.org/10.1145/237814.237866) 4, 11, 57, 69, 99, 121
- [14] John Preskill. Quantum computing in the NISQ era and beyond. *Quantum*, 2:79, 2018. DOI: [10.22331/q-2018-08-06-79](https://doi.org/10.22331/q-2018-08-06-79) 5, 10, 70, 138
- [15] Catherine C. McGeoch. Adiabatic quantum computation and quantum annealing: Theory and practice. *Synthesis Lectures on Quantum Computing*, 5(2):1–93, 2014. DOI: [10.2200/s00585ed1v01y201407qmc008](https://doi.org/10.2200/s00585ed1v01y201407qmc008) 6
- [16] Arnab Das and Bikas K. Chakrabarti. Colloquium: Quantum annealing and analog quantum computation. *Reviews of Modern Physics*, 80(3):1061, 2008. DOI: [10.1103/revmodphys.80.1061](https://doi.org/10.1103/revmodphys.80.1061) 6
- [17] Andrew M. Childs, Edward Farhi, and John Preskill. Robustness of adiabatic quantum computation. *Physical Review A*, 65(1):012322, 2001. DOI: [10.1103/physreva.65.012322](https://doi.org/10.1103/physreva.65.012322) 6
- [18] Dorit Aharonov, Wim Van Dam, Julia Kempe, Zeph Landau, Seth Lloyd, and Oded Regev. Adiabatic quantum computation is equivalent to standard quantum computation. *SIAM Review*, 50(4):755–787, 2008. DOI: [10.1137/080734479](https://doi.org/10.1137/080734479) 6
- [19] Tadashi Kadowaki and Hidetoshi Nishimori. Quantum annealing in the transverse Ising model. *Physical Review E*, 58(5):5355, 1998. DOI: [10.1103/physreve.58.5355](https://doi.org/10.1103/physreve.58.5355) 6
- [20] Aleta Berk Finnila, M. A. Gomez, C. Sebenik, Catherine Stenson, and Jimmie D. Doll. Quantum annealing: A new method for minimizing multidimensional functions. *Chemical Physics Letters*, 219(5–6):343–348, 1994. DOI: [10.1016/0009-2614\(94\)00117-0](https://doi.org/10.1016/0009-2614(94)00117-0) 6
- [21] Mohammad H. S. Amin, Dmitri V. Averin, and James A. Nesteroff. Decoherence in adiabatic quantum computation. *Physical Review A*, 79(2):022107, 2009. DOI: [10.1103/physreva.79.022107](https://doi.org/10.1103/physreva.79.022107) 6
- [22] Eric Dennis, Alexei Kitaev, Andrew Landahl, and John Preskill. Topological quantum memory. *Journal of Mathematical Physics*, 43(9):4452–4505, 2002. DOI: [10.1063/1.1499754](https://doi.org/10.1063/1.1499754) 6, 77, 141, 166
- [23] Daniel Gottesman. An introduction to quantum error correction and fault-tolerant quantum computation. In *Quantum Information Science and its Contributions to Mathematics, Proceedings of Symposia in Applied Mathematics*, 68:13–58, 2010. DOI: [10.1090/psapm/068/2762145](https://doi.org/10.1090/psapm/068/2762145) 6, 150

- [24] Simon J. Devitt, William J. Munro, and Kae Nemoto. Quantum error correction for beginners. *Reports on Progress in Physics*, 76(7):076001, 2013. DOI: [10.1088/0034-4885/76/7/076001](https://doi.org/10.1088/0034-4885/76/7/076001) 6
- [25] Barbara M. Terhal. Quantum error correction for quantum memories. *Reviews of Modern Physics*, 87(2):307, 2015. DOI: [10.1103/revmodphys.87.307](https://doi.org/10.1103/revmodphys.87.307) 6, 141, 150
- [26] Chetan Nayak, Steven H. Simon, Ady Stern, Michael Freedman, and Sankar Das Sarma. Non-abelian anyons and topological quantum computation. *Reviews of Modern Physics*, 80(3):1083, 2008. DOI: [10.1103/revmodphys.80.1083](https://doi.org/10.1103/revmodphys.80.1083) 6
- [27] Austin G. Fowler, Matteo Mariantoni, John M. Martinis, and Andrew N. Cleland. Surface codes: Towards practical large-scale quantum computation. *Physical Review A*, 86(3):032324, 2012. DOI: [10.1103/physreva.86.032324](https://doi.org/10.1103/physreva.86.032324) 6, 77, 117
- [28] Sergey Bravyi and Alexei Kitaev. Universal quantum computation with ideal Clifford gates and noisy ancillas. *Physical Review A*, 71(2):022316, 2005. DOI: [10.1103/physreva.71.022316](https://doi.org/10.1103/physreva.71.022316) 6, 148
- [29] Robert Raussendorf, Daniel E. Browne, and Hans J. Briegel. Measurement-based quantum computation on cluster states. *Physical Review A*, 68(2):022312, 2003. DOI: [10.1103/physreva.68.022312](https://doi.org/10.1103/physreva.68.022312) 6
- [30] Michael A. Nielsen. Cluster-state quantum computation. *Reports on Mathematical Physics*, 57(1):147–161, 2006. DOI: [10.1016/s0034-4877\(06\)80014-5](https://doi.org/10.1016/s0034-4877(06)80014-5) 6
- [31] Frederic T. Chong, Diana Franklin, and Margaret Martonosi. Programming languages and compiler design for realistic quantum hardware. *Nature*, 549(7671):180, 2017. DOI: [10.1038/nature23459](https://doi.org/10.1038/nature23459) 8, 12, 124, 125
- [32] Margaret Martonosi and Martin Roetteler. Next steps in quantum computing: Computer science’s role. *ArXiv Preprint ArXiv:1903.10541*, 2019. 8, 12
- [33] Mathias Soeken, Thomas Haener, and Martin Roetteler. Programming quantum computers using design automation. In *Design, Automation and Test in Europe Conference and Exhibition (DATE)*, pages 137–146, IEEE, 2018. DOI: [10.23919/date.2018.8341993](https://doi.org/10.23919/date.2018.8341993) 9
- [34] Nicolas Gisin and Rob Thew. Quantum communication. *Nature Photonics*, 1(3):165, 2007. DOI: [10.1038/nphoton.2007.22](https://doi.org/10.1038/nphoton.2007.22) 9
- [35] H.-J. Briegel, Wolfgang Dür, Juan I. Cirac, and Peter Zoller. Quantum repeaters: The role of imperfect local operations in quantum communication. *Physical Review Letters*, 81(26):5932, 1998. DOI: [10.1103/physrevlett.81.5932](https://doi.org/10.1103/physrevlett.81.5932) 9

- [36] Sreraman Muralidharan, Jungsang Kim, Norbert Lütkenhaus, Mikhail D. Lukin, and Liang Jiang. Ultrafast and fault-tolerant quantum communication across long distances. *Physical Review Letters*, 112(25):250501, 2014. DOI: [10.1103/PhysRevLett.112.250501](https://doi.org/10.1103/PhysRevLett.112.250501) 9
- [37] Romain Alléaume, Cyril Branciard, Jan Bouda, Thierry Debuisschert, Mehrdad Dianati, Nicolas Gisin, Mark Godfrey, Philippe Grangier, Thomas Länger, Norbert Lütkenhaus, et al. Using quantum key distribution for cryptographic purposes: A survey. *Theoretical Computer Science*, 560:62–81, 2014. DOI: [10.1016/j.tcs.2014.09.018](https://doi.org/10.1016/j.tcs.2014.09.018) 9
- [38] Juan Yin, Yuan Cao, Yu-Huai Li, Sheng-Kai Liao, Liang Zhang, Ji-Gang Ren, Wen-Qi Cai, Wei-Yue Liu, Bo Li, Hui Dai, et al. Satellite-based entanglement distribution over 1,200 kilometers. *Science*, 356(6343):1140–1144, 2017. DOI: [10.1126/science.aan3211](https://doi.org/10.1126/science.aan3211) 9
- [39] Boris Korzh, Charles Ci Wen Lim, Raphael Houlmann, Nicolas Gisin, Ming Jun Li, Daniel Nolan, Bruno Sanguinetti, Rob Thew, and Hugo Zbinden. Provably secure and practical quantum key distribution over 307 km of optical fibre. *Nature Photonics*, 9(3):163, 2015. DOI: [10.1038/nphoton.2014.327](https://doi.org/10.1038/nphoton.2014.327) 9
- [40] Robert B. Laughlin and David Pines. The theory of everything. *Proc. of the National Academy of Sciences*, 97(1):28–31, 2000. DOI: [10.7551/mitpress/9780262026215.003.0017](https://doi.org/10.7551/mitpress/9780262026215.003.0017) 9
- [41] Markus Reiher, Nathan Wiebe, Krysta M. Svore, Dave Wecker, and Matthias Troyer. Elucidating reaction mechanisms on quantum computers. *Proc. of the National Academy of Sciences*, 114(29):7555–7560, 2017. DOI: [10.1073/pnas.1619152114](https://doi.org/10.1073/pnas.1619152114) 9
- [42] Attila Szabo and Neil S. Ostlund. *Modern Quantum Chemistry: Introduction to Advanced Electronic Structure Theory*. Courier Corporation, 2012. 9
- [43] Ben P. Lanyon, Cornelius Hempel, Daniel Nigg, Markus Müller, Rene Gerritsma, F. Zähringer, Philipp Schindler, Julio T. Barreiro, Markus Rambach, Gerhard Kirchmair, et al. Universal digital quantum simulation with trapped ions. *Science*, 334(6052):57–61, 2011. DOI: [10.1126/science.1208001](https://doi.org/10.1126/science.1208001) 9
- [44] Benjamin P. Lanyon, James D. Whitfield, Geoff G. Gillett, Michael E. Goggin, Marcelo P. Almeida, Ivan Kassal, Jacob D. Biamonte, Masoud Mohseni, Ben J. Powell, Marco Barbieri, et al. Towards quantum chemistry on a quantum computer. *Nature Chemistry*, 2(2):106, 2010. DOI: [10.1038/nchem.483](https://doi.org/10.1038/nchem.483) 9
- [45] Andrew A. Houck, Hakan E. Türeci, and Jens Koch. On-chip quantum simulation with superconducting circuits. *Nature Physics*, 8(4):292, 2012. DOI: [10.1038/nphys2251](https://doi.org/10.1038/nphys2251) 9

- [46] Peter J. J. O'Malley, Ryan Babbush, Ian D. Kivlichan, Jonathan Romero, Jarrod R. McClean, Rami Barends, Julian Kelly, Pedram Roushan, Andrew Tranter, Nan Ding, et al. Scalable quantum simulation of molecular energies. *Physical Review X*, 6(3):031007, 2016. DOI: [10.1103/physrevx.6.031007](https://doi.org/10.1103/physrevx.6.031007) 9, 67, 70
- [47] Christian L. Degen, F. Reinhard, and P. Cappellaro. Quantum sensing. *Reviews of Modern Physics*, 89(3):035002, 2017. DOI: [10.1103/revmodphys.89.035002](https://doi.org/10.1103/revmodphys.89.035002) 9
- [48] Jens M. Boss, K. S. Cujia, Jonathan Zopes, and Christian L. Degen. Quantum sensing with arbitrary frequency resolution. *Science*, 356(6340):837–840, 2017. DOI: [10.1126/science.aam7009](https://doi.org/10.1126/science.aam7009) 9
- [49] Sebastian Zaiser, Torsten Rendler, Ingmar Jakobi, Thomas Wolf, Sang-Yun Lee, Samuel Wagner, Ville Bergholm, Thomas Schulte-Herbrüggen, Philipp Neumann, and Jörg Wrachtrup. Enhancing quantum sensing sensitivity by a quantum memory. *Nature Communications*, 7:12279, 2016. DOI: [10.1038/ncomms12279](https://doi.org/10.1038/ncomms12279) 9
- [50] Robert R. Schaller. Moore's law: Past, present and future. *IEEE Spectrum*, 34(6):52–59, 1997. DOI: [10.1109/6.591665](https://doi.org/10.1109/6.591665) 10, 15
- [51] IBM Unveils World's First Integrated Quantum Computing System for Commercial Use. <https://newsroom.ibm.com/2019-01-08-IBM-Unveils-Worlds-First-Integrated-Quantum-Computing-System-for-Commercial-Use> 10, 77, 119, 138, 140
- [52] IBM Opens Quantum Computation Center in New York. <https://newsroom.ibm.com/2019-09-18-IBM-Opens-Quantum-Computation-Center-in-New-York-Brings-Worlds-Largest-Fleet-of-Quantum-Computing-Systems-Online-Unveils-New-53-Qubit-Quantum-System-for-Broad-Use> 10
- [53] Quantum Supremacy Using a Programmable Superconducting Processor. <https://ai.googleblog.com/2019/10/quantum-supremacy-using-programmable.html> 10
- [54] The Future of Quantum Computing is Counted in Qubits. <https://newsroom.intel.com/news/future-quantum-computing-counted-qubits/#gs.qih7ym> 10
- [55] Intel Introduces “Horse Ridge” to Enable Commercially Viable Quantum Computers. <https://newsroom.intel.com/news/intel-introduces-horse-ridge-enable-commercially-viable-quantum-computers/#gs.qihieg> 10
- [56] IonQ Newsletter. <https://ionq.co/news/december-11-2018> 10, 77, 138, 167
- [57] Hartmut Häffner, Wolfgang Hänsel, C. F. Roos, Jan Benhelm, Michael Chwalla, Timo Körber, U. D. Rapol, Mark Riebe, P. O. Schmidt, Christoph Becher, et al. Scalable multiparticle entanglement of trapped ions. *Nature*, 438(7068):643–646, 2005. DOI: [10.1038/nature04279](https://doi.org/10.1038/nature04279) 11

- [58] Dietrich Leibfried, Brian DeMarco, Volker Meyer, David Lucas, Murray Barrett, Joe Britton, Wayne M. Itano, B. Jelenković, Chris Langer, Till Rosenband, et al. Experimental demonstration of a robust, high-fidelity geometric two ion-qubit phase gate. *Nature*, 422(6930):412–415, 2003. DOI: [10.1038/nature01492](https://doi.org/10.1038/nature01492) 11
- [59] Ferdinand Schmidt-Kaler, Hartmut Häffner, Mark Riebe, Stephan Gulde, Gavin P. T. Lancaster, Thomas Deuschle, Christoph Becher, Christian F. Roos, Jürgen Eschner, and Rainer Blatt. Realization of the Cirac–Zoller controlled-not quantum gate. *Nature*, 422(6930):408–411, 2003. DOI: [10.1038/nature01494](https://doi.org/10.1038/nature01494) 11
- [60] Matthias Steffen, M. Ansmann, Radoslaw C. Bialczak, Nadav Katz, Erik Lucero, R. McDermott, Matthew Neeley, Eva Maria Weig, Andrew N. Cleland, and John M. Martinis. Measurement of the entanglement of two superconducting qubits via state tomography. *Science*, 313(5792):1423–1425, 2006. DOI: [10.1126/science.1130886](https://doi.org/10.1126/science.1130886) 11, 51
- [61] Leonardo DiCarlo, Jerry M. Chow, Jay M. Gambetta, Lev S. Bishop, Blake R. Johnson, D. I. Schuster, J. Majer, Alexandre Blais, Luigi Frunzio, S. M. Girvin, et al. Demonstration of two-qubit algorithms with a superconducting quantum processor. *Nature*, 460(7252):240–244, 2009. DOI: [10.1038/nature08121](https://doi.org/10.1038/nature08121) 11, 49, 51
- [62] Jerry M. Chow, Jay M. Gambetta, A. D. Córcoles, Seth T. Merkel, John A. Smolin, Chad Rigetti, S. Poletto, George A. Keefe, Mary B. Rothwell, J. R. Rozen, et al. Universal quantum gate set approaching fault-tolerant thresholds with superconducting qubits. *Physical Review Letters*, 109(6):060501, 2012. DOI: [10.1103/physrevlett.109.060501](https://doi.org/10.1103/physrevlett.109.060501) 11
- [63] Sarah Sheldon, Easwar Magesan, Jerry M. Chow, and Jay M. Gambetta. Procedure for systematically tuning up cross-talk in the cross-resonance gate. *Physical Review A*, 93(6):060302, 2016. DOI: [10.1103/physreva.93.060302](https://doi.org/10.1103/physreva.93.060302) 11
- [64] John P. Gaebler, Ting Rei Tan, Y. Lin, Y. Wan, R. Bowler, Adam C. Keith, S. Glancy, K. Coakley, E. Knill, D. Leibfried, et al. High-fidelity universal gate set for be 9+ ion qubits. *Physical Review Letters*, 117(6):060505, 2016. DOI: [10.1103/physrevlett.117.060505](https://doi.org/10.1103/physrevlett.117.060505) 11
- [65] K. Wright, K. M. Beck, S. Debnath, J. M. Amini, Y. Nam, N. Grzesiak, J. S. Chen, N. C. Pisenti, M. Chmielewski, C. Collins, K. M. Hudek, J. Mizrahi, J. D. Wong-Campos, S. Allen, J. Apisdorf, P. Solomon, M. Williams, A. M. Ducore, A. Blinov, S. M. Kreike-meier, V. Chaplin, M. Keesan, C. Monroe, and J. Kim. Benchmarking an 11-qubit quantum computer. *Nature Communications*, 10(1):5464, 2019. DOI: [10.1038/s41467-019-13534-2](https://doi.org/10.1038/s41467-019-13534-2) 11
- [66] Frank Arute, Kunal Arya, Ryan Babbush, Dave Bacon, Joseph C. Bardin, Rami Barends, Rupak Biswas, Sergio Boixo, Fernando G. S. L. Brandao, David A. Buell, et al. Quantum supremacy using a programmable superconducting processor. *Nature*, 574(7779):505–510, 2019. DOI: [10.1038/s41586-019-1666-5](https://doi.org/10.1038/s41586-019-1666-5) 11, 140

- [67] J. M. Pino, J. M. Dreiling, C. Figgatt, J. P. Gaebler, S. A. Moses, C. H. Baldwin, M. Foss-Feig, D. Hayes, K. Mayer, C. Ryan-Anderson, et al. Demonstration of the QCCD trapped-ion quantum computer architecture. *ArXiv Preprint ArXiv:2003.01293*, 2020. [11](#)
- [68] Edward Farhi, Jeffrey Goldstone, and Sam Gutmann. A quantum approximate optimization algorithm. *ArXiv Preprint ArXiv:1411.4028*, 2014. [11](#), [67](#), [68](#), [70](#)
- [69] Dmitri Maslov. Basic circuit compilation techniques for an ion-trap quantum machine. *New Journal of Physics*, 19(2):023035, 2017. DOI: [10.1088/1367-2630/aa5e47](#) [12](#)
- [70] National Academies of Sciences, Engineering and Medicine, *Quantum computing: Progress and prospects*. National Academies Press, 2019. DOI: [10.17226/25196](#) [12](#)
- [71] Antonio Acín, Immanuel Bloch, Harry Buhrman, Tommaso Calarco, Christopher Eichler, Jens Eisert, Daniel Esteve, Nicolas Gisin, Steffen J. Glaser, Fedor Jelezko, et al. The quantum technologies roadmap: A European community view. *New Journal of Physics*, 20(8):080201, 2018. DOI: [10.1088/1367-2630/aad1ea](#) [12](#)
- [72] Andrew Waterman, Yunsup Lee, David A. Patterson, and Krste Asanovic. The RISC-V instruction set manual, volume I: Base user-level ISA. *EECS Department, Tech. Rep. UCB/EECS-2011-62*, 116, UC Berkeley, 2011. DOI: [10.21236/ada605735](#) [15](#)
- [73] Rolf Landauer. Irreversibility and heat generation in the computing process. *IBM Journal of Research and Development*, 5(3):183–191, 1961. DOI: [10.1147/rd.441.0261](#) [16](#)
- [74] Charles H. Bennett. Logical reversibility of computation. *IBM Journal of Research and Development*, 17(6):525–532, 1973. DOI: [10.1147/rd.176.0525](#) [16](#), [120](#)
- [75] Albert Einstein, Boris Podolsky, and Nathan Rosen. Can quantum-mechanical description of physical reality be considered complete? *Physical Review*, 47(10):777, 1935. DOI: [10.1007/978-3-322-91080-6\\_6](#) [21](#), [23](#)
- [76] John S. Bell. On the Einstein Podolsky rosen paradox. *Physica Physique Fizika*, 1(3):195, 1964. DOI: [10.1142/9789812386540\\_0002](#) [21](#), [23](#), [24](#)
- [77] Richard Phillips Feynman. Space-time approach to non-relativistic quantum mechanics. In *Feynman's Thesis—A New Approach To Quantum Theory*, pages 71–109. World Scientific, 2005. DOI: [10.1103/revmodphys.20.367](#) [22](#)
- [78] Richard P. Feynman, Albert R. Hibbs, and Daniel F. Styer. *Quantum Mechanics and Path Integrals*. Courier Corporation, 2010. DOI: [10.1063/1.3048320](#) [22](#)
- [79] Scott Aaronson. Bell inequality violation finally done right. <https://www.scottaaronson.com/blog/?p=2464> [24](#)

- [80] John F. Clauser, Michael A. Horne, Abner Shimony, and Richard A. Holt. Proposed experiment to test local hidden-variable theories. *Physical Review Letters*, 23(15):880, 1969. DOI: [10.1103/physrevlett.24.549](https://doi.org/10.1103/physrevlett.24.549) 24
- [81] Ryszard Horodecki, Paweł Horodecki, Michał Horodecki, and Karol Horodecki. Quantum entanglement. *Reviews of Modern Physics*, 81(2):865, 2009. DOI: [10.1103/revmodphys.81.865](https://doi.org/10.1103/revmodphys.81.865) 24
- [82] William K. Wootters and Wojciech H. Zurek. A single quantum cannot be cloned. *Nature*, 299(5886):802–803, 1982. DOI: [10.1038/299802a0](https://doi.org/10.1038/299802a0) 25
- [83] Daniel Oliveira, Laércio Pilla, Nathan DeBardleben, Sean Blanchard, Heather Quinn, Israel Koren, Philippe Navaux, and Paolo Rech. Experimental and analytical study of xeon phi reliability. In *Proc. of the International Conference for High Performance Computing, Networking, Storage and Analysis*, page 28, ACM, 2017. DOI: [10.1145/3126908.3126960](https://doi.org/10.1145/3126908.3126960) 26
- [84] IBM Quantum Computing. <https://www.ibm.com/quantum-computing/> 26, 83
- [85] Karl Kraus, Arno Böhm, John D. Dollard, and W. H. Wootters. States, effects, and operations: Fundamental notions of quantum theory. Lectures in mathematical physics, University of Texas, Austin, TX. *Lecture Notes in Physics*, 190, 1983. DOI: [10.1007/3-540-12732-1](https://doi.org/10.1007/3-540-12732-1) 41
- [86] Michael A. Nielsen and Isaac Chuang. Quantum computation and quantum information, Cambridge University Press, 2002. DOI: [10.1017/cbo9780511976667](https://doi.org/10.1017/cbo9780511976667) 42, 94, 95, 96, 141, 146, 150
- [87] David P. DiVincenzo. The physical implementation of quantum computation. *Fortschritte der Physik: Progress of Physics*, 48(9–11):771–783, 2000. DOI: [10.1002/3527603182.ch143](https://doi.org/10.1002/3527603182.ch143)
- [88] Steve Olmschenk, Kelly C. Younge, David L. Moehring, Dzmitry N. Matsukevich, Peter Maunz, and Christopher Monroe. Manipulation and detection of a trapped yb+ hyperfine qubit. *Physical Review A*, 76(5):052314, 2007. DOI: [10.1103/physreva.76.052314](https://doi.org/10.1103/physreva.76.052314) 44
- [89] Boris B. Blinov, Dietrich Leibfried, C. Monroe, and David J. Wineland. Quantum computing with trapped ion hyperfine qubits. *Quantum Information Processing*, 3(1–5):45–59, 2004. DOI: [10.1007/0-387-27732-3\\_4](https://doi.org/10.1007/0-387-27732-3_4) 44
- [90] Rachel Noek, Geert Vrijsen, Daniel Gaultney, Emily Mount, Taehyun Kim, Peter Maunz, and Jungsang Kim. High speed, high fidelity detection of an atomic hyperfine qubit. *Optics Letters*, 38(22):4735–4738, 2013. DOI: [10.1364/ol.38.004735](https://doi.org/10.1364/ol.38.004735) 44



- [91] A. H. Myerson, D. J. Szwer, S. C. Webster, D. T. C. Allcock, M. J. Curtis, G. Imreh, J. A. Sherman, D. N. Stacey, A. M. Steane, and D. M. Lucas. High-fidelity readout of trapped-ion qubits. *Physical Review Letters*, 100(20):200502, 2008. DOI: [10.1103/physrevlett.100.200502](https://doi.org/10.1103/physrevlett.100.200502) 44
- [92] Juan I. Cirac and Peter Zoller. Quantum computations with cold trapped ions. *Physical Review Letters*, 74(20):4091, 1995. DOI: [10.1103/physrevlett.74.4091](https://doi.org/10.1103/physrevlett.74.4091) 45
- [93] Anders Sørensen and Klaus Mølmer. Quantum computation with ions in thermal motion. *Physical Review Letters*, 82(9):1971, 1999. DOI: [10.1103/physrevlett.82.1971](https://doi.org/10.1103/physrevlett.82.1971) 45
- [94] E. Solano, R. L. de Matos Filho, and N. Zagury. Deterministic bell states and measurement of the motional state of two trapped ions. *Physical Review A*, 59(4):R2539, 1999. DOI: [10.1103/physreva.59.r2539](https://doi.org/10.1103/physreva.59.r2539) 45
- [95] G. J. Milburn, S. Schneider, and D. F. V. James. Ion trap quantum computing with warm ions. *Fortschritte der Physik: Progress of Physics*, 48(9–11):801–810, 2000. DOI: [10.1002/3527603182.ch3](https://doi.org/10.1002/3527603182.ch3) 45
- [96] Wolfgang Paul. Electromagnetic traps for charged and neutral particles. *Reviews of Modern Physics*, 62(3):531, 1990. DOI: [10.1103/revmodphys.62.531](https://doi.org/10.1103/revmodphys.62.531) 47
- [97] Hans G. Dehmelt. Radiofrequency spectroscopy of stored ions I: Storage. In *Advances in Atomic and Molecular Physics*, 3:53–72, Elsevier, 1968. DOI: [10.1016/s0065-2199\(08\)60170-0](https://doi.org/10.1016/s0065-2199(08)60170-0) 47
- [98] Christopher Monroe and Jungsang Kim. Scaling the ion trap quantum processor. *Science*, 339(6124):1164–1169, 2013. DOI: [10.1126/science.1231298](https://doi.org/10.1126/science.1231298) 48
- [99] G.-D. Lin, S.-L. Zhu, Rajibul Islam, Kihwan Kim, M.-S. Chang, Simcha Korenblit, Christopher Monroe, and L.-M. Duan. Large-scale quantum computation in an anharmonic linear ion trap. *EPL (Europhysics Letters)*, 86(6):60004, 2009. DOI: [10.1209/0295-5075/86/60004](https://doi.org/10.1209/0295-5075/86/60004) 48
- [100] Peter Lukas Wilhelm Maunz. Characterization of two-qubit quantum gates in Sandia’s high optical access surface ion trap. *Technical Report*, Sandia National Lab. (SNL-NM), Albuquerque, NM, 2016. 48
- [101] Brian David Josephson. Possible new effects in superconductive tunnelling. *Physics Letters*, 1(7):251–253, 1962. DOI: [10.1016/0031-9163\(62\)91369-0](https://doi.org/10.1016/0031-9163(62)91369-0) 48
- [102] B. D. Josephson. Coupled superconductors. *Reviews of Modern Physics*, 36(1):216, 1964. DOI: [10.1103/revmodphys.36.216](https://doi.org/10.1103/revmodphys.36.216) 48

- [103] Yu Nakamura, Yu A. Pashkin, and Jaw Shen Tsai. Coherent control of macroscopic quantum states in a single-cooper-pair box. *Nature*, 398(6730):786–788, 1999. DOI: [10.1038/19718](https://doi.org/10.1038/19718) 49
- [104] Denis Vion, A. Aassime, Audrey Cottet, P. L. Joyez, H. Pothier, C. Urbina, Daniel Esteve, and Michel H. Devoret. Manipulating the quantum state of an electrical circuit. *Science*, 296(5569):886–889, 2002. DOI: [10.1126/science.1069372](https://doi.org/10.1126/science.1069372) 49
- [105] Tim Duty, D. Gunnarsson, K. Bladh, and Per Delsing. Coherent dynamics of a Josephson charge qubit. *Physical Review B*, 69(14):140503, 2004. DOI: [10.1103/physrevb.69.140503](https://doi.org/10.1103/physrevb.69.140503) 49
- [106] Jens Koch, M. Yu Terri, Jay Gambetta, Andrew A. Houck, D. I. Schuster, J. Majer, Alexandre Blais, Michel H. Devoret, Steven M. Girvin, and Robert J. Schoelkopf. Charge-insensitive qubit design derived from the cooper pair box. *Physical Review A*, 76(4):042319, 2007. DOI: [10.1103/physreva.76.042319](https://doi.org/10.1103/physreva.76.042319) 49
- [107] T. P. Orlando, J. E. Mooij, Lin Tian, Caspar H. Van Der Wal, L. S. Levitov, Seth Lloyd, and J. J. Mazo. Superconducting persistent-current qubit. *Physical Review B*, 60(22):15398, 1999. DOI: [10.1103/physrevb.60.15398](https://doi.org/10.1103/physrevb.60.15398) 49
- [108] J. E. Mooij, T. P. Orlando, L. Levitov, Lin Tian, Caspar H. Van der Wal, and Seth Lloyd. Josephson persistent-current qubit. *Science*, 285(5430):1036–1039, 1999. DOI: [10.1126/science.285.5430.1036](https://doi.org/10.1126/science.285.5430.1036) 49
- [109] Michael Tinkham. *Introduction to Superconductivity*. Courier Corporation, 2004. DOI: [10.1063/1.2807811](https://doi.org/10.1063/1.2807811) 49
- [110] Ioan M. Pop, Kurtis Geerlings, Gianluigi Catelani, Robert J. Schoelkopf, Leonid I. Glazman, and Michel H. Devoret. Coherent suppression of electromagnetic dissipation due to superconducting quasiparticles. *Nature*, 508(7496):369, 2014. DOI: [10.1038/nature13017](https://doi.org/10.1038/nature13017) 50
- [111] John M. Martinis, S. Nam, J. Aumentado, and C. Urbina. Rabi oscillations in a large Josephson-junction qubit. *Physical Review Letters*, 89(11):117901, 2002. DOI: [10.1103/physrevlett.89.117901](https://doi.org/10.1103/physrevlett.89.117901) 50
- [112] Raymond W. Simmonds, K. M. Lang, Dustin A. Hite, S. Nam, David P. Pappas, and John M. Martinis. Decoherence in Josephson phase qubits from junction resonators. *Physical Review Letters*, 93(7):077003, 2004. DOI: [10.1103/physrevlett.93.077003](https://doi.org/10.1103/physrevlett.93.077003) 50
- [113] Philip Krantz, Morten Kjaergaard, Fei Yan, Terry P. Orlando, Simon Gustavsson, and William D. Oliver. A quantum engineer’s guide to superconducting qubits. *Applied Physics Reviews*, 6(2):021318, 2019. DOI: [10.1063/1.5089550](https://doi.org/10.1063/1.5089550) 50, 51

- [114] Daniel Thomas Sank. Fast, accurate state measurement in superconducting qubits. Ph.D. thesis, UC Santa Barbara, 2014. 50
- [115] Uri Vool and Michel Devoret. Introduction to quantum electromagnetic circuits. *International Journal of Circuit Theory and Applications*, 45(7):897–934, 2017. DOI: [10.1002/cta.2359](https://doi.org/10.1002/cta.2359) 50
- [116] Edwin T. Jaynes and Frederick W. Cummings. Comparison of quantum and semiclassical radiation theories with application to the beam maser. *Proc. of the IEEE*, 51(1):89–109, 1963. DOI: [10.1109/proc.1963.1664](https://doi.org/10.1109/proc.1963.1664) 50
- [117] Alexandre Blais, Ren-Shou Huang, Andreas Wallraff, Steven M. Girvin, and R. Jun Schoelkopf. Cavity quantum electrodynamics for superconducting electrical circuits: An architecture for quantum computation. *Physical Review A*, 69(6):062320, 2004. DOI: [10.1103/physreva.69.062320](https://doi.org/10.1103/physreva.69.062320) 50
- [118] Vladimir B. Braginsky and F. Ya Khalili. Quantum nondemolition measurements: The route from toys to tools. *Reviews of Modern Physics*, 68(1):1, 1996. DOI: [10.1103/revmodphys.68.1](https://doi.org/10.1103/revmodphys.68.1) 50
- [119] M. D. Reed, L. DiCarlo, B. R. Johnson, L. Sun, D. I. Schuster, L. Frunzio, and R. J. Schoelkopf. High-fidelity readout in circuit quantum electrodynamics using the Jaynes-cummings nonlinearity. *Physical Review Letters*, 105(17):173601, 2010. DOI: [10.1103/physrevlett.105.173601](https://doi.org/10.1103/physrevlett.105.173601) 50
- [120] David C. McKay, Christopher J. Wood, Sarah Sheldon, Jerry M. Chow, and Jay M. Gambetta. Efficient z gates for quantum computing. *Physical Review A*, 96(2):022330, 2017. DOI: [10.1103/physreva.96.022330](https://doi.org/10.1103/physreva.96.022330) 51
- [121] J. Majer, J. M. Chow, J. M. Gambetta, Jens Koch, B. R. Johnson, J. A. Schreier, L. Frunzio, D. I. Schuster, Andrew Addison Houck, Andreas Wallraff, et al. Coupling superconducting qubits via a cavity bus. *Nature*, 449(7161):443, 2007. DOI: [10.1038/nature06184](https://doi.org/10.1038/nature06184) 51
- [122] Göran Wendin and V. S. Shumeiko. Superconducting quantum circuits, qubits and computing. *ArXiv Preprint cond-mat/0508729*, 2005. 51
- [123] Radoslaw C. Bialczak, Markus Ansmann, Max Hofheinz, Erik Lucero, Matthew Neeley, A. D. O’Connell, Daniel Sank, Haohua Wang, James Wenner, Matthias Steffen, et al. Quantum process tomography of a universal entangling gate implemented with Josephson phase qubits. *Nature Physics*, 6(6):409–413, 2010. DOI: [10.1038/nphys1639](https://doi.org/10.1038/nphys1639) 51

- [124] Matthew Neeley, Radosław C. Bialczak, M. Lenander, Erik Lucero, Matteo Mariantoni, A. D. O'connell, D. Sank, H. Wang, M. Weides, J. Wenner, et al. Generation of three-qubit entangled states using superconducting phase qubits. *Nature*, 467(7315):570, 2010. DOI: [10.1038/nature09418](https://doi.org/10.1038/nature09418) 51
- [125] Frederick W. Strauch, Philip R. Johnson, Alex J. Dragt, C. J. Lobb, J. R. Anderson, and F. C. Wellstood. Quantum logic gates for coupled superconducting phase qubits. *Physical Review Letters*, 91(16):167005, 2003. DOI: [10.1103/physrevlett.91.167005](https://doi.org/10.1103/physrevlett.91.167005) 51
- [126] G. S. Paraoanu. Microwave-induced coupling of superconducting qubits. *Physical Review B*, 74(14):140504, 2006. DOI: [10.1103/physrevb.74.140504](https://doi.org/10.1103/physrevb.74.140504) 51
- [127] Chad Rigetti and Michel Devoret. Fully microwave-tunable universal gates in superconducting qubits with linear couplings and fixed transition frequencies. *Physical Review B*, 81(13):134507, 2010. DOI: [10.1103/physrevb.81.134507](https://doi.org/10.1103/physrevb.81.134507) 51
- [128] P. C. De Groot, J. Lisenfeld, R. N. Schouten, S. Ashhab, A. Lupaşcu, C. J. P. M. Harmans, and J. E. Mooij. Selective darkening of degenerate transitions demonstrated with two superconducting quantum bits. *Nature Physics*, 6(10):763, 2010. DOI: [10.1038/nphys1733](https://doi.org/10.1038/nphys1733) 51
- [129] Jerry M. Chow, Jay M. Gambetta, Andrew W. Cross, Seth T. Merkel, Chad Rigetti, and M. Steffen. Microwave-activated conditional-phase gate for superconducting qubits. *New Journal of Physics*, 15(11):115012, 2013. DOI: [10.1088/1367-2630/15/11/115012](https://doi.org/10.1088/1367-2630/15/11/115012) 51, 53
- [130] Daniel Loss and David P. DiVincenzo. Quantum computation with quantum dots. *Physical Review A*, 57(1):120, 1998. DOI: [10.1103/physreva.57.120](https://doi.org/10.1103/physreva.57.120) 54
- [131] Bruce E. Kane. A silicon-based nuclear spin quantum computer. *Nature*, 393(6681):133, 1998. DOI: [10.1038/30156](https://doi.org/10.1038/30156) 54, 132
- [132] Rutger Vrijen, Eli Yablonovitch, Kang Wang, Hong Wen Jiang, Alex Balandin, Vwani Roychowdhury, Tal Mor, and David DiVincenzo. Electron-spin-resonance transistors for quantum computing in silicon-germanium heterostructures. *Physical Review A*, 62(1):012306, 2000. DOI: [10.1103/physreva.62.012306](https://doi.org/10.1103/physreva.62.012306) 54
- [133] L. C. L. Hollenberg, A. D. Greentree, A. G. Fowler, and C. J. Wellard. Two-dimensional architectures for donor-based quantum computing. *Physical Review B*, 74(4):045311, 2006. DOI: [10.1103/physrevb.74.045311](https://doi.org/10.1103/physrevb.74.045311) 54
- [134] Emanuel Knill, Raymond Laflamme, and Gerald J. Milburn. A scheme for efficient quantum computation with linear optics. *Nature*, 409(6816):46, 2001. DOI: [10.1038/35051009](https://doi.org/10.1038/35051009) 54

- [135] T. B. Pittman, B. C. Jacobs, and J. D. Franson. Probabilistic quantum logic operations using polarizing beam splitters. *Physical Review A*, 64(6):062311, 2001. DOI: [10.1103/physreva.64.062311](https://doi.org/10.1103/physreva.64.062311) 54
- [136] James D. Franson, M. M. Donegan, M. J. Fitch, B. C. Jacobs, and T. B. Pittman. High-fidelity quantum logic operations using linear optical elements. *Physical Review Letters*, 89(13):137901, 2002. DOI: [10.1103/physrevlett.89.137901](https://doi.org/10.1103/physrevlett.89.137901) 54
- [137] A. Yu Kitaev. Fault-tolerant quantum computation by anyons. *Annals of Physics*, 303(1):2–30, 2003. DOI: [10.1016/s0003-4916\(02\)00018-0](https://doi.org/10.1016/s0003-4916(02)00018-0) 54
- [138] M. T. Deng, S. Vaitiekėnas, Esben Bork Hansen, Jeroen Danon, M. Leijnse, Karsten Flensberg, Jesper Nygård, P. Krogstrup, and Charles M. Marcus. Majorana bound state in a coupled quantum-dot hybrid-nanowire system. *Science*, 354(6319):1557–1562, 2016. DOI: [10.1126/science.aaf3961](https://doi.org/10.1126/science.aaf3961) 54
- [139] Torsten Karzig, Christina Knapp, Roman M. Lutchyn, Parsa Bonderson, Matthew B. Hastings, Chetan Nayak, Jason Alicea, Karsten Flensberg, Stephan Plugge, Yuval Oreg, et al. Scalable designs for quasiparticle-poisoning-protected topological quantum computation with Majorana zero modes. *Physical Review B*, 95(23):235305, 2017. DOI: [10.1103/physrevb.95.235305](https://doi.org/10.1103/physrevb.95.235305) 54
- [140] R. M. T. Lutchyn, Epam Bakkers, Leo P. Kouwenhoven, Peter Krogstrup, C. M. Marcus, and Y. Oreg. Majorana zero modes in superconductor-semiconductor heterostructures. *Nature Reviews Materials*, 3(5):52–68, 2018. DOI: [10.1038/s41578-018-0003-1](https://doi.org/10.1038/s41578-018-0003-1) 54
- [141] Gilles Brassard, Peter Hoyer, and Alain Tapp. Quantum algorithm for the collision problem. *ArXiv Preprint quant-ph/9705002*, 1997. DOI: [10.1007/978-3-642-27848-8\\_304-2](https://doi.org/10.1007/978-3-642-27848-8_304-2) 57
- [142] Scott Aaronson and Yaoyun Shi. Quantum lower bounds for the collision and the element distinctness problems. *Journal of the ACM (JACM)*, 51(4):595–605, 2004. DOI: [10.1145/1008731.1008735](https://doi.org/10.1145/1008731.1008735) 57
- [143] David Deutsch and Richard Jozsa. Rapid solution of problems by quantum computation. *Proc. of the Royal Society of London. Series A: Mathematical and Physical Sciences*, 439(1907):553–558, 1992. DOI: [10.1098/rspa.1992.0167](https://doi.org/10.1098/rspa.1992.0167) 62, 64
- [144] Alberto Peruzzo, Jarrod McClean, Peter Shadbolt, Man-Hong Yung, Xiao-Qi Zhou, Peter J. Love, Alán Aspuru-Guzik, and Jeremy L. O’Brien. A variational eigenvalue solver on a photonic quantum processor. *Nature Communications*, 5:4213, 2014. DOI: [10.1038/ncomms5213](https://doi.org/10.1038/ncomms5213) 67, 70

- [145] Jarrod R. McClean, Jonathan Romero, Ryan Babbush, and Alán Aspuru-Guzik. The theory of variational hybrid quantum-classical algorithms. *New Journal of Physics*, 18(2):023023, 2016. DOI: [10.1088/1367-2630/18/2/023023](https://doi.org/10.1088/1367-2630/18/2/023023) 67, 70, 75
- [146] Aram W. Harrow and Ashley Montanaro. Quantum computational supremacy. *Nature*, 549(7671):203, 2017. DOI: [10.1038/nature23458](https://doi.org/10.1038/nature23458) 70, 85
- [147] Ewin Tang. A quantum-inspired classical algorithm for recommendation systems. In *Proc. of the 51st Annual ACM SIGACT Symposium on Theory of Computing*, pages 217–228, 2019. DOI: [10.1145/3313276.3316310](https://doi.org/10.1145/3313276.3316310) 70
- [148] Dave Wecker, Matthew B. Hastings, and Matthias Troyer. Progress towards practical quantum variational algorithms. *Physical Review A*, 92(4):042303, 2015. DOI: [10.1103/physreva.92.042303](https://doi.org/10.1103/physreva.92.042303) 70
- [149] Jonathan Romero, Jonathan P. Olson, and Alan Aspuru-Guzik. Quantum autoencoders for efficient compression of quantum data. *Quantum Science and Technology*, 2(4):045001, 2017. DOI: [10.1088/2058-9565/aa8072](https://doi.org/10.1088/2058-9565/aa8072) 70
- [150] Guillaume Verdon, Michael Broughton, and Jacob Biamonte. A quantum algorithm to train neural networks using low-depth circuits. *ArXiv Preprint ArXiv:1712.05304*, 2017. 70
- [151] Marcello Benedetti, Delfina Garcia-Pintos, Oscar Perdomo, Vicente Leyton-Ortega, Yunseong Nam, and Alejandro Perdomo-Ortiz. A generative modeling approach for benchmarking and training shallow quantum circuits. *NPJ Quantum Information*, 5(1):45, 2019. DOI: [10.1038/s41534-019-0157-8](https://doi.org/10.1038/s41534-019-0157-8) 70
- [152] Scott Aaronson and Alex Arkhipov. The computational complexity of linear optics. In *Proc. of the 43rd Annual ACM Symposium on Theory of Computing*, pages 333–342, ACM, 2011. DOI: [10.1364/qim.2014.qth1a.2](https://doi.org/10.1364/qim.2014.qth1a.2) 70
- [153] Jacques Carolan, Christopher Harrold, Chris Sparrow, Enrique Martín-López, Nicholas J. Russell, Joshua W. Silverstone, Peter J. Shadbolt, Nobuyuki Matsuda, Manabu Oguma, Mikitaka Itoh, et al. Universal linear optics. *Science*, 349(6249):711–716, 2015. DOI: [10.1126/science.aab3642](https://doi.org/10.1126/science.aab3642) 70
- [154] Peter Clifford and Raphaël Clifford. The classical complexity of boson sampling. In *Proc. of the 29th Annual ACM-SLAM Symposium on Discrete Algorithms*, pages 146–155. Society for Industrial and Applied Mathematics, 2018. DOI: [10.1137/1.9781611975031.10](https://doi.org/10.1137/1.9781611975031.10) 70
- [155] Sergio Boixo, Sergei V. Isakov, Vadim N. Smelyanskiy, Ryan Babbush, Nan Ding, Zhang Jiang, Michael J. Bremner, John M. Martinis, and Hartmut Neven. Characterizing quantum supremacy in near-term devices. *Nature Physics*, 14(6):595, 2018. DOI: [10.1038/s41567-018-0124-x](https://doi.org/10.1038/s41567-018-0124-x) 70, 85

- [156] Adam Bouland, Bill Fefferman, Chinmay Nirkhe, and Umesh Vazirani. Quantum supremacy and the complexity of random circuit sampling. *ArXiv Preprint ArXiv:1803.04402*, 2018. 70
- [157] Daniel Gottesman. Stabilizer codes and quantum error correction. *ArXiv Preprint quant-ph/9705052*, 1997. 77, 88, 141
- [158] Rigetti computing. <https://www.rigetti.com/systems> 77, 83
- [159] Pranav Gokhale, Yongshan Ding, Thomas Propson, Christopher Winkler, Nelson Leung, Yunong Shi, David I. Schuster, Henry Hoffmann, and Frederic T. Chong. Partial compilation of variational algorithms for noisy intermediate-scale quantum machines. In *Proc. of the 52nd Annual IEEE/ACM International Symposium on Microarchitecture*, pages 266–278, 2019. DOI: [10.1145/3352460.3358313](https://doi.org/10.1145/3352460.3358313) 79, 131, 132, 140
- [160] Ali Javadi-Abhari, Pranav Gokhale, Adam Holmes, Diana Franklin, Kenneth R. Brown, Margaret Martonosi, and Frederic T. Chong. Optimized surface code communication in superconducting quantum computers. In *Proc. of the 50th Annual IEEE/ACM International Symposium on Microarchitecture*, pages 692–705, 2017. DOI: [10.1145/3123939.3123949](https://doi.org/10.1145/3123939.3123949) 79, 112
- [161] Yongshan Ding, Adam Holmes, Ali Javadi-Abhari, Diana Franklin, Margaret Martonosi, and Frederic Chong. Magic-state functional units: Mapping and scheduling multi-level distillation circuits for fault-tolerant quantum architectures. In *51st Annual IEEE/ACM International Symposium on Microarchitecture (MICRO)*, pages 828–840, 2018. DOI: [10.1109/micro.2018.00072](https://doi.org/10.1109/micro.2018.00072) 79, 106, 113, 117, 118
- [162] A. W. Cross. Unpublished. <https://www.media.mit.edu/quanta/quanta-web/projects/qasm-tools/> 81
- [163] Andrew W. Cross, Lev S. Bishop, John A. Smolin, and Jay M. Gambetta. Open quantum assembly language. *ArXiv Preprint ArXiv:1707.03429*, 2017. 82, 89
- [164] S. Bourdeauducq, et al. Advanced Real-Time Infrastructure for Quantum physics, ARTIQ 1.0. zenodo. <https://github.com/m-labs/artiq> 82
- [165] David C. McKay, Thomas Alexander, Luciano Bello, Michael J. Biercuk, Lev Bishop, Jiayin Chen, Jerry M. Chow, Antonio D. Córcoles, Daniel Egger, Stefan Filipp, et al. Qiskit backend specifications for openqasm and openpulse experiments. *ArXiv Preprint ArXiv:1809.03452*, 2018. 82, 106, 112, 113
- [166] Alexander S. Green, Peter LeFanu Lumsdaine, Neil J. Ross, Peter Selinger, and Benoît Valiron. Quipper: A scalable quantum programming language. In *ACM SIGPLAN Notices*, 48:333–342, 2013. DOI: [10.1145/2491956.2462177](https://doi.org/10.1145/2491956.2462177) 83, 89

- [167] Andrei Lapets, Marcus P. da Silva, Mike Thome, Aaron Adler, Jacob Beal, and Martin Rötteler. Quaff: A typed DSL for quantum programming. In *Proc. of the 1st Annual Workshop on Functional Programming Concepts in Domain-Specific Languages*, pages 19–26, ACM, 2013. DOI: [10.1145/2505351.2505357](https://doi.org/10.1145/2505351.2505357) 83
- [168] Dave Wecker and Krysta M. Svore. Liqui|>: A software design architecture and domain-specific language for quantum computing. *ArXiv Preprint ArXiv:1402.4467*, 2014. 83
- [169] Krysta M. Svore, Alan Geller, Matthias Troyer, John Azariah, Christopher Granade, Bettina Heim, Vadym Kliuchnikov, Mariia Mykhailova, Andres Paz, and Martin Roetteler. Q#: Enabling scalable quantum computing and development with a high-level domain-specific language. *ArXiv Preprint ArXiv:1803.00652*, 2018. 83, 89
- [170] Ali JavadiAbhari, Shruti Patil, Daniel Kudrow, Jeff Heckey, Alexey Lvov, Frederic T. Chong, and Margaret Martonosi. ScaffCC: Scalable compilation and analysis of quantum programs. *Parallel Computing*, 45:2–17, 2015. DOI: [10.1016/j.parco.2014.12.001](https://doi.org/10.1016/j.parco.2014.12.001) 83, 105, 113
- [171] Damian S. Steiger, Thomas Häner, and Matthias Troyer. Projectq: An open source software framework for quantum computing. *Quantum*, 2(49):10–22331, 2018. DOI: [10.22331/q-2018-01-31-49](https://doi.org/10.22331/q-2018-01-31-49) 83
- [172] Robert S. Smith, Michael J. Curtis, and William J. Zeng. A practical quantum instruction set architecture. *ArXiv Preprint ArXiv:1608.03355*, 2016. 83, 89
- [173] Microsoft Quantum Computing. <https://www.microsoft.com/en-us/quantum/> 83
- [174] Amazon Braket. <https://aws.amazon.com/braket/> 83
- [175] Ashley Montanaro and Ronald de Wolf. A survey of quantum property testing. *ArXiv Preprint ArXiv:1310.2035*, 2013. 84, 86, 87
- [176] Anne Broadbent. How to verify a quantum computation. *ArXiv Preprint ArXiv:1509.09180*, 2015. 84
- [177] Urmila Mahadev. Classical verification of quantum computations. In *IEEE 59th Annual Symposium on Foundations of Computer Science (FOCS)*, pages 259–267, 2018. DOI: [10.1109/focs.2018.00033](https://doi.org/10.1109/focs.2018.00033) 84
- [178] Ben W. Reichardt, Falk Unger, and Umesh Vazirani. Classical command of quantum systems. *Nature*, 496(7446):456, 2013. DOI: [10.1038/nature12035](https://doi.org/10.1038/nature12035) 84
- [179] John Preskill. Quantum computing and the entanglement frontier. *ArXiv Preprint ArXiv:1203.5813*, 2012. 85



- [180] Sergey Bravyi and David Gosset. Improved classical simulation of quantum circuits dominated by Clifford gates. *Physical Review Letters*, 116(25):250501, 2016. DOI: [10.1103/physrevlett.116.250501](https://doi.org/10.1103/physrevlett.116.250501) 85, 148, 164
- [181] Harry Buhrman, Richard Cleve, John Watrous, and Ronald De Wolf. Quantum fingerprinting. *Physical Review Letters*, 87(16):167902, 2001. DOI: [10.1103/physrevlett.87.167902](https://doi.org/10.1103/physrevlett.87.167902) 87
- [182] Hirotada Kobayashi, Keiji Matsumoto, and Tomoyuki Yamakami. Quantum Merlin-Arthur proof systems: Are multiple Merlins more helpful to Arthur? In *International Symposium on Algorithms and Computation*, pages 189–198, Springer, 2003. DOI: [10.1007/978-3-540-24587-2\\_21](https://doi.org/10.1007/978-3-540-24587-2_21) 87
- [183] Masaru Kada, Harumichi Nishimura, and Tomoyuki Yamakami. The efficiency of quantum identity testing of multiple states. *Journal of Physics A: Mathematical and Theoretical*, 41(39):395309, 2008. DOI: [10.1088/1751-8113/41/39/395309](https://doi.org/10.1088/1751-8113/41/39/395309) 87
- [184] Florian Mintert, Marek Kuś, and Andreas Buchleitner. Concurrence of mixed multipartite quantum states. *Physical Review Letters*, 95(26):260502, 2005. DOI: [10.1103/physrevlett.95.260502](https://doi.org/10.1103/physrevlett.95.260502) 87
- [185] Aram W. Harrow and Ashley Montanaro. Testing product states, quantum merlin-arthur games and tensor optimization. *Journal of the ACM (JACM)*, 60(1):3, 2013. DOI: [10.1145/2432622.2432625](https://doi.org/10.1145/2432622.2432625) 87
- [186] Scott Aaronson and Daniel Gottesman. Identifying stabilizer states, 2008. 88
- [187] David Perez-Garcia, Frank Verstraete, Michael M. Wolf, and J. Ignacio Cirac. Matrix product state representations. *ArXiv Preprint quant-ph/0608197*, 2006. 88
- [188] Andrew M. Childs, Aram W. Harrow, and Paweł Woćjan. Weak fourier-schur sampling, the hidden subgroup problem, and the quantum collision problem. In *Annual Symposium on Theoretical Aspects of Computer Science*, pages 598–609, Springer, 2007. DOI: [10.1007/978-3-540-70918-3\\_51](https://doi.org/10.1007/978-3-540-70918-3_51) 88
- [189] Otfried Gühne and Géza Tóth. Entanglement detection. *Physics Reports*, 474(1-6):1–75, 2009. DOI: [10.1016/j.physrep.2009.02.004](https://doi.org/10.1016/j.physrep.2009.02.004) 88
- [190] Guoming Wang. Property testing of unitary operators. *Physical Review A*, 84(5):052328, 2011. DOI: [10.1103/physreva.84.052328](https://doi.org/10.1103/physreva.84.052328) 88, 89
- [191] Man-Duen Choi. Completely positive linear maps on complex matrices. *Linear Algebra and its Applications*, 10(3):285–290, 1975. DOI: [10.1016/0024-3795\(75\)90075-0](https://doi.org/10.1016/0024-3795(75)90075-0) 88

- [192] Andrzej Jamiołkowski. Linear transformations which preserve trace and positive semidefiniteness of operators. *Reports on Mathematical Physics*, 3(4):275–278, 1972. DOI: [10.1016/0034-4877\(72\)90011-0](https://doi.org/10.1016/0034-4877(72)90011-0) 88
- [193] Ashley Montanaro and Tobias J. Osborne. Quantum boolean functions. *ArXiv Preprint ArXiv:0810.2435*, 2008. 89
- [194] Lev Glebsky. Almost commuting matrices with respect to normalized Hilbert–Schmidt norm. *ArXiv Preprint ArXiv:1002.3082*, 2010. 89
- [195] Robert Rand, Jennifer Paykin, and Steve Zdancewic. Qwire practice: Formal verification of quantum circuits in COQ. *ArXiv Preprint ArXiv:1803.00699*, 2018. DOI: [10.4204/eptcs.266.8](https://doi.org/10.4204/eptcs.266.8) 89
- [196] Bruno Barras, Samuel Boutin, Cristina Cornes, Judicael Courant, Jean-Christophe Filliatre, Eduardo Gimenez, Hugo Herbelin, Gerard Huet, Cesar Munoz, Chetan Murthy, et al. The Coq proof assistant reference manual: Version 6.1. 1997. 89
- [197] Matthew Amy. Towards large-scale functional verification of universal quantum circuits. *ArXiv Preprint ArXiv:1805.06908*, 2018. DOI: [10.4204/eptcs.287.1](https://doi.org/10.4204/eptcs.287.1) 89
- [198] Mingsheng Ying. Floyd–hoare logic for quantum programs. *ACM Transactions on Programming Languages and Systems (TOPLAS)*, 33(6):19, 2011. DOI: [10.1145/2049706.2049708](https://doi.org/10.1145/2049706.2049708) 89
- [199] Mingsheng Ying. *Foundations of Quantum Programming*. Morgan Kaufmann, 2016. DOI: [10.1016/c2014-0-02660-3](https://doi.org/10.1016/c2014-0-02660-3) 89
- [200] Dominique Unruh. Quantum relational hoare logic. *Proc. of the ACM on Programming Languages*, 3(POPL):33, 2019. DOI: [10.1145/3290346](https://doi.org/10.1145/3290346) 89
- [201] Matthew Amy, Martin Roetteler, and Krysta M. Svore. Verified compilation of space-efficient reversible circuits. In *International Conference on Computer Aided Verification*, pages 3–21, Springer, 2017. DOI: [10.1007/978-3-319-63390-9\\_1](https://doi.org/10.1007/978-3-319-63390-9_1) 89, 121
- [202] André Van Tonder. A lambda calculus for quantum computation. *SIAM Journal on Computing*, 33(5):1109–1135, 2004. DOI: [10.1137/s0097539703432165](https://doi.org/10.1137/s0097539703432165) 89
- [203] Peter Selinger and Benoit Valiron. A lambda calculus for quantum computation with classical control. *Mathematical Structures in Computer Science*, 16(3):527–552, 2006. DOI: [10.1007/11417170\\_26](https://doi.org/10.1007/11417170_26) 89
- [204] Bob Coecke and Ross Duncan. Interacting quantum observables. In *International Colloquium on Automata, Languages, and Programming*, pages 298–310, Springer, 2008. DOI: [10.1007/978-3-540-70583-3\\_25](https://doi.org/10.1007/978-3-540-70583-3_25) 90

- [205] Miriam Backens. The  $zx$ -calculus is complete for stabilizer quantum mechanics. *New Journal of Physics*, 16(9):093021, 2014. DOI: [10.1088/1367-2630/16/9/093021](https://doi.org/10.1088/1367-2630/16/9/093021) 90
- [206] Amar Hadzihasanovic. The algebra of entanglement and the geometry of composition. *ArXiv Preprint ArXiv:1709.08086*, 2017. 90
- [207] Ken Matsumoto and Kazuyuki Amano. Representation of quantum circuits with Clifford and  $\pi/8$  gates. *ArXiv Preprint ArXiv:0806.3834*, 2008. 94, 100, 101
- [208] Neil J. Ross and Peter Selinger. Optimal ancilla-free clifford+  $t$  approximation of  $z$ -rotations. *ArXiv Preprint ArXiv:1403.2975*, 2014. 94, 100, 101
- [209] Simon Forest, David Gosset, Vadym Kliuchnikov, and David McKinnon. Exact synthesis of single-qubit unitaries over Clifford-cyclotomic gate sets. *Journal of Mathematical Physics*, 56(8):082201, 2015. DOI: [10.1063/1.4927100](https://doi.org/10.1063/1.4927100) 94, 101
- [210] Alex Bocharov, Yuri Gurevich, and Krysta M. Svore. Efficient decomposition of single-qubit gates into  $v$  basis circuits. *Physical Review A*, 88(1):012313, 2013. DOI: [10.1103/physreva.88.012313](https://doi.org/10.1103/physreva.88.012313) 94, 100, 101
- [211] Vadym Kliuchnikov, Alex Bocharov, and Krysta M. Svore. Asymptotically optimal topological quantum compiling. *Physical Review Letters*, 112(14):140504, 2014. DOI: [10.1103/physrevlett.112.140504](https://doi.org/10.1103/physrevlett.112.140504) 94, 101, 105
- [212] Alex Parent, Martin Roetteler, and Krysta M. Svore. Reversible circuit compilation with space constraints. *ArXiv Preprint ArXiv:1510.00377*, 2015. 99, 121, 122
- [213] Charles Bennett. Time/space trade-offs for reversible computation. *SLAM Journal on Computing*, 18(4):766–776, 1989. DOI: [10.1137/0218053](https://doi.org/10.1137/0218053) 99, 121, 122
- [214] Aram W. Harrow, Avinandan Hassidim, and Seth Lloyd. Quantum algorithm for linear systems of equations. *Physical Review Letters*, 103(15):150502, 2009. DOI: [10.1103/physrevlett.103.150502](https://doi.org/10.1103/physrevlett.103.150502) 99, 121
- [215] Vadym Kliuchnikov, Dmitri Maslov, and Michele Mosca. Fast and efficient exact synthesis of single qubit unitaries generated by Clifford and  $t$  gates. *ArXiv Preprint ArXiv:1206.5236*, 2012. 100, 149
- [216] Brett Giles and Peter Selinger. Remarks on Matsumoto and Amano’s normal form for single-qubit Clifford+  $t$  operators. *ArXiv Preprint ArXiv:1312.6584*, 2013. 100, 101
- [217] Matthew Amy, Andrew N. Glauddell, and Neil J. Ross. Number-theoretic characterizations of some restricted Clifford+  $t$  circuits. *Quantum*, 4:252, 2020. DOI: [10.22331/q-2020-04-06-252](https://doi.org/10.22331/q-2020-04-06-252) 101

- [218] Neil J. Ross. Optimal ancilla-free Clifford+  $v$  approximation of  $z$ -rotations. *Quantum Information and Computation*, 15(11–12):932–950, 2015. 101
- [219] Andrew N. Glaudell, Neil J. Ross, and Jacob M. Taylor. Optimal two-qubit circuits for universal fault-tolerant quantum computation. *ArXiv Preprint ArXiv:2001.05997*, 2020. 101
- [220] Christopher M. Dawson and Michael A. Nielsen. The Solovay–Kitaev algorithm. *ArXiv Preprint quant-ph/0505030*, 2005. 103
- [221] Matthew Amy, Dmitri Maslov, Michele Mosca, and Martin Roetteler. A meet-in-the-middle algorithm for fast synthesis of depth-optimal quantum circuits. *IEEE Transactions on Computer-Aided Design of Integrated Circuits and Systems*, 32(6):818–830, 2013. DOI: 10.1109/tcad.2013.2244643 103
- [222] Aram W. Harrow, Benjamin Recht, and Isaac L. Chuang. Efficient discrete approximations of quantum gates. *Journal of Mathematical Physics*, 43(9):4445–4451, 2002. DOI: 10.1063/1.1495899 104
- [223] Alex Bocharov, Shawn X. Cui, Martin Roetteler, and Krysta M. Svore. Improved quantum ternary arithmetics. *ArXiv Preprint ArXiv:1512.03824*, 2015. 105
- [224] Alex Bocharov, Kingshan Cui, Vadym Kliuchnikov, and Zhenghan Wang. Efficient topological compilation for a weakly integral anyonic model. *Physical Review A*, 93(1):012313, 2016. DOI: 10.1103/physreva.93.012313 105
- [225] Andrew N. Glaudell, Neil J. Ross, and Jacob M. Taylor. Canonical forms for single-qutrit Clifford+  $t$  operators. *Annals of Physics*, 406:54–70, 2019. DOI: 10.1016/j.aop.2019.04.001 105
- [226] Pranav Gokhale, Jonathan M. Baker, Casey Duckering, Natalie C. Brown, Kenneth R. Brown, and Frederic T. Chong. Asymptotic improvements to quantum circuits via qutrits. In *Proc. of the 46th International Symposium on Computer Architecture*, pages 554–566, ACM, 2019. DOI: 10.1145/3307650.3322253 105, 124
- [227] Yongshan Ding, Xin-Chuan Wu, Adam Holmes, Ash Wiseth, Diana Franklin, Margaret Martonosi, and Frederic T. Chong. Square: Strategic quantum ancilla reuse for modular quantum programs via cost-effective uncomputation. *ArXiv Preprint ArXiv:2004.08539*, 2020. 106, 123
- [228] Prakash Murali, Jonathan M. Baker, Ali Javadi-Abhari, Frederic T. Chong, and Margaret Martonosi. Noise-adaptive compiler mappings for noisy intermediate-scale quantum computers. In *Proc. of the 24th International Conference on Architectural Support for Programming Languages and Operating Systems*, pages 1015–1029, ACM, 2019. DOI: 10.1145/3297858.3304075 106, 140

- [229] Swamit S. Tannu and Moinuddin K. Qureshi. Not all qubits are created equal: A case for variability-aware policies for NISQ era quantum computers. In *Proc. of the 24th International Conference on Architectural Support for Programming Languages and Operating Systems*, pages 987–999, ACM, 2019. DOI: [10.1145/3297858.3304007](https://doi.org/10.1145/3297858.3304007) 106, 140
- [230] Gushu Li, Yufei Ding, and Yuan Xie. Tackling the qubit mapping problem for NISQ era quantum devices. In *Proc. of the 24th International Conference on Architectural Support for Programming Languages and Operating Systems*, pages 1001–1014, 2019. DOI: [10.1145/3297858.3304023](https://doi.org/10.1145/3297858.3304023) 106
- [231] Shin Nishio, Yulu Pan, Takahiko Satoh, Hideharu Amano, and Rodney Van Meter. Extracting success from IBM’s 20-qubit machines using error-aware compilation. *ArXiv Preprint ArXiv:1903.10963*, 2019. 106
- [232] Prakash Murali, David C. McKay, Margaret Martonosi, and Ali Javadi-Abhari. Software mitigation of crosstalk on noisy intermediate-scale quantum computers. *ArXiv Preprint ArXiv:2001.02826*, 2020. DOI: [10.1145/3373376.3378477](https://doi.org/10.1145/3373376.3378477) 106, 140, 141
- [233] Daniel Gottesman and Isaac L. Chuang. Demonstrating the viability of universal quantum computation using teleportation and single-qubit operations. *Nature*, 402(6760):390–393, 1999. DOI: [10.1038/46503](https://doi.org/10.1038/46503) 106, 114, 148
- [234] Daniel Gottesman and Isaac L. Chuang. Quantum teleportation is a universal computational primitive. *ArXiv Preprint quant-ph/9908010*, 1999. 106, 147
- [235] Dong-Sheng Wang. Choi states, symmetry-based quantum gate teleportation, and stored-program quantum computing. *Physical Review A*, 101(5):052311, 2020. DOI: [10.1103/physreva.101.052311](https://doi.org/10.1103/physreva.101.052311) 106
- [236] Mark Oskin, Frederic T. Chong, Isaac L. Chuang, and John Kubiatowicz. Building quantum wires: The long and the short of it. In *Proc. of the 30th Annual International Symposium on Computer Architecture*, pages 374–385, IEEE, 2003. DOI: [10.1145/871656.859661](https://doi.org/10.1145/871656.859661) 106
- [237] Sumeet Khatri, Ryan LaRose, Alexander Poremba, Lukasz Cincio, Andrew T. Sornborger, and Patrick J. Coles. Quantum-assisted quantum compiling. *Quantum*, 3:140, 2019. DOI: [10.22331/q-2019-05-13-140](https://doi.org/10.22331/q-2019-05-13-140) 106
- [238] Gian Giacomo Guerreschi and Jongsoo Park. Two-step approach to scheduling quantum circuits. *Quantum Science and Technology*, 3(4):045003, 2018. DOI: [10.1088/2058-9565/aacf0b](https://doi.org/10.1088/2058-9565/aacf0b) 110

- [239] Jeff Heckey, Shruti Patil, Ali JavadiAbhari, Adam Holmes, Daniel Kudrow, Kenneth R. Brown, Diana Franklin, Frederic T. Chong, and Margaret Martonosi. Compiler management of communication and parallelism for quantum computation. In *ACM SIGARCH Computer Architecture News*, 43:445–456, 2015. DOI: [10.1145/2775054.2694357](https://doi.org/10.1145/2775054.2694357) 112
- [240] Adam Holmes, Yongshan Ding, Ali Javadi-Abhari, Diana Franklin, Margaret Martonosi, and Frederic T. Chong. Resource optimized quantum architectures for surface code implementations of magic-state distillation. *Microprocessors and Microsystems*, 67:56–70, 2019. DOI: [10.1016/j.micpro.2019.02.007](https://doi.org/10.1016/j.micpro.2019.02.007) 113
- [241] Michael R. Garey and David S. Johnson. Crossing number is NP-complete. *SIAM Journal on Algebraic Discrete Methods*, 4(3):312–316, 1983. DOI: [10.1137/0604033](https://doi.org/10.1137/0604033) 118
- [242] Julia Chuzhoy, Yury Makarychev, and Anastasios Sidiropoulos. On graph crossing number and edge planarization. In *Proc. of the 22nd Annual ACM-SIAM Symposium on Discrete Algorithms*, pages 1050–1069, 2011. DOI: [10.1137/1.9781611973082.80](https://doi.org/10.1137/1.9781611973082.80) 118
- [243] Walter Schnyder. Embedding planar graphs on the grid. In *Proc. of the 1st Annual ACM-SIAM Symposium on Discrete Algorithms*, pages 138–148, Society for Industrial and Applied Mathematics, 1990. 118
- [244] Brian W. Kernighan and Shen Lin. An efficient heuristic procedure for partitioning graphs. *The Bell System Technical Journal*, 49(2):291–307, 1970. DOI: [10.1002/j.1538-7305.1970.tb01770.x](https://doi.org/10.1002/j.1538-7305.1970.tb01770.x) 118
- [245] Earl R. Barnes. An algorithm for partitioning the nodes of a graph. *SIAM Journal on Algebraic Discrete Methods*, 3(4):541–550, 1982. DOI: [10.1109/cdc.1981.269534](https://doi.org/10.1109/cdc.1981.269534) 118
- [246] George Karypis and Vipin Kumar. Multilevel  $k$ -way hypergraph partitioning. *VLSI Design*, 11(3):285–300, 2000. DOI: [10.1145/309847.309954](https://doi.org/10.1145/309847.309954) 118
- [247] George Karypis and Vipin Kumar. Metis—unstructured graph partitioning and sparse matrix ordering system, version 2.0. 1995. 118
- [248] François Pellegrini and Jean Roman. Scotch: A software package for static mapping by dual recursive bipartitioning of process and architecture graphs. In *International Conference on High-Performance Computing and Networking*, pages 493–498, Springer, 1996. DOI: [10.1007/3-540-61142-8\\_588](https://doi.org/10.1007/3-540-61142-8_588) 118
- [249] Thomas M. J. Fruchterman and Edward M. Reingold. Graph drawing by force-directed placement. *Software: Practice and Experience*, 21(11):1129–1164, 1991. DOI: [10.1002/spe.4380211102](https://doi.org/10.1002/spe.4380211102) 118

- [250] Chun-Cheng Lin and Hsu-Chun Yen. A new force-directed graph drawing method based on edge—edge repulsion. *Journal of Visual Languages and Computing*, 23(1):29–42, 2012. DOI: [10.1109/iv.2005.10](https://doi.org/10.1109/iv.2005.10) 118
- [251] Yifan Hu. Efficient, high-quality force-directed graph drawing. *Mathematica Journal*, 10(1):37–71, 2005. 118
- [252] William E. Donath and Alan J. Hoffman. Lower bounds for the partitioning of graphs. *IBM Journal of Research and Development*, 17(5):420–425, 1973. DOI: [10.1142/9789812796936\\_0044](https://doi.org/10.1142/9789812796936_0044) 119
- [253] Michelle Girvan and Mark E. J. Newman. Community structure in social and biological networks. *Proc. of the National Academy of Sciences*, 99(12):7821–7826, 2002. DOI: [10.1073/pnas.122653799](https://doi.org/10.1073/pnas.122653799) 119
- [254] Miroslav Fiedler. Algebraic connectivity of graphs. *Czechoslovak Mathematical Journal*, 23(2):298–305, 1973. 119
- [255] Barry D. Hughes. Random walks and random environments. 1995. 119
- [256] Vincent D. Blondel, Jean-Loup Guillaume, Renaud Lambiotte, and Etienne Lefebvre. Fast unfolding of communities in large networks. *Journal of Statistical Mechanics: Theory and Experiment*, (10):10008, 2008. DOI: [10.1088/1742-5468/2008/10/p10008](https://doi.org/10.1088/1742-5468/2008/10/p10008) 119
- [257] Jordi Duch and Alex Arenas. Community detection in complex networks using extremal optimization. *Physical Review E*, 72(2):027104, 2005. DOI: [10.1103/physreve.72.027104](https://doi.org/10.1103/physreve.72.027104) 119
- [258] Tapas Kanungo, David M. Mount, Nathan S. Netanyahu, Christine D. Piatko, Ruth Silverman, and Angela Y. Wu. An efficient  $k$ -means clustering algorithm: Analysis and implementation. *IEEE Transactions on Pattern Analysis and Machine Intelligence*, 24(7):881–892, 2002. DOI: [10.1109/tpami.2002.1017616](https://doi.org/10.1109/tpami.2002.1017616) 119
- [259] David Arthur and Sergei Vassilvitskii.  $k$ -means++: The advantages of careful seeding. In *Proc. of the 18th Annual ACM-SIAM Symposium on Discrete Algorithms*, pages 1027–1035, Society for Industrial and Applied Mathematics, 2007. 119
- [260] Alexandru Paler, Austin G. Fowler, and Robert Wille. Faster manipulation of large quantum circuits using wire label reference diagrams. *Microprocessors and Microsystems*, 66:55–66, 2019. DOI: [10.1016/j.micpro.2019.02.008](https://doi.org/10.1016/j.micpro.2019.02.008) 119
- [261] Alexandru Paler, Robert Wille, and Simon J. Devitt. Wire recycling for quantum circuit optimization. *Physical Review A*, 94(4):042337, 2016. DOI: [10.1103/physreva.94.042337](https://doi.org/10.1103/physreva.94.042337) 119

- [262] Thomas Häner, Martin Roetteler, and Krysta M. Svore. Factoring using  $2n + 2$  qubits with Toffoli based modular multiplication. *ArXiv Preprint ArXiv:1611.07995*, 2016. [120](#)
- [263] Craig Gidney. Factoring with  $n + 2$  clean qubits and  $n - 1$  dirty qubits. *ArXiv Preprint ArXiv:1706.07884*, 2017. [120](#)
- [264] Harry Buhrman, John Tromp, and Paul Vitányi. Time and space bounds for reversible simulation. In *International Colloquium on Automata, Languages, and Programming*, pages 1017–1027, Springer, 2001. DOI: [10.1088/0305-4470/34/35/308](#) [121](#), [122](#)
- [265] Siu Man Chan, Massimo Lauria, Jakob Nordstrom, and Marc Vinyals. Hardness of approximation in pspace and separation results for pebble games. In *IEEE 56th Annual Symposium on Foundations of Computer Science*, pages 466–485, 2015. DOI: [10.1109/focs.2015.36](#) [121](#)
- [266] Michael Patrick Frank and Thomas F. Knight Jr. Reversibility for efficient computing. Ph.D. thesis, Massachusetts Institute of Technology, Dept. of Electrical Engineering and Computer Science, 1999. [121](#)
- [267] Emanuel Knill. An analysis of Bennett’s pebble game. *ArXiv Preprint math/9508218*, 1995. [121](#)
- [268] Balagopal Komarath, Jayalal Sarma, and Saurabh Sawlani. Pebbling meets coloring: Reversible pebble game on trees. *Journal of Computer and System Sciences*, 91:33–41, 2018. DOI: [10.1016/j.jcss.2017.07.009](#) [121](#)
- [269] Giulia Meuli, Mathias Soeken, Martin Roetteler, Nikolaj Bjorner, and Giovanni De Micheli. Reversible pebbling game for quantum memory management. In *Design, Automation and Test in Europe Conference and Exhibition (DATE)*, pages 288–291, IEEE, 2019. DOI: [10.23919/date.2019.8715092](#) [121](#)
- [270] Thomas Häner, Damian S. Steiger, Krysta Svore, and Matthias Troyer. A software methodology for compiling quantum programs. *Quantum Science and Technology*, 3(2):020501, 2018. DOI: [10.1088/2058-9565/aaa5cc](#) [124](#)
- [271] Stephen S. Bullock, Dianne P. O’Leary, and Gavin K. Brennen. Asymptotically optimal quantum circuits for  $d$ -level systems. *Physical Review Letters*, 94(23):230502, 2005. DOI: [10.1103/physrevlett.94.230502](#) [124](#)
- [272] Marek Perkowski, Anas Al-Rabadi, and Pawel Kerttopf. Multiple-valued quantum logic synthesis. 2002. [124](#)
- [273] S. S. Ivanov, H. S. Tonchev, and N. V. Vitanov. Time-efficient implementation of quantum search with qudits. *Physical Review A*, 85(6):062321, 2012. DOI: [10.1103/physreva.85.062321](#) [124](#)



- [274] Alex Bocharov, Martin Roetteler, and Krysta M. Svore. Factoring with qutrits: Shor's algorithm on ternary and metaplectic quantum architectures. *Physical Review A*, 96(1):012306, 2017. DOI: [10.1103/physreva.96.012306](https://doi.org/10.1103/physreva.96.012306) 124
- [275] Greater Quantum Efficiency by Breaking Abstractions. <https://www.sigarch.org/greater-quantum-efficiency-by-breaking-abstractions/> 125
- [276] Domenico d'Alessandro. *Introduction to Quantum Control and Dynamics*. Chapman and Hall/CRC, 2007. DOI: [10.1201/9781584888833](https://doi.org/10.1201/9781584888833) 129
- [277] Gabriel Turinici and Herschel Rabitz. Quantum wavefunction controllability. *Chemical Physics*, 267(1–3):1–9, 2001. DOI: [10.1016/s0301-0104\(01\)00216-6](https://doi.org/10.1016/s0301-0104(01)00216-6) 129
- [278] Gabriel Turinici and Herschel Rabitz. Wavefunction controllability for finite-dimensional bilinear quantum systems. *Journal of Physics A: Mathematical and General*, 36(10):2565, 2003. DOI: [10.1088/0305-4470/36/10/316](https://doi.org/10.1088/0305-4470/36/10/316) 129
- [279] Warren S. Warren, Herschel Rabitz, and Mohammed Dahleh. Coherent control of quantum dynamics: The dream is alive. *Science*, 259(5101):1581–1589, 1993. DOI: [10.1126/science.259.5101.1581](https://doi.org/10.1126/science.259.5101.1581) 129
- [280] Seth Lloyd. Coherent quantum feedback. *Physical Review A*, 62(2):022108, 2000. DOI: [10.1103/physreva.62.022108](https://doi.org/10.1103/physreva.62.022108) 129
- [281] Moshe Shapiro and Paul Brumer. *Quantum Control of Molecular Processes*. John Wiley & Sons, 2012. DOI: [10.1002/9783527639700](https://doi.org/10.1002/9783527639700) 129
- [282] Mazyar Mirrahimi, Pierre Rouchon, and Gabriel Turinici. Lyapunov control of bilinear Schrödinger equations. *Automatica*, 41(11):1987–1994, 2005. DOI: [10.1016/j.automatica.2005.05.018](https://doi.org/10.1016/j.automatica.2005.05.018) 129
- [283] Sen Kuang and Shuang Cong. Lyapunov control methods of closed quantum systems. *Automatica*, 44(1):98–108, 2008. DOI: [10.1016/j.automatica.2007.05.013](https://doi.org/10.1016/j.automatica.2007.05.013) 129
- [284] Herschel Rabitz, Regina de Vivie-Riedle, Marcus Motzkus, and Karl Kompa. Whither the future of controlling quantum phenomena? *Science*, 288(5467):824–828, 2000. DOI: [10.1126/science.288.5467.824](https://doi.org/10.1126/science.288.5467.824) 129, 132
- [285] Richard S. Judson and Herschel Rabitz. Teaching lasers to control molecules. *Physical Review Letters*, 68(10):1500, 1992. DOI: [10.1103/physrevlett.68.1500](https://doi.org/10.1103/physrevlett.68.1500) 129
- [286] Marlan O. Scully and M. Suhail Zubairy. *Quantum optics*, 1999. DOI: [10.1017/cbo9780511813993](https://doi.org/10.1017/cbo9780511813993) 129

- [287] Moshe Shapiro and Paul Brumer. Principles of the quantum control of molecular processes. *Principles of the Quantum Control of Molecular Processes*, by Moshe Shapiro, Paul Brumer, page 250. Wiley-VCH, February, 2003. DOI: [10.1002/9783527311111.ch129](https://doi.org/10.1002/9783527311111.ch129)
- [288] Andrew C. Doherty, Salman Habib, Kurt Jacobs, Hideo Mabuchi, and Sze M. Tan. Quantum feedback control and classical control theory. *Physical Review A*, 62(1):012105, 2000. DOI: [10.1103/physreva.62.012105](https://doi.org/10.1103/physreva.62.012105)
- [289] Daoyi Dong and Ian R. Petersen. Quantum control theory and applications: A survey. *IET Control Theory and Applications*, 4(12):2651–2671, 2010. DOI: [10.1049/iet-cta.2009.0508](https://doi.org/10.1049/iet-cta.2009.0508)
- [290] Navin Khaneja, Timo Reiss, Cindie Kehlet, Thomas Schulte-Herbrüggen, and Steffen J. Glaser. Optimal control of coupled spin dynamics: Design of NMR pulse sequences by gradient ascent algorithms. *Journal of Magnetic Resonance*, 172(2):296–305, 2005. DOI: [10.1016/j.jmr.2004.11.004](https://doi.org/10.1016/j.jmr.2004.11.004)
- [291] P. de Fouquieres, S. G. Schirmer, S. J. Glaser, and I. Kuprov. Second order gradient ascent pulse engineering. *Journal of Magnetic Resonance*, 212:412–417, October 2011. DOI: [10.1016/j.jmr.2011.07.023](https://doi.org/10.1016/j.jmr.2011.07.023)
- [292] Nelson Leung, Mohamed Abdelhafez, Jens Koch, and David Schuster. Speedup for quantum optimal control from automatic differentiation based on graphics processing units. *Physical Review A*, 95(4):042318, 2017. DOI: [10.1103/physreva.95.042318](https://doi.org/10.1103/physreva.95.042318)
- [293] Mohamed Abdelhafez, David I. Schuster, and Jens Koch. Gradient-based optimal control of open quantum systems using quantum trajectories and automatic differentiation, 2019. DOI: [10.1103/physreva.99.052327](https://doi.org/10.1103/physreva.99.052327)
- [294] Florian Dolde, Ville Bergholm, Ya Wang, Ingmar Jakobi, Boris Naydenov, Sébastien Pezzagna, Jan Meijer, Fedor Jelezko, Philipp Neumann, Thomas Schulte-Herbrüggen, Jacob Biamonte, and Jörg Wrachtrup. High-fidelity spin entanglement using optimal control. *Nature Communications*, 5:3371 EP–, February 2014. DOI: [10.1038/ncomms4371](https://doi.org/10.1038/ncomms4371)
- [295] Yi Chou, Shang-Yu Huang, and Hsi-Sheng Goan. Optimal control of fast and high-fidelity quantum gates with electron and nuclear spins of a nitrogen-vacancy center in diamond. *Phys. Rev. A*, 91:052315, May 2015. DOI: [10.1103/physreva.91.052315](https://doi.org/10.1103/physreva.91.052315)
- [296] Steven Chu. Cold atoms and quantum control. *Nature*, 416(6877):206, 2002. DOI: [10.1038/416206a](https://doi.org/10.1038/416206a)

- [297] Howard M. Wiseman and Gerard J. Milburn. Quantum theory of optical feedback via homodyne detection. *Physical Review Letters*, 70(5):548, 1993. DOI: [10.1103/physrevlett.70.548](https://doi.org/10.1103/physrevlett.70.548) 132
- [298] Kenneth R. Brown, Aram W. Harrow, and Isaac L. Chuang. Arbitrarily accurate composite pulse sequences. *Physical Review A*, 70(5):052318, 2004. DOI: [10.1103/physreva.70.052318](https://doi.org/10.1103/physreva.70.052318) 132, 150
- [299] Erwin L. Hahn. Spin echoes. *Physical Review*, 80(4):580, 1950. DOI: [10.1063/1.3066708](https://doi.org/10.1063/1.3066708) 132
- [300] Herman Y. Carr and Edward M. Purcell. Effects of diffusion on free precession in nuclear magnetic resonance experiments. *Physical Review*, 94(3):630, 1954. DOI: [10.1103/physrev.94.630](https://doi.org/10.1103/physrev.94.630) 132
- [301] Saul Meiboom and David Gill. Modified spin-echo method for measuring nuclear relaxation times. *Review of Scientific Instruments*, 29(8):688–691, 1958. DOI: [10.1063/1.1716296](https://doi.org/10.1063/1.1716296) 132
- [302] Jonas Bylander, Simon Gustavsson, Fei Yan, Fumiki Yoshihara, Khalil Harrabi, George Fitch, David G. Cory, Yasunobu Nakamura, Jaw-Shen Tsai, and William D. Oliver. Noise spectroscopy through dynamical decoupling with a superconducting flux qubit. *Nature Physics*, 7(7):565–570, 2011. DOI: [10.1038/nphys1994](https://doi.org/10.1038/nphys1994) 132
- [303] Mohamed Abdelhafez, David I. Schuster, and Jens Koch. Gradient-based optimal control of open quantum systems using quantum trajectories and automatic differentiation. *Physical Review A*, 99(5):052327, 2019. DOI: [10.1103/physreva.99.052327](https://doi.org/10.1103/physreva.99.052327) 132
- [304] Navin Khaneja, Timo Reiss, Cindie Kehlet, Thomas Schulte-Herbrüggen, and Steffen J. Glaser. Optimal control of coupled spin dynamics: Design of NMR pulse sequences by gradient ascent algorithms. *Journal of Magnetic Resonance*, 172(2):296–305, 2005. DOI: [10.1016/j.jmr.2004.11.004](https://doi.org/10.1016/j.jmr.2004.11.004) 132
- [305] Yunong Shi, Nelson Leung, Pranav Gokhale, Zane Rossi, David I. Schuster, Henry Hoffmann, and Frederic T. Chong. Optimized compilation of aggregated instructions for realistic quantum computers. In *Proc. of the 24th International Conference on Architectural Support for Programming Languages and Operating Systems*, pages 1031–1044, ACM, 2019. DOI: [10.1145/3297858.3304018](https://doi.org/10.1145/3297858.3304018) 132, 140
- [306] A. J. Skinner, M. E. Davenport, and Bruce E. Kane. Hydrogenic spin quantum computing in silicon: A digital approach. *Physical Review Letters*, 90(8):087901, 2003. DOI: [10.1103/physrevlett.90.087901](https://doi.org/10.1103/physrevlett.90.087901) 132

- [307] Stephen H. Gunther, Frank Binns, Jack D. Pippin, Linda J. Rankin, Edward A. Burton, Douglas M. Carmean, and John M. Bauer. Methods and apparatus for thermal management of an integrated circuit die, September 7, 2004. U.S. Patent 6,789,037. 132
- [308] Adam Holmes, Mohammad Reza Jokar, Ghasem Pasandi, Yongshan Ding, Massoud Pedram, and Frederic T. Chong. NISQ+: Boosting quantum computing power by approximating quantum error correction. *ArXiv Preprint ArXiv:2004.04794*, 2020. 132
- [309] Swamit S. Tannu, Douglas M. Carmean, and Moinuddin K. Qureshi. Cryogenic-dram based memory system for scalable quantum computers: A feasibility study. In *Proc. of the International Symposium on Memory Systems*, pages 189–195, ACM, 2017. DOI: [10.1145/3132402.3132436](https://doi.org/10.1145/3132402.3132436) 132
- [310] Isaac L. Chuang and Michael A. Nielsen. Prescription for experimental determination of the dynamics of a quantum black box. *Journal of Modern Optics*, 44(11–12):2455–2467, 1997. DOI: [10.1080/09500349708231894](https://doi.org/10.1080/09500349708231894) 136
- [311] J. F. Poyatos, J. Ignacio Cirac, and Peter Zoller. Complete characterization of a quantum process: The two-bit quantum gate. *Physical Review Letters*, 78(2):390, 1997. DOI: [10.1103/physrevlett.78.390](https://doi.org/10.1103/physrevlett.78.390) 136
- [312] Marcus P. da Silva, Olivier Landon-Cardinal, and David Poulin. Practical characterization of quantum devices without tomography. *Physical Review Letters*, 107(21):210404, 2011. DOI: [10.1103/physrevlett.107.210404](https://doi.org/10.1103/physrevlett.107.210404) 136
- [313] Steven T. Flammia, David Gross, Yi-Kai Liu, and Jens Eisert. Quantum tomography via compressed sensing: Error bounds, sample complexity and efficient estimators. *New Journal of Physics*, 14(9):095022, 2012. DOI: [10.1088/1367-2630/14/9/095022](https://doi.org/10.1088/1367-2630/14/9/095022) 136
- [314] Steven T. Flammia and Yi-Kai Liu. Direct fidelity estimation from few Pauli measurements. *Physical Review Letters*, 106(23):230501, 2011. DOI: [10.1103/physrevlett.106.230501](https://doi.org/10.1103/physrevlett.106.230501) 136
- [315] Joseph Emerson, Robert Alicki, and Karol Życzkowski. Scalable noise estimation with random unitary operators. *Journal of Optics B: Quantum and Semiclassical Optics*, 7(10):S347, 2005. DOI: [10.1088/1464-4266/7/10/021](https://doi.org/10.1088/1464-4266/7/10/021) 136
- [316] Benjamin Lévi, Cecilia C. López, Joseph Emerson, and David G. Cory. Efficient error characterization in quantum information processing. *Physical Review A*, 75(2):022314, 2007. DOI: [10.1103/physreva.75.022314](https://doi.org/10.1103/physreva.75.022314) 136
- [317] Emanuel Knill, Dietrich Leibfried, Rolf Reichle, Joe Britton, R. Brad Blakestad, John D. Jost, Chris Langer, Roe Ozeri, Signe Seidelin, and David J. Wineland. Randomized benchmarking of quantum gates. *Physical Review A*, 77(1):012307, 2008. DOI: [10.1103/physreva.77.012307](https://doi.org/10.1103/physreva.77.012307) 136

- [318] Christoph Dankert, Richard Cleve, Joseph Emerson, and Etera Livine. Exact and approximate unitary 2-designs and their application to fidelity estimation. *Physical Review A*, 80(1):012304, 2009. DOI: [10.1103/physreva.80.012304](https://doi.org/10.1103/physreva.80.012304) 136
- [319] Easwar Magesan, Jay M. Gambetta, and Joseph Emerson. Scalable and robust randomized benchmarking of quantum processes. *Physical Review Letters*, 106(18):180504, 2011. DOI: [10.1103/physrevlett.106.180504](https://doi.org/10.1103/physrevlett.106.180504) 136
- [320] True-Q design by quantum benchmark. <https://trueq.quantumbenchmark.com/index.html> 137
- [321] Easwar Magesan, Jay M. Gambetta, Blake R. Johnson, Colm A. Ryan, Jerry M. Chow, Seth T. Merkel, Marcus P. Da Silva, George A. Keefe, Mary B. Rothwell, Thomas A. Ohki, et al. Efficient measurement of quantum gate error by interleaved randomized benchmarking. *Physical Review Letters*, 109(8):080505, 2012. DOI: [10.1103/physrevlett.109.080505](https://doi.org/10.1103/physrevlett.109.080505) 137
- [322] Joseph Emerson, Marcus Silva, Osama Moussa, Colm Ryan, Martin Laforest, Jonathan Baugh, David G. Cory, and Raymond Laflamme. Symmetrized characterization of noisy quantum processes. *Science*, 317(5846):1893–1896, 2007. DOI: [10.1126/science.1145699](https://doi.org/10.1126/science.1145699) 137
- [323] Joel Wallman, Chris Granade, Robin Harper, and Steven T. Flammia. Estimating the coherence of noise. *New Journal of Physics*, 17(11):113020, 2015. DOI: [10.1088/1367-2630/17/11/113020](https://doi.org/10.1088/1367-2630/17/11/113020) 137
- [324] Joel J. Wallman, Marie Barnhill, and Joseph Emerson. Robust characterization of loss rates. *Physical Review Letters*, 115(6):060501, 2015. DOI: [10.1103/physrevlett.115.060501](https://doi.org/10.1103/physrevlett.115.060501) 137
- [325] Andrew W. Cross, Easwar Magesan, Lev S. Bishop, John A. Smolin, and Jay M. Gambetta. Scalable randomised benchmarking of non-clifford gates. *NPJ Quantum Information*, 2:16012, 2016. DOI: [10.1038/npjqi.2016.12](https://doi.org/10.1038/npjqi.2016.12) 137
- [326] Arnaud Carignan-Dugas, Joel J. Wallman, and Joseph Emerson. Characterizing universal gate sets via dihedral benchmarking. *Physical Review A*, 92(6):060302, 2015. DOI: [10.1103/physreva.92.060302](https://doi.org/10.1103/physreva.92.060302) 137
- [327] Bas Dirkse, Jonas Helsen, and Stephanie Wehner. Efficient unitarity randomized benchmarking of few-qubit Clifford gates. *Physical Review A*, 99(1):012315, 2019. DOI: [10.1103/physreva.99.012315](https://doi.org/10.1103/physreva.99.012315) 137
- [328] Alexander Erhard, Joel James Wallman, Lukas Postler, Michael Meth, Roman Stricker, Esteban Adrian Martinez, Philipp Schindler, Thomas Monz, Joseph Emerson, and

- Rainer Blatt. Characterizing large-scale quantum computers via cycle benchmarking. *ArXiv Preprint ArXiv:1902.08543*, 2019. DOI: [10.1038/s41467-019-13068-7](https://doi.org/10.1038/s41467-019-13068-7) 137, 150
- [329] Joel J. Wallman and Joseph Emerson. Noise tailoring for scalable quantum computation via randomized compiling. *Physical Review A*, 94(5):052325, 2016. DOI: [10.1103/physreva.94.052325](https://doi.org/10.1103/physreva.94.052325) 139
- [330] Prakash Murali, Norbert Matthias Linke, Margaret Martonosi, Ali Javadi Abhari, Nhung Hong Nguyen, and Cinthia Huerta Alderete. Full-stack, real-system quantum computer studies: Architectural comparisons and design insights. In *Proc. of the 46th International Symposium on Computer Architecture*, pages 527–540, ACM, 2019. DOI: [10.1145/3307650.3322273](https://doi.org/10.1145/3307650.3322273) 140
- [331] Markus Brink, Jerry M. Chow, Jared Hertzberg, Easwar Magesan, and Sami Rosenblatt. Device challenges for near term superconducting quantum processors: Frequency collisions. In *IEEE International Electron Devices Meeting (IEDM)*, pages 6–1, 2018. DOI: [10.1109/iedm.2018.8614500](https://doi.org/10.1109/iedm.2018.8614500) 140
- [332] Gushu Li, Yufei Ding, and Yuan Xie. Towards efficient superconducting quantum processor architecture design. In *Proc. of the 25th International Conference on Architectural Support for Programming Languages and Operating Systems*, pages 1031–1045, 2020. DOI: [10.1145/3373376.3378500](https://doi.org/10.1145/3373376.3378500) 140, 141
- [333] M. D. Hutchings, Jared B. Hertzberg, Yebin Liu, Nicholas T. Bronn, George A. Keefe, Markus Brink, Jerry M. Chow, and B. L. T. Plourde. Tunable superconducting qubits with flux-independent coherence. *Physical Review Applied*, 8(4):044003, 2017. DOI: [10.1103/physrevapplied.8.044003](https://doi.org/10.1103/physrevapplied.8.044003) 140
- [334] R. Barends, C. M. Quintana, A. G. Petukhov, Yu Chen, D. Kafri, K. Kechedzhi, R. Collins, O. Naaman, S. Boixo, F. Arute, et al. Diabatic gates for frequency-tunable superconducting qubits. *Physical Review Letters*, 123(21):210501, 2019. DOI: [10.1103/physrevlett.123.210501](https://doi.org/10.1103/physrevlett.123.210501) 140
- [335] R. Versluis, S. Poletto, N. Khammassi, B. Tarasinski, N. Haider, D. J. Michalak, A. Bruno, K. Bertels, and L. DiCarlo. Scalable quantum circuit and control for a superconducting surface code. *Physical Review Applied*, 8(3):034021, 2017. DOI: [10.1103/physrevapplied.8.034021](https://doi.org/10.1103/physrevapplied.8.034021) 140
- [336] Ferdinand Helmer, Matteo Mariantoni, Austin G. Fowler, Jan von Delft, Enrique Solano, and Florian Marquardt. Cavity grid for scalable quantum computation with superconducting circuits. *EPL (Europhysics Letters)*, 85(5):50007, 2009. DOI: [10.1209/0295-5075/85/50007](https://doi.org/10.1209/0295-5075/85/50007) 140

- [337] Yu Chen, C. Neill, P. Roushan, N. Leung, M. Fang, R. Barends, J. Kelly, B. Campbell, Z. Chen, B. Chiaro, et al. Qubit architecture with high coherence and fast tunable coupling. *Physical Review Letters*, 113(22):220502, 2014. DOI: [10.1103/physrevlett.113.220502](https://doi.org/10.1103/physrevlett.113.220502) 140
- [338] A Robert Calderbank and Peter W. Shor. Good quantum error-correcting codes exist. *Physical Review A*, 54(2):1098, 1996. DOI: [10.1103/physreva.54.1098](https://doi.org/10.1103/physreva.54.1098) 141
- [339] Andrew M. Steane. Simple quantum error-correcting codes. *Physical Review A*, 54(6):4741, 1996. DOI: [10.1103/physreva.54.4741](https://doi.org/10.1103/physreva.54.4741) 141
- [340] Aleksei Yur'evich Kitaev. Quantum computations: Algorithms and error correction. *Uspekhi Matematicheskikh Nauk*, 52(6):53–112, 1997. DOI: [10.1070/rm1997v052n06abeh002155](https://doi.org/10.1070/rm1997v052n06abeh002155) 141
- [341] Daniel Gottesman. An introduction to quantum error correction. In *Proc. of Symposia in Applied Mathematics*, 58:221–236, 2002. DOI: [10.1090/psapm/058/1922900](https://doi.org/10.1090/psapm/058/1922900) 141
- [342] Emanuel Knill. Quantum computing with realistically noisy devices. *Nature*, 434(7029):39–44, 2005. DOI: [10.1038/nature03350](https://doi.org/10.1038/nature03350) 147, 148
- [343] Swamit S. Tannu, Zachary A. Myers, Prashant J. Nair, Douglas M. Carmean, and Moinuddin K. Qureshi. Taming the instruction bandwidth of quantum computers via hardware-managed error correction. In *Proc. of the 50th Annual IEEE/ACM International Symposium on Microarchitecture*, pages 679–691, 2017. DOI: [10.1145/3123939.3123940](https://doi.org/10.1145/3123939.3123940) 148
- [344] Nemanja Isailovic, Mark Whitney, Yatish Patel, and John Kubiawicz. Running a quantum circuit at the speed of data. In *ACM SIGARCH Computer Architecture News*, 36:177–188, IEEE Computer Society, 2008. DOI: [10.1109/isca.2008.5](https://doi.org/10.1109/isca.2008.5) 148
- [345] Dave Wecker, Bela Bauer, Bryan K. Clark, Matthew B. Hastings, and Matthias Troyer. Gate-count estimates for performing quantum chemistry on small quantum computers. *Physical Review A*, 90(2):022305, 2014. DOI: [10.1103/physreva.90.022305](https://doi.org/10.1103/physreva.90.022305) 149
- [346] Sergey Bravyi and Jeongwan Haah. Magic-state distillation with low overhead. *Physical Review A*, 86(5):052329, 2012. DOI: [10.1103/physreva.86.052329](https://doi.org/10.1103/physreva.86.052329) 149
- [347] Lorenza Viola, Emanuel Knill, and Seth Lloyd. Dynamical decoupling of open quantum systems. *Physical Review Letters*, 82(12):2417, 1999. DOI: [10.1103/physrevlett.82.2417](https://doi.org/10.1103/physrevlett.82.2417) 150
- [348] Robin Harper, Steven T. Flammia, and Joel J. Wallman. Efficient learning of quantum noise. *ArXiv Preprint ArXiv:1907.13022*, 2019. 150

- [349] Aram W. Harrow and Michael A. Nielsen. Robustness of quantum gates in the presence of noise. *Physical Review A*, 68(1):012308, 2003. DOI: [10.1103/physreva.68.012308](https://doi.org/10.1103/physreva.68.012308) 150
- [350] Mauricio Gutiérrez, Lukas Svec, Alexander Vargo, and Kenneth R. Brown. Approximation of realistic errors by Clifford channels and Pauli measurements. *Physical Review A*, 87(3):030302, 2013. DOI: [10.1103/physreva.87.030302](https://doi.org/10.1103/physreva.87.030302) 150, 164
- [351] Daniel Puzzuoli, Christopher Granade, Holger Haas, Ben Criger, Easwar Magesan, and David G. Cory. Tractable simulation of error correction with honest approximations to realistic fault models. *Physical Review A*, 89(2):022306, 2014. DOI: [10.1103/physreva.89.022306](https://doi.org/10.1103/physreva.89.022306) 150
- [352] Dorit Aharonov and Michael Ben-Or. Fault-tolerant quantum computation with constant error rate. *SIAM Journal on Computing*, 2008. DOI: [10.1137/s0097539799359385](https://doi.org/10.1137/s0097539799359385) 150
- [353] M. Nest. Classical simulation of quantum computation, the Gottesman–Knill theorem, and slightly beyond. *ArXiv Preprint ArXiv:0811.0898*, 2008. 152
- [354] Alison L. Gibbs and Francis Edward Su. On choosing and bounding probability metrics. *International Statistical Review*, 70(3):419–435, 2002. DOI: [10.1111/j.1751-5823.2002.tb00178.x](https://doi.org/10.1111/j.1751-5823.2002.tb00178.x) 153
- [355] Costin Bădescu, Ryan O’Donnell, and John Wright. Quantum state certification. In *Proc. of the 51st Annual ACM SIGACT Symposium on Theory of Computing*, pages 503–514, 2019. DOI: [10.1145/3313276.3316344](https://doi.org/10.1145/3313276.3316344) 153
- [356] Xin-Chuan Wu, Sheng Di, Franck Cappello, Hal Finkel, Yuri Alexeev, and Frederic T. Chong. Amplitude-aware lossy compression for quantum circuit simulation. *ArXiv Preprint ArXiv:1811.05140*, 2018. 155
- [357] Xin-Chuan Wu, Sheng Di, Franck Cappello, Hal Finkel, Yuri Alexeev, and Frederic T. Chong. Memory-efficient quantum circuit simulation by using lossy data compression. *ArXiv Preprint ArXiv:1811.05630*, 2018. 155
- [358] Richard Jozsa and Noah Linden. On the role of entanglement in quantum-computational speed-up. In *Proc. of the Royal Society of London A: Mathematical, Physical and Engineering Sciences*, 459:2011–2032, The Royal Society, 2003. DOI: [10.1098/rspa.2002.1097](https://doi.org/10.1098/rspa.2002.1097) 156
- [359] Guifré Vidal. Efficient classical simulation of slightly entangled quantum computations. *Physical Review Letters*, 91(14):147902, 2003. DOI: [10.1103/physrevlett.91.147902](https://doi.org/10.1103/physrevlett.91.147902) 156
- [360] Richard Jozsa. On the simulation of quantum circuits. *ArXiv Preprint quant-ph/0603163*, 2006. 156



- [361] Maarten Van den Nest, Wolfgang Dür, Guifré Vidal, and H. J. Briegel. Classical simulation versus universality in measurement-based quantum computation. *Physical Review A*, 75(1):012337, 2007. DOI: [10.1103/physreva.75.012337](https://doi.org/10.1103/physreva.75.012337) 156
- [362] Daniel Gottesman. Talk at international conference on group theoretic methods in physics. *arXiv preprint quant-ph/9807006*, 1998. 158
- [363] Scott Aaronson and Daniel Gottesman. Improved simulation of stabilizer circuits. *Physical Review A*, 70(5):052328, 2004. DOI: [10.1103/physreva.70.052328](https://doi.org/10.1103/physreva.70.052328) 159
- [364] Igor L. Markov and Yaoyun Shi. Simulating quantum computation by contracting tensor networks. *SIAM Journal on Computing*, 38(3):963–981, 2008. DOI: [10.1137/050644756](https://doi.org/10.1137/050644756) 162
- [365] Sergio Boixo, Sergei V. Isakov, Vadim N. Smelyanskiy, and Hartmut Neven. Simulation of low-depth quantum circuits as complex undirected graphical models. *ArXiv Preprint ArXiv:1712.05384*, 2017. 163
- [366] Mauricio Gutiérrez and Kenneth R. Brown. Comparison of a quantum error-correction threshold for exact and approximate errors. *Physical Review A*, 91(2):022335, 2015. DOI: [10.1103/physreva.91.022335](https://doi.org/10.1103/physreva.91.022335) 164
- [367] Hakop Pashayan, Joel J. Wallman, and Stephen D. Bartlett. Estimating outcome probabilities of quantum circuits using quasiprobabilities. *Physical Review Letters*, 115(7):070501, 2015. DOI: [10.1103/physrevlett.115.070501](https://doi.org/10.1103/physrevlett.115.070501) 164
- [368] Mark Howard and Earl Campbell. Application of a resource theory for magic states to fault-tolerant quantum computing. *Physical Review Letters*, 118(9):090501, 2017. DOI: [10.1103/physrevlett.118.090501](https://doi.org/10.1103/physrevlett.118.090501) 164
- [369] Sergey Bravyi, Graeme Smith, and John A. Smolin. Trading classical and quantum computational resources. *Physical Review X*, 6(2):021043, 2016. DOI: [10.1103/physrevx.6.021043](https://doi.org/10.1103/physrevx.6.021043) 164
- [370] Eliot Kapit. Hardware-efficient and fully autonomous quantum error correction in superconducting circuits. *Physical Review Letters*, 116(15):150501, 2016. DOI: [10.1103/physrevlett.116.150501](https://doi.org/10.1103/physrevlett.116.150501) 166
- [371] Kanav Setia, Sergey Bravyi, Antonio Mezzacapo, and James D. Whitfield. Superfast encodings for fermionic quantum simulation. *ArXiv Preprint ArXiv:1810.05274*, 2018. DOI: [10.1103/physrevresearch.1.033033](https://doi.org/10.1103/physrevresearch.1.033033) 166

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