Final Project

Quantum Computing 1

You may work individually or in groups of up to three people. (Note, however, that the expectations will scale with the number of people involved.)

This document contains some examples of final project topics, but you need not constrain yourself to these ideas. **You may choose a topic that is not listed here!** Feel free to discuss your ideas with us.

Please submit a written report and provide an oral presentation at the end of the semester according to the following time table:

- **Part 0:** Select topic and groups.
- **Part 1:** Reports and all supplemental material due
- **Part 2:** Presentations due
- Conference-style presentations on due date (and the following class if needed)

Quantum Simulator

Description: Using your favorite programming language, write a quantum computer simulator. Your code should take as its input a QASM file, such as that produced by the IBM Quantum Experience, and an integer number of shots. The software should compute the quantum state *before* measurement as a vector of complex numbers. In addition, it should produce the number of counts (out of the total number of shots) for each possible outcome.

For a group of two or more: Add the option to model noisy gates as either a depolarizing or amplitude damping channel with user-defined parameters. To do this, you will need to either represent your quantum state as a matrix or else apply an appropriate random unitary with each shot.

For a group of three: Add visualization tools (histograms, Bloch spheres, etc.) to help understand/analyze the results.

Randomized Benchmarking

Description: Use the IBM Quantum Experience to measure the gate error of a single-qubit gate using randomized benchmarking. (See the supplemental lecture Randomized Benchmarking.) You will need to apply a random sequence of unitary operations to an initial $|1\rangle$, then apply a single unitary that "undoes" the others and measure the final state. In theory, this should just be an identity operation. In practice, the fidelity will drop as the sequence lengthens. You will need to perform a regression analysis on the fidelity to extract the average error rate, assuming it falls off exponentially with the sequence length.

For a group of two or more: Perform randomized benchmarking for each of the five available qubits. How do they compare?

For a group of three: Perform *interleaved* randomized benchmarking to determine the error rate of specific gate operations. (For a description of this approach, see https://arxiv.org/pdf/1504.06597.pdf)

Bell Inequality Violations

Description: Bell's inequality is a famous result by physicist John Bell used to prove the incompatibility of quantum mechanics with the classical assumptions of local realism. Use the IBM Quantum Experience to design and perform a test of the Clauser-Horne-Shimony-Holt (CHSH) version of Bell's inequality. (See the supplemental lecture Bell Inequality.) Give a proof of the CHSH inequality, identify the initial entangled state to use and the observables to measure. How large of a violation can you achieve?

For a group of two or more: How can quantum mechanics allow a mathematical proof to be violated? Discuss loopholes to testing local realism using Bell's inequality and how they might be applicable to your experiment.

For a group of three: Expand your analysis to consider a three-qubit Greenberger-Horne-Zeilinger (GHZ) state. Find a way to prepare this state and demostrate a violation of the related Mermin inequality. (You'll need to look this up.)

Alternative QKD Protocols

Description: In class we learned the BB84 protocol, the oldest and simplest of the QKD protocols. Find an alternative QKD protocol, describe it, and implement it in software. (See, for example, the article *List of quantum key distribution protocols* on Wikipedia.)

For a group of two: Compare the performance of your chosen protocol to that of BB84 for "realistic" photons, such as were used in the QKD project (non-entanglement protocols only).

For a group of three: Describe and implement an entanglement-based QKD protocol. Discuss its performance under realistic conditions. What conditions are needed to guarantee security?

Popular Article on Quantum Computing

Description: Write a popular article on quantum computing. Describe how quantum information differs from classical information and what it's good for. You should consider all of quantum information science (communication, computing, and sensing). Some points to consider: (1) What are the applications? (2) How will it impact people's lives? (3) What is the current state of the art? (4) What are the technological challenges? (5) Discuss the broader impacts of quantum information science on society. The article should be written at a level that a non-expert (a friend or relative, say) can understand. (Note: This is *not* an easy assignment!)

For a group of two: Read (and cite) at least five other popular articles on the subject and comment on their accuracy and clarity.

This topic does not have an option for groups of three.

Create a Quantum Time Machine!

Description The popular press reported that scientists have reversed the flow of time using a quantum computer. Read the journal paper (see below), read the hype (many sources), and comment. Implement the protocol yourself in the IBM Quantum Experience and analyze the results. Can *you* reverse time?

This topic can only be done in groups of two, one of whom goes back in time.

Lesovik, Sadovskyy, Suslov, Lebedev, and Vinokur, "Arrow of time and its reversal on the IBM quantum computer," *Scientific Reports* **9**, 4396 (2019). `https://www.nature.com/articles/s41598-019-40765-6`

Teacher for a Day! for 5 minutes

Description: Identify a quantum information topic that we did not cover explicitly, and prepare a lesson about it. The lesson should be similar to our lessons in length and thoroughness including at least one exercise. Then prepare a 5-minute presentation that summarizes your lesson topic and conveys the "Main Idea" to the class.

For a group of two: In addition to the in-lesson exercise, prepare 3 more in-depth "homework" problems with solutions. Your lesson thoroughness will also be judged more critically.

Journal Article Review

Description: Identify a journal paper on quantum information science, either recent or historical, read it, and describe it in detail. Your choice should be approved ahead of time. A sample of possible articles is given below.

For a group of two: Read and discuss one other related paper, and focus on the connection between the two articles.

This topic does not have an option for groups of three.

1. John. F. Clauser and Michael A. Horne, "Experimental consequences of objective local theories", *Physical Review D* Volume 10, p. 526 (1974).
2. Nick Herbert, "FLASH – A Superluminal Communicator Based Upon a New Kind of Quantum Measurement", *Foundations of Physics* Volume 12, p. 1171 (1982). [Note: Their conclusion is *wrong*—see Wooters and Zurek below.]
3. W. K. Wootters and W. H. Zurek, "A single quantum cannot be cloned", *Nature* Volume 299, p. 802 (1982). [This choice must be paired with another, related paper.]
4. Artur K. Ekert, "Quantum Cryptography Based on Bell's Theorem", *Physical Review Letters* Volume 67, p. 661 (1991).
5. Charles H. Bennett, Giles Brassard, Claude Crepeau, Richard Jozsa, Asher Peres, and William K. Wootters, "Teleporting an Unknown Quantum State via Dual Classical and Einstein-Podolsky-Rosen Channels", *Physical Review Letters* Volume 70, p. 1895 (1993).
6. David P. DiVencenzo, "Two-bit gates are universal for quantum computation", *Physical Review A*, Volume 51, p. 1015 (1995).
7. Charles H. Bennett, Giles Brassard, Sandu Popescu, Benjamin Schumacher, John A. Smolin, and William K. Wootters. "Purification of Noisy Entanglement and Faithful Teleportation via Noisy Channels", *Physical Review Letters* Volume 76, p. 772 (1996).
8. A. M. Steane, "Error Correcting Codes in Quantum Theory", *Physical Review Letters* Volume 77, p. 793 (1996).
9. Rolf Landauer, "The physical nature of information", *Physics Letters A* Volume 217, p. 188 (1996).
10. David P. DiVencenzo. "The Physical Implementation of Quantum Computation", *Fortschritte der Physik*, Volume 48, p.771 (2000).
11. Scott Aaronson, "NP-Complete Problems and Physical Reality", *ACM SIGACT News* Volume 36, p. 30 (2005).

12. Marissa Giustina, *et al.*, "Significant-Loophole-Free Test of Bell's Theorem with Entangled Photons", *Physical Review Letters* Volume 115, 250401 (2015). (And Supplemental Material)

13. Lyndem K. Shalm, *et al.*, "Strong Loophole-free Test of Local Realism", *Physical Review Letters* Volume 115, 250402 (2015). (And Supplemental Material)

14. D. Bouwmeester, J.-W. Pan, K. Mattle, M. Eibl, H. Weinfurter, and A. Zeilinger. "Experimental quantum teleportation," *Nature* Volume 390, 575 (1997).