Quantum Computing: Foundations to Frontier
Course Project Guidelines

The course project is the capstone of the class. In groups of two or three, you and your groupmates will choose a topic in quantum computing, read a few relevant papers in that topic, and write a survey on the subject. Original research is encouraged, but not necessary. It is an opportunity for you to combine your own expertise (whether that be in machine learning or pure mathematics or physics, etc) with what you've learned in the course.

Importantly, you will need to pick a project that is doable in the time frame given (from mid-October to early December). You and your group will have to submit a project proposal, and I will give guidance on whether the scope is appropriate for the course. Here are some suggestions on how you can pick topics for your project:

1. Take something you're already doing research in, and explore if there is a quantum version of it.
2. Take a topic covered in the class, and investigate it more deeply.
3. Take a topic in quantum computing you've always wanted to learn about (but wasn't talked about in class).
4. Look at the most recent proceedings of quantum computing conferences and pick a topic that interests you. Some conferences to check out:
   (a) Quantum Information Processing (QIP)
   (b) Theory of Quantum Computation, Communication, and Cryptography (TQC)
   (c) QCrypt
   (d) Quantum Journal (url: `https://quantum-journal.org/`)
5. Check the "quant-ph" section of arxiv for exciting new papers on quantum computing (url: `https://arxiv.org/list/quant-ph/new`).
6. Check out the overlay site SciRate, which pulls papers from arxiv every day, and allows people to upvote papers (url: `https://www.scirate.com`).

If you have any general questions about the project, please ask them on Piazza (this will be helpful for others!).

Deliverables Here is what is expected of you (the last two are optional).

1. (**Project proposal**) Your group will send one email to `hyuen@cs.toronto.edu` by **Wednesday, October 17** with "Quantum Computing Project Proposal" in the subject line. Please write who the group members are, and write one paragraph describing your proposed project, along with some relevant papers/resources. I will give feedback and suggest additional papers. Feel free to make an appointment to discuss your project in person.
2. (**Class presentation**) Each group must give a 10-15 minute presentation[1] on their project to the class. There will be two days of presentations (held the **week of December 3rd**). The presentation should be on Powerpoint or Beamer.

[1] The actual timing will be finalized closer to the date.

3. (**Written report**) Your group must send a written project report by **Friday, December 7** midnight. The report should be 7 to 10 pages long. It can be longer, but I will read anything past the first ten pages at my own discretion. Font sizes and margins should be reasonable.

4. (**Online showcase**) I plan to showcase the students project on the course homepage for other students and researchers to see what cool things you've done. Participation in the showcase is optional, and has no effect on your grade. Benefits: your project gets some publicity, and also the quantum computing community benefits from what you've learned!

5. (**Publication**) If your group has been able to carry out some original research (which would be fantastic!), and you're interested in publishing it more formally, I would be able to assist you with the process (which venues to publish in, ways to write up the result, etc).

Types of projects Here are the types of projects that you can do.

1. **Survey**. Write an accessible, clear, and informative survey on a frontier research topic for an audience whose background is that they have just taken CSC2451/MAT1751.

2. **Theoretical research**. This includes: solve an open problem (or a special case of it), design and analyze a new protocol, design and analyze a new quantum algorithm, design and analyze a classical algorithm for simulating quantum systems. There are many more possibilities.

3. **Numerical experiments**. Run experiments on IBM/Rigetti's cloud quantum computers. For example, this could include benchmarking them to estimate their noise rate, or to implement a quantum algorithm on them and see how well it does. There are also development environments/SDKs that can simulate quantum algorithms from any number of companies (Rigetti, Microsoft, Xanadu, Google, etc.). Any projects of this type should also have a component that explains the theory background behind your experiment, what one might expect from the experiment before running it, and an analysis of the results. Here are some links:

   (a) IBM Q Experience (`https://quantumexperience.ng.bluemix.net/qx`)

   (b) Rigetti Cloud and Forest SDK (`https://www.rigetti.com/`)

      i. If you would like access to the Rigetti Cloud service, please contact me.

   (c) Microsoft Quantum Development Kit (`https://www.microsoft.com/en-us/quantum/development-kit`)

Course project topics Here are some course project topic areas. This is by no means an exhaustive list; these are meant as sources of inspiration for your group. There are many more possible areas I could list – just ask me to see if a topic would be appropriate for the course project. If you're curious about specific references for any of these topics, write a message on Piazza and I will respond with pointers (this will help others as well).

1. Near-term quantum computing (simulating quantum circuits on classical computers, quantum supremacy results, variational eigensolvers, classical-quantum hybrid algorithms, quantum circuit compilation)

2. Quantum cryptography (Quantum money, Device-independent quantum cryptography, randomness expansion, Post-quantum cryptography (i.e. which classical encryption schemes should remain secure against quantum computers), homomorphic encryption).

3. Connections with quantum gravity/high-energy physics (Error-correcting codes and the AdS/CFT correspondence, possible resolutions to the blackhole firewall paradox, quantum chaos and scrambling)

4. Paradoxes in Quantum Mechanics (Wigner's friends, the Frauchiger-Renner paradox)

5. Testing and verification of quantum computers (Multiprover interactive proofs, single-prover protocols)

6. Quantum machine learning (training Boltzmann machines, exponential speedups for solving linear systems/PCA, quantum neural networks, recommendation systems, quantum speedups for optimization tasks, architectures for quantum RAM)
7. Quantum simulation and quantum chemistry (improved Hamiltonian simulation algorithms, Fermion-to-qubit mappings, fast quantum algorithms for simulating specific molecules)
8. Quantum algorithms (mild-speedups for NP-hard problems, constructing ground states of local Hamiltonians, query algorithms)
9. Quantum complexity theory (QMA/MIP*/BQP vs classical complexity classes, query complexity, communication complexity)
10. Quantum Hamiltonian complexity (algorithms, Quantum PCP, area laws, tensor networks, stoquastic Hamiltonians)
11. Other models of quantum computing (annealing, adiabatic quantum computation)
12. Error-correction and fault tolerance (Threshold theorems, efficient fault tolerant schemes, error correction on near-term quantum devices)

Important dates.

- **October 17**: Project proposal due
- **December 3** and **December 5**: Project presentations. The December 3rd date is subject to change.
- **December 7**: Project writeups due.