Physics 513 Research Project -2019

In lieu of a course final, every student in the class will participate in an in-depth research project, which will be worth 30% of the final grade (homeworks being the other 70%). As described below, there will be two main options for satisfying this requirement, plus a third new option; I anticipate that approximately ½ of the students will end up in category 1, 1/3 in category 2, and 1/6 in category 3.

1. Group research presentation:

A group of 3-4 students will give a "lecture" on a topic of relevance to our course. These actually will be given in the last three weeks of the semester, and will focus on the primary physical systems currently under investigation for quantum computing. Each presentation will be divided into four (or in some cases, five) sections, and each student will be responsible for presenting one or more of these sections:

1. Introduction: system overview, system specifics (e.g., ion species, LOQC vs. cluster states, phase vs flux superconducting qubit, etc.), and main research groups working in this area.
2. Summary of gates (how they are implemented, and what has been achieved), algorithms (which have been implemented, how well they work, etc.).
3. Decoherence mechanisms (theoretical, and measured) and error correction (including gate sequences, DFS, loss-encoding, etc.).
4. Scalability issues (what are the main challenges to scalability, what integrated systems have been created/planned, how far from fault tolerant operation and how to close the gap, etc.).

(5.) Special topic, if applicable (what this particular architecture was used for, some not quite quantum computing application of relevance to our course, e.g., generation of Schrödinger's cat state, or other unique nonclassical states, etc.).

Individual grades will be assigned both on the basis of the individual presentation (70%) as well as the overall group presentation (30%). In most (all?) cases I have quite good review articles to recommend, as well as several research articles which should definitely be included, and in many cases even one or two recent PowerPoint presentations from some of the key figures in the field; any of this material may be incorporated into the lecture/presentation.

Below is the list of possible lecture presentation topics:

- A. Trapped ion quantum computing
- B. Superconducting quantum computing
- C. Neutral atom quantum computing
- D. Semiconductor-based quantum computing
- E. Implementations of quantum repeaters
- F. Macroscopic quantum interference (i.e., various cantilever and membrane superposition experiments).

If you are interested in following this track for your final research project, **you should email the TA, Yulia Maximenko (maximen2@illinois.edu) an ordered list of your top four choices for what presentation teams you would like to be on.** On the basis of this information, we will try to match people up with their desired projects. **Please submit your choices to Yulia by Feb. 14, 2019.** We will announce the assignments and approximate 'schedule' by **Feb. 26**.

2. Individual research project:

a. Research Paper

For those of you not participating in a group presentation (which may unfortunately include some of you that wanted to), I would like you to prepare a research paper of approximately the length of a *Physical Review Letter*, but at the level of *Physics Today* article. Below I list a number of possible topics; you can choose one of these, or suggest another one if you prefer (***however, in either case you should first obtain approval from me***). As indicated by the list of topics, the purpose of this is to condense the results of several recent research articles into a single cohesive research summary. As with any good article, your paper should include an abstract, probably several figures, and a bibliography (following the *Physical Review Letter* style). Papers should be submitted both in hard copy and emailed as a pdf. For your own experience, I would recommend doing this project in LaTeX (and we can give some assistance in how to go about this, if you've never done it before); however, as I only want the final product, the choice is up to you. **You should email me (kwiat@illinois.edu) 2-3 proposed topics (and the reference information on at least 3 papers[1] that are relevant to them) by March 1, 2019, and I will give feedback by March 12 (I'm trying to make sure you don't try a topic that's too general, too specific, or already covered by other people).**

Quantum games
Quantum simulation
Atom interferometric sensors (i.e., gravity and rotation)
Tests of nonlocality in higher dimensions
Other characterizations of nonlocality, e.g., quantum discord and quantum steering
Multiparticle (>2) entanglement
Weak measurements/direct measurement of the wavefunction
Generalized uncertainty relations
Single-photon source overview (q. dots, NV-centers, molecules, atoms, SPDC)
Entanglement from quantum dots
Entangled photons via four-wave mixing
Ghost imaging (classical versus quantum)
Quantum cryptography using continuous variables
Fiber-based quantum cryptography systems/networks
Quantum communication with larger alphabets
Q. algorithms beyond factoring
Theory and practice on fault-tolerant quantum computation
Algorithms for Noisy Intermediate Scale Quantum (NISQ) processors
Algorithms for quantum simulation
Algorithms for optimization
Topological quantum computing
Quantum annealing-based processors
Thermodynamics of quantum machines
Maxwell's demon

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[1] You can use more than that for the actual paper; I just want to make sure there's enough material, and that you don't overlook any particularly relevant papers.

The role of quantum effects in photosynthesis

b. Quantum Programming
This is a new option this year, given the new availability of (small-scale) online processors, like the IBM Quantum Experience. We'll have a simple problem set using this, but some of you might want to do a more extended project with this (they have a full python-controlled instruction set). Here you would propose a project to investigate using the simulator and the actual (noisy) processor. This will involve a writeup of the problem, including an abstract, figures, refs., as well as results and conclusions.

Here are few ideas:

Study nonlocal effects (Bell tests, quantum steering) in the system.
Simulate a small-scale repeater network, and investigate the scaling.
Study q. zeno effect and q. zeno-based gates.
Study some error-correction/decoherence mitigation method, toward preserving a 'logical qubit'.
Implement Trotter-Suzuki Hamiltonian simulation

The goal is 3-fold:
1. learn about the topic you're trying to implement (we'll touch on many of these in class, but this is a chance to go into much more depth)
2. gain experience with an actual quantum processor
3. come up with CLEAR examples (which I might very well incorporate in future semesters), i.e., writing about your investigation at the Phys. Today level.

If you are interested in this track (I'll take at most 8 of these), please propose a topic by Feb. 21.