EE 520 Introduction to Quantum Information Processing

Units: 4

Fall 2020, Tu-Thu 11 am-12:50 pm

Location: ONLINE

Instructor: Prof. Todd A. Brun
Office: ONLINE
Office Hours: Mon 2-4 pm, Thu 9-10 am
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Course Description
This class will give a one-semester graduate-level introduction to the theory behind quantum computers and quantum information processing in general, aimed at students without previous exposure to the subject.

Learning Objectives
The class will begin by introducing the mathematical notation used in the field (Dirac notation), then giving a brief introduction to those aspects of quantum mechanics necessary for the rest of the course: quantum states and tensor products, unitary transformations, generalized measurements, density operators, entanglement and decoherence. We will also introduce the basics of computational complexity.

We then cover the basic concepts of quantum information processing, and some of the quantum algorithms and protocols that have been developed. The topics covered will include: quantum bits and registers; quantum cryptography; quantum gates and circuits; universal sets of quantum gates; quantum algorithms, including Deutsch's algorithm, Shor's factoring algorithm, the search algorithm of Grover, quantum simulation, and quantum sampling problems; quantum metrology; decoherence, quantum error correction, and the basics of fault-tolerant quantum computation. We will study the advantages and disadvantages of different experimental approaches to quantum computers, current noisy intermediate-scale quantum (NISQ) processors, and demonstrations of quantum supremacy.

Recommended Preparation: An advanced course in complex linear algebra, such as EE 510.

Course Notes
This course will comprise lectures, homework, midterm and final exams, and a student project. The course will ordinarily be taken for a letter grade. Documents, including lecture notes, homework assignments, and additional readings, will be distributed online via the course Blackboard site.

Technological Proficiency and Hardware/Software Required
While no particular hardware or software proficiency is required for this class, some student projects may involve programming.

Required Readings and Supplementary Materials
Quantum Computation and Quantum Information, Michael A. Nielsen and Isaac L. Chuang (Cambridge, 2000), available from the USC Bookstore; lecture notes, and possibly some research papers or other handouts, available via Blackboard.

Description and Assessment of Assignments
The coursework will include 5 problem sets and a student project. The problem sets will draw on the material learned in class, and will include exercises from the textbook as well as additional problems.

Description of Student Project
The project will be one of: (1) a programming project on a NISQ machine; (2) a piece of original research; or (3) a reading project on a topic beyond what is covered in class. The subject of the project will be agreed on between the student and the course instructor; the instructor will suggest suitable sources for the selected topic, and will meet with each student in the second half of the semester to give guidance on the project. The students will read the suggested references, bring any questions to the instructor, and carry out the proposed project over the last several weeks of the semester. For the NISQ programming option, and the research option (if appropriate), the students will have access over the cloud to NISQ machines from IBM and Rigetti, and to the D-Wave processor at ISI. Project deliverables will include a written report

(approximately 10 pages) and an oral presentation in class (approximately 15 minutes, though the time will depend on the number of students). The grade will be based equally on the report and the presentation, including the ability to answer questions. Normally these will be individual projects, but at the instructor's discretion a small team may be allowed to undertake a larger project, with a suitably longer report and joint presentation; in this case, the students must indicate what portions of the work they performed.

Grading Breakdown

Course Element	**% of Grade**
Problem Sets (5)	15%
Midterm Exam	25%
Student Project (paper and presentation)	15%
Final Exam	45%
TOTAL	100%

Assignment Submission Policy

Problem sets will be submitted in class on the assigned date. Late homework will not be accepted. After the midterm exam, students will choose their project topics; the presentations will be scheduled for the last week of class, and the project reports will be due on the last day of class. Problem sets and reports can be handed in through the Blackboard site for this class.

Grading Timeline

Strong effort will be made to grade and return homework a week after it is received. Homework solutions will be posted on Blackboard.

Online Class Policies

Because of the COVID-19 pandemic, this class is being offered only online. The regular lecture classes will be held as online Zoom meetings. I will be offering online office hours as well, by holding Zoom meetings at the times listed above. The links to both the classes and the office hours are posted on the Blackboard site. I will do my best to make this class both enjoyable and informative within the online format. In addition to our regular class meetings, I will post some additional asynchronous material (videos and readings) on the Blackboard site. Please do not hesitate to contact me if you have any questions or are experiencing any difficulty in accessing the class. We're going through a hard time, but we will get through it together.

Course Schedule: A Weekly Breakdown

All readings are in Nielsen and Chuang unless otherwise notes. The course notes are also available, and are not listed separately.

	Topics	Readings	Deliverables
Week 1	General overview. The Stern-Gerlach experiment and spin-1/2 particles. Quantum bits. Review of linear algebra; Dirac notation; projectors; decompositions of the identity; tensor products.	Secs. 1.1, 1.2, 1.5, 2.1	HW #1 assigned
Week 2	Postulates of quantum mechanics. Quantum registers. Unitary transformations and time evolution. Schrödinger equation. No-cloning theorem. Entangling interactions. Examples of implementations using optical systems.	Secs. 2.2.1-5	HW #1 due HW #2 assigned
Week 3	Quantum gates. Quantum circuits. Entanglement. Quantum teleportation. Measurement and interference. Born rule. Complementarity and uncertainty. BB84 quantum cryptography. Quantum metrology. Shannon entropy.	Secs. 1.3, 1.6, 2.2.6-9, 2.3, 2.6, 4.1-4	
Week 4	Classical bits, circuits and Boolean functions. Reversible and irreversible gates. Computational complexity classes. Quantum oracles and Deutsch's algorithm. Universal sets of quantum gates. Circuits and general unitary transformations.	Chap. 3, Secs. 1.4, 4.5	HW #2 due HW #3 assigned
Week 5	Quantum Fourier transform and period finding. Phase estimation and Shor's factoring algorithm. Computational complexity of Shor's algorithm. Comparison to best classical algorithm.	Secs. 4.6, 5.1-4	
Week 6	Quantum Simulation. Quantum Chemistry. Sampling algorithms. What can be done with small quantum processors? Grover's search algorithm.	Secs. 4.7, 6.1, 6.2, handouts	HW #3 due HW #4 assigned
Week 7	**Midterm Exam**. Mixed states and density matrices. Completely positive maps. Partial trace. Von Neumann entropy.	Secs. 2.4, 2.5, 2.6, 8.1, 8.2, 8.3	
Week 8	Decoherence and effect of environment. Schmidt basis. Effective evolutions. Master equations. Quantum trajectories. Random error model.	Secs. 8.3, 8.4, 8.5	HW #4 due HW #5 assigned
Week 9	Simple error correction. Quantum error correcting codes. Stabilizer codes. Operations on encoded qubits.	Secs. 10.1-5, handouts	Choose projects
Week 10	Concatenated codes. Fault-tolerant quantum computation. Threshold theorems. Surface code.	Secs. 10.5, 10.6, handouts	HW #5 due
Week 11	Implementations. The DiVincenzo criteria. Ion trap quantum processors. NMR. Superconducting qubits. Quantum annealing.	Chap. 7, handouts	
Week 12	NISQ processors and their capabilities. Programming NISQ machines. Brief overview of other topics in quantum information. Other potential applications.	handouts	
Week 13	Presentation of student projects.		Projects due
FINAL	Final exam will be taken online after Thanksgiving, day and time to be announced.		

Statement on Academic Conduct and Support Systems

Academic Conduct:

Plagiarism – presenting someone else's ideas as your own, either verbatim or recast in your own words – is a serious academic offense with serious consequences. Please familiarize yourself with the discussion of plagiarism in SCampus in Part B, Section 11, "Behavior Violating University Standards" policy.usc.edu/scampus-part-b. Other forms of academic dishonesty are equally unacceptable. See additional information in SCampus and university policies on scientific misconduct, policy.usc.edu/scientific-misconduct.

Support Systems:

Counseling and Mental Health - (213) 740-9355 – 24/7 on call
studenthealth.usc.edu/counseling
Free and confidential mental health treatment for students, including short-term psychotherapy, group counseling, stress fitness workshops, and crisis intervention.

National Suicide Prevention Lifeline - 1 (800) 273-8255 – 24/7 on call
suicidepreventionlifeline.org
Free and confidential emotional support to people in suicidal crisis or emotional distress 24 hours a day, 7 days a week.

Relationship and Sexual Violence Prevention Services (RSVP) - (213) 740-9355(WELL), press "0" after hours – 24/7 on call
studenthealth.usc.edu/sexual-assault
Free and confidential therapy services, workshops, and training for situations related to gender-based harm.

Office of Equity and Diversity (OED) - (213) 740-5086 | Title IX – (213) 821-8298
equity.usc.edu, titleix.usc.edu
Information about how to get help or help someone affected by harassment or discrimination, rights of protected classes, reporting options, and additional resources for students, faculty, staff, visitors, and applicants.

Reporting Incidents of Bias or Harassment - (213) 740-5086 or (213) 821-8298
usc-advocate.symplicity.com/care_report
Avenue to report incidents of bias, hate crimes, and microaggressions to the Office of Equity and Diversity |Title IX for appropriate investigation, supportive measures, and response.

The Office of Disability Services and Programs - (213) 740-0776
dsp.usc.edu
Support and accommodations for students with disabilities. Services include assistance in providing readers/notetakers/interpreters, special accommodations for test taking needs, assistance with architectural barriers, assistive technology, and support for individual needs.

USC Campus Support and Intervention - (213) 821-4710
campussupport.usc.edu
Assists students and families in resolving complex personal, financial, and academic issues adversely affecting their success as a student.

Diversity at USC - (213) 740-2101
diversity.usc.edu
Information on events, programs and training, the Provost's Diversity and Inclusion Council, Diversity Liaisons for each academic school, chronology, participation, and various resources for students.

USC Emergency - UPC: (213) 740-4321, HSC: (323) 442-1000 – 24/7 on call
dps.usc.edu, emergency.usc.edu
Emergency assistance and avenue to report a crime. Latest updates regarding safety, including ways in which instruction will be continued if an officially declared emergency makes travel to campus infeasible.

USC Department of Public Safety - UPC: (213) 740-6000, HSC: (323) 442-120 – 24/7 on call
dps.usc.edu
Non-emergency assistance or information.