EE 520 Introduction to Quantum Information Processing

Units: 4

Fall 2022, Tu-Thu 11 am-12:50 pm

Location: CPA 258

Instructor: Prof. Todd A. Brun
Office: EEB 502
Office Hours: Mon 12-2, Thu 3-5, in person and by Zoom
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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 advantage.

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 6 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 10 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 (6)	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.

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.

Course Schedule: A Weekly Breakdown

All readings are in Nielsen and Chuang unless otherwise noted. 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.	Secs. 1.1, 1.2, 1.5	HW #1 assigned
Week 2	Review of linear algebra; Dirac notation; projectors; decompositions of the identity; tensor products. Postulates of quantum mechanics. Quantum registers. Unitary transformations and time evolution. Schrödinger equation. No-cloning theorem. Entangling interactions.	Secs. 2.1, 2.2.1-5	HW #1 due HW #2 assigned
Week 3	Examples of implementations using optical systems. Quantum gates. Quantum circuits. Entanglement. Quantum teleportation. Measurement and interference. Born rule. Complementarity and uncertainty.	Secs. 1.3, 1.6, 2.2.6-9, 2.3, 2.6, 4.1, 4.2, 4.3	
Week 4	BB84 quantum cryptography. Quantum metrology. Shannon entropy. Classical bits, circuits and Boolean functions. Reversible and irreversible gates.	Sec. 4.4, Chap. 3	HW #2 due HW #3 assigned
Week 5	Computational complexity classes. Quantum oracles and Deutsch's algorithm. Universal sets of quantum gates. Circuits and general unitary transformations.	Chap. 3, Sec. 1.4, 4.5, 4.6	
Week 6	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. 5.1, 5.2, 5.3, 5.4	HW #3 due HW #4 assigned
Week 7	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	
Week 8	Mixed states and density matrices. Completely positive maps. Partial trace. Von Neumann entropy. Decoherence and effect of environment. Schmidt basis.	Secs. 2.4, 2.5, 2.6, 8.1, 8.2, 8.3	HW #4 due HW #5 assigned
Week 9	**Midterm Exam**. Effective evolutions. Master equations.	Secs. 8.3, 8.4, 8.5	
Week 10	Quantum trajectories. Random error model. Simple error correction. Quantum error correcting codes. Stabilizer codes.	Secs. 10.1, 10.2, 10.3, 10.4, handouts	HW #5 due HW #6 assigned Choose projects
Week 11	Operations on encoded qubits. Concatenated codes. Fault-tolerant quantum computation. Threshold theorems. Surface code.	Secs. 10.5, 10.6	
Week 12	Implementations. The DiVincenzo criteria. Ion trap quantum processors. NMR.	Chap. 7, handouts	HW #6 due
Week 13	Superconducting qubits. Quantum annealing. NISQ processors and their capabilities.	handouts	
Week 14	Programming NISQ machines. Brief overview of other topics in quantum information. Other potential applications.	handouts	
Week 15	Presentation of student projects.		Projects due
FINAL	Refer to the final exam schedule in the USC *Schedule of Classes* at classes.usc.edu.		

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 Research and Scholarship Misconduct.

Students and Disability Accommodations:

USC welcomes students with disabilities into all of the University's educational programs. The Office of Student Accessibility Services (OSAS) is responsible for the determination of appropriate accommodations for students who encounter disability-related barriers. Once a student has completed the OSAS process (registration, initial appointment, and submitted documentation) and accommodations are determined to be reasonable and appropriate, a Letter of Accommodation (LOA) will be available to generate for each course. The LOA must be given to each course instructor by the student and followed up with a discussion. This should be done as early in the semester as possible as accommodations are not retroactive. More information can be found at osas.usc.edu. You may contact OSAS at (213) 740-0776 or via email at osasfrontdesk@usc.edu.

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 for Equity, Equal Opportunity, and Title IX (EEO-TIX) - (213) 740-5086
eeotix.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 for Equity, Equal Opportunity, and Title for appropriate investigation, supportive measures, and response.

The Office of Student Accessibility Services (OSAS) - (213) 740-0776
osas.usc.edu
OSAS ensures equal access for students with disabilities through providing academic accommodations and auxiliary aids in accordance with federal laws and university policy.
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, Equity and Inclusion - (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.

Office of the Ombuds - (213) 821-9556 (UPC) / (323-442-0382 (HSC)
ombuds.usc.edu
A safe and confidential place to share your USC-related issues with a University Ombuds who will work with you to explore options or paths to manage your concern.

*Occupational Therapy Faculty Practice - (323) 442-33*40 or otfp@med.usc.edu
chan.usc.edu/otfp
Confidential Lifestyle Redesign services for USC students to support health promoting habits and routines that enhance quality of life and academic performance.