CS378 - M375T - PHY341
Introduction to Quantum Information Science

UT Austin, Spring 2017

http://www.scottaaronson.com/cs378/

Discussion site: https://piazza.com/class/iy14ebe4vkh1at

Place and Time	Tuesdays and Thursdays 2-3:30PM, Burdine Hall 130
Instructor	Scott Aaronson aaronson@cs.utexas.edu www.scottaaronson.com GDC 4.422 Office hours: Tuesdays 3:30-4:30PM or by appointment
TAs	Patrick Rall (patrickjrall@gmail.com) Office hours Wednesdays 2-3:30PM in GDC 4.408D Corey Ostrove (costrove@utexas.edu) Office hours Thursdays 12:30-1:30PM in RLM 7.206
Recitation Sections	Corey: Fridays 10-11AM in RLM 5.124 Patrick: Fridays 3:30-4:30PM in RLM 5.126

This is a new undergraduate-level introduction to the theory of quantum computing and information. We'll cover the rules of quantum mechanics (qubits, unitary transformations, density matrices, measurements); quantum gates and circuits; entanglement; the Bell inequality; protocols for teleportation, quantum key distribution, and other tasks; basic quantum algorithms such as Shor's and Grover's; basic quantum complexity theory; basic quantum error correction; decoherence and the measurement problem; and the challenges of building scalable quantum computers. Previous exposure to quantum mechanics is not required.

Prerequisites. Since some of the course assumes knowledge of classical algorithms, the prerequisite is CS331 with a grade of at least B, or permission of instructor. However, the *most important* prerequisite is a good level of comfort with linear algebra: vector spaces, bases, eigenvalues, rank, inner product, etc.

Requirements and Grading. There will be a short problem set approximately every week, beginning the second week. Problem sets will be due approximately one week after being assigned. There will also be one midterm exam (date and time to be determined) and one final exam. Course grading will be done as follows:

40% problem sets
25% midterm exam
35% final exam

In borderline cases, extra credit will also be given for regular participation in class and recitation sections, coming to office hours, and participation on the Piazza site.

Problem Set Policies. Submission of problem sets will be entirely electronic, and done through the Canvas page at http://canvas.utexas.edu/. If you prefer to write your solutions by hand, you can upload hi-res photos of your solutions (e.g., using a mobile phone). Otherwise, you can type solutions in Word, LaTeX, or other software of your choice.

A single problem set (the one with the lowest score) will automatically be dropped. For all other problem sets, 20% will be taken off for each day the problem set is handed in late, *unless* late permission is obtained for a reason such as illness, family emergency, religious observance, or UT-related travel. General busyness or other coursework is never a valid reason.

You're free to discuss the problem sets with classmates, but solutions must be written up entirely on your own. If you discuss with classmates, list the names of everyone you discussed with at the beginning of the problem set.

Piazza Site. You're encouraged to ask questions and discuss the lectures at the Piazza site:
https://piazza.com/class/iy14ebe4vkh1at
Questions might be answered by Prof. Aaronson, the TAs, or your fellow students.

Textbook. While we won't be following it particularly closely, we strongly recommend *Quantum Computer Science: An Introduction* by N. David Mermin. This is a short book that nevertheless covers much of the course material in a friendly, accessible way. Here are some other useful resources (which also cover more advanced topics than we'll get to in this course):

- Prof. Aaronson's *Quantum Computing Since Democritus*: http://www.scottaaronson.com/democritus/
- Some of Prof. Aaronson's other lecture notes: http://stellar.mit.edu/S/course/6/fa14/6.845/materials.html and http://www.scottaaronson.com/barbados-2016.pdf
- Umesh Vazirani's lecture notes for Qubits, Quantum Mechanics, and Computers (UC Berkeley): http://www-inst.eecs.berkeley.edu/~cs191/sp05/

Disabilities notice. The University of Texas at Austin provides upon request appropriate academic accommodations for qualified students with disabilities. For more information, contact the Office of the Dean of Students at 471-6259, 471-6641 TTY.

Approximate List of Topics.

Unit I: Introduction

- Motivation: Extended Church-Turing Thesis. What is Nature?
- The double-slit experiment and quantum mechanics
- Probability theory in linear algebra terms
- 1 qubit - unitary transformations and Born rule
- Dirac bra/ket notation
- Example unitary matrices: Hadamard, NOT, Phase, $\sqrt{NOT}$...
- Quantum circuit notation
- The role of interference
- Irrelevance of global phase
- Complex inner product and complex norm
- The distinguishability of pure states

- Measurement in arbitrary bases
- Specialness of the 1-norm and 2-norm
- Why complex numbers?

Unit I Applications

- The Quantum Zeno effect
- The Elitzur-Vaidman bomb
- Detecting whether a coin is fair or ε-biased

Unit II: Entanglement

- Two or more qubits
- The partial measurement rule
- Tensor products of states and unitaries
- Entangled vs. separable states
- Example 2-qubit gates: CNOT, SWAP, CPHASE...
- Tracing out and density matrices
- EPR and weirdness of the singlet state
- The No-Communication Theorem
- The No-Cloning Theorem (vs. CNOT)
- Monogamy of Entanglement

Unit II Applications

- Wiesner's quantum money scheme
- BB84 quantum key distribution
- Superdense quantum coding
- Quantum teleportation

Unit III: Interpretation

- The measurement problem
- Schrödinger's cat and Wigner's friend
- Decoherence and the CNOT gate
- The Many-Worlds Interpretation
- The idea of hidden variables
- The Bell Inequality and the CHSH game
- The GHZ game

Unit III Application

- Guaranteed randomness expansion

Unit IV: Quantum Computing

- Exponential size of Hilbert space
- Universal sets of quantum gates
- Circuit size; Shannon's counting argument applied to QC
- Need to exploit interference and to succeed w.h.p.
- Deutsch-Jozsa algorithm
- Bernstein-Vazirani algorithm
- Simon's algorithm
- Shor's algorithm
- Grover's algorithm
- Comments about limitations of quantum computers
- Comments about implementation of quantum computers

Unit V: Robustness of Quantum States

- Trace distance; the triangle inequality
- Classical error correction
- Quantum error correction: the Shor 9-qubit code
- The Gentle Measurement Lemma
- Robustness of a state under repeated measurements

Unit V Applications

- Ruling out quantum Random Access Codes
- A version of Holevo's Theorem

Possible Additional Topics

- The swap test and relative phase test
- Separations in quantum one-way communication complexity
- Bosons and fermions / the Pauli exclusion principle
- The stabilizer formalism
- Hamiltonians and the Schrödinger equation
- Entanglement swapping