DRAFT

Specialization in Quantum Information

UMD Working Group on Quantum Education

Motivation

As quantum computers come closer to realization, there is an increasing need for students to gain familiarity with this subject. In particular, the National Quantum Initiative Act, which was recently signed into law (https://www.congress.gov/bill/115th-congress/house-bill/6227), calls for programs

> "to expand the number of researchers, educators, and students with training in quantum information science and technology to develop a workforce pipeline"

and

> "to promote the development and inclusion of multidisciplinary curriculum and research opportunities for quantum information science at the undergraduate, graduate, and postdoctoral level."

Recent funding opportunities from the National Science Foundation, Department of Energy, and other agencies have emphasized the importance of such efforts.

While there are several active graduate programs in quantum information worldwide, few universities have developed undergraduate offerings beyond a single course on quantum computing. Developing an undergraduate specialization in this area would leverage our strength in quantum science and show UMD leadership at a critical time.

Program structure

We propose developing parallel undergraduate specializations in three departments: Computer Science, Electrical and Computer Engineering, and Physics. Students in these three units will have the chance to take a common set of courses that provide a basic working knowledge of quantum information concepts and prepare them for further study.

Proposed requirements

- CMSC 457 (Introduction to quantum computing)

  This course has been offered twice, in the spring semesters of 2018 and 2019, with 30–35 students participating in each offering. It covers the mathematical foundations of quantum computing, including quantum circuits, basic quantum algorithms, and quantum error correction. Prerequisites are knowledge of linear algebra and mathematical maturity (but not previous coursework in quantum mechanics).

- ECE/PHYS 4xx (Introduction to quantum technology)

  This course will be an undergraduate version of PHYS 720, which covers the theory of devices for quantum information. Students will learn about platforms for constructing qubits (neutral atoms, trapped ions, superconducting circuits, etc.) and explore their relative merits.

  This course will require some background in quantum mechanics and electromagnetism at the undergraduate level. However, not all the material covered in standard physics courses on those subjects will be required. To make the course more accessible to computer science students, we will offer a short course (in the winter or summer terms) that introduces the necessary background.

CMSC/PHYS 457 Spring 2019

Introduction to quantum computing

Course website

http://www.cs.umd.edu/class/spring2019/cmsc457/

Overview

An introduction to the concept of a quantum computer, including algorithms that outperform classical computation and methods for performing quantum computation reliably in the presence of noise. As this is a multidisciplinary subject, the course will cover basic concepts in theoretical computer science and physics in addition to introducing core quantum computing topics.

Course topics

The following is list of topics is tentative and subject to change: quantum phenomena, basics of quantum information, quantum entanglement and quantum protocols, quantum circuits and universality, relationship between quantum and classical complexity classes, simple quantum algorithms, quantum Fourier transform, Shor factoring algorithm, Grover search algorithm and its optimality, quantum error correction and fault tolerance, and selected additional topics as time permits.

Prerequisites

(MATH240 or PHYS274) and (CMSC351 or PHYS373)

Coordinates

Tuesday/Thursday, 12:30–1:45 pm, CSI 1122

Instructor

Andrew Childs (amchilds@umd.edu)
Office hours: Tuesday and Wednesday, 2–3 pm, ATL 3100F

Teaching assistants

	Email	*Office hours (in AVW 4101/4103)*
Nishant Rodrigues	ngrodrig@cs.umd.edu	Monday, 10–11 am
Jue Xu	juexu@cs.umd.edu	Wednesday, 1–2 pm

Piazza

We will use Piazza for class announcements and discussion. You should sign yourself up for the course Piazza page at https://piazza.com/umd/spring2019/cmscphys457. This is the best way to quickly get help from classmates, TAs, and the instructor. Instead of emailing questions to the teaching staff, please post questions at https://piazza.com/umd/spring2019/cmscphys457/home. Please do not use any other online forum for course discussion without prior permission of the instructor.

Texts

Primary: Paul Kaye, Raymond Laflamme, and Michele Mosca, *An Introduction to Quantum Computing*, Oxford University Press (2007).

Supplemental: Michael A. Nielsen and Isaac L. Chuang, *Quantum Computation and Quantum Information*, Cambridge University Press (2000).

Evaluation

Your final grade will be determined as follows:

Assignments	30% (lowest assignment grade will be dropped)
Midterm exam	10%
Project	30%
Final exam	30%

Assignments

There will be 5 homework assignments during the course. Assignments will be made available on the course website and should be submitted to Gradescope (https://www.gradescope.com). Please register for Gradescope using the course code (to be provided in class) and check that you are able to upload solutions by making a test submission well in advance of the first assignment deadline. You should submit your completed assignments in PDF format, either as a typeset document (preferred) or a clear scan of handwritten solutions.

Your solutions must be submitted before the start of class on the due date. Gradescope will not accept submissions after the deadline, and since solutions will be posted on the course website promptly, *late assignments will not be accepted*. The lowest assignment grade will be dropped.

Your solutions should be written neatly and concisely, and you should always aim to present the simplest possible solution. Your assignment grades will be based on both correctness and clarity. Graded assignments will be returned via Gradescope, and grades will be available through that system. If you think a problem has been graded incorrectly, you may submit a regrade request on Gradescope within one week. Regrade requests must include a detailed justification. The course staff will carefully review your solution and could raise or lower your score.

You are encouraged to discuss homework problems with your peers, with the TA, and with the course instructor. However, your solutions should be based on your own understanding and should be written independently. For each assignment, you must either include a list of students in the class with whom you discussed the problems, or else state that you did not discuss the assignment with your classmates.

Project

A significant component of the course will be a project on a topic of your choice. The goals of this project are to explore a topic in in depth, to give you experience reading the research literature, to identify possible future research directions, and to practice your scientific communication skills through both an in-class presentation and a written report.

You will have considerable freedom in deciding how to structure your project. You may work either on your own or in a group of two or three students. Suggested project types include

- an expository paper on a quantum information topic that is not covered in the course,
- a software project that implements a classical computation related to quantum information,
- an implementation of a quantum algorithm or protocol using the IBM Quantum Experience (https://quantumexperience.ng.bluemix.net/), or
- an original research project on a theoretical aspect of quantum information processing.

Your project will include the following deliverables:

- a project proposal, due Thursday, February 14 (5% of your project grade);
- a midterm project report, due Thursday, March 28 (15%);
- a brief project presentation, to be scheduled in the last 2–3 weeks of class (40%); and
- a final project report, due Tuesday, May 14 (40%).

Your project proposal and reports must be typeset in LaTeX and submitted in PDF format via Gradescope. Further parameters for the project will be discussed in class and on Piazza.

Exams

The course will include a midterm exam and a comprehensive final exam. Both exams will be given in our regular lecture room (CSI 1122). The midterm exam will be held on Thursday, March 14, at the regular class time (12:30–1:45 pm). The final exam will be held on Tuesday, May 21, from 1:30–3:30 pm (as scheduled by the registrar).

Academic accommodations

You should be familiar with the University of Maryland course policies¡/a¿ (http://www.ugst.umd.edu/courserelatedpolicies.html).

As mentioned above, extensions to assignment due dates will not be granted for any reason, so that all students can have timely access to solutions. In circumstances that justify an excused absence, appropriate accommodations will be made, in accordance with the course-related policies described at the above link.

Any student eligible for and requesting reasonable academic accommodations due to a disability is asked to provide, to the instructor during office hours, a letter of accommodation from the Accessibility and Disability Service (ADS) office within the first two weeks of the semester.

If you plan to observe any holidays during the semester that are not listed on the university calendar, please provide a list of these dates by the end of the first two weeks of the semester.

Course evaluations

Student feedback is an important part of evaluating instruction. The Department of Computer Science and its faculty take this feedback seriously and appreciate your input. Toward the end of the semester, please go to http://www.courseevalum.umd.edu to complete your evaluation.

Introduction to quantum technology

Jake Taylor, jmtaylor@umd.edu

This advanced undergraduate class delves into how to construct and operate the physical systems behind quantum computers. Working from a discrete, circuit-based approach, no knowledge of physics or quantum mechanics is assumed, though a background in appropriate mathematical concepts is necessary. Over the course of 13 weeks, students will learn the basics of atomic clocks, laser interferometers, quantum key distribution, quantum networks, and three types of qubits (ion-based, superconductor-based, semiconductor-based). A creative project to develop new applications of quantum technologies to potential real-world problems will be developed in lieu of a final exam.

Prerequisites

- Linear algebra (inner product spaces, eigenvectors and eigenvalues, unitary and Hermitian matrices, tensor product);
- Continuous math (real analysis, Taylor series, Fourier transforms, simple differential equations, definite and indefinite integrals over single variables);
- Probability theory (discrete probability distributions, Markov chains, Bayes rule);
- Discrete math (classical bit operations, matrix-based transformations, finite groups).

Course structure

- Week 1: Review of basic probability theory, 2x2 matrices. Introduction to bits and qubits. Born's rule for qubits. The Bloch sphere.
- Week 2: Evolution of a qubit. Ramsey interferometry. Operation of atomic clocks.
- Week 3: From one qubit to two. The CNOT gate. Getting to Born's rule from conditional dynamics. The concept of positive operator valued measures. The role of entanglement.
- Week 4: From two qubits to many. Introduction of the density matrix and Schmidt decomposition. Discrete-time open systems. Input-output relationship.
- Week 5: Decoherence and the master equation. Wigner-Weisskopf model of spontaneous emission. T_2 and T_2^*: the role of spin echo. Limits to sensing.
- Week 6: The quantum harmonic oscillator. Interferometry with light. Classical vs. quantum light. The role of squeezing, entanglement, and photon loss. The standard quantum limit and beyond. Discussion of LIGO.
- Week 7: Ion-based qubits: the atom as spin-1/2. The Jaynes-Cummings interaction. Readout of qubits via light. Resonance fluorescence vs dispersive readout. Light-based entanglement between qubits.

- Week 8: Qubit and harmonic oscillator coupling schemes. The phonon ‘bus’ concept. Molmer-Sorensen gates. Dephasing mechanisms.
- Week 9: Quantum networking protocols. Quantum key distribution. Teleportation-based gates.
- Week 10: Introduction of the quantum rotor. Discussion of register types. The Josephson effect. The Cooper-pair box qubit. The transmon qubit.
- Week 11: Coupling and control of superconducting qubits. Discussion of the Anderson pseudo-spin model of superconductivity and quasiparticles. Dephasing mechanisms.
- Week 12: Gentle introduction to fermions. The dynamics of two electrons. Quantum dot-based qubits. Hubbard-like models. Exchange-based computing. Dephasing mechanisms.
- Week 13: Architectures for quantum computing.

Homework and exams

- Weekly problem sets will be assigned on Mondays and due the following Monday. They comprise 80% of your final grade. You are encouraged to work in groups of 3-4, though you must each turn in your own homework and list your group members’ names.
- There will be a final project in lieu of an exam. Topics will be chosen the first week in April, and projects will be presented in class on the final day.

Supplementary texts

- *Quantum Computation and Quantum Information* Nielsen & Chuang
- *Lecture Notes on Quantum Information* Preskill