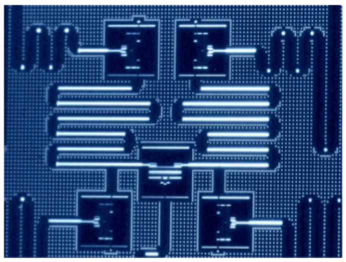
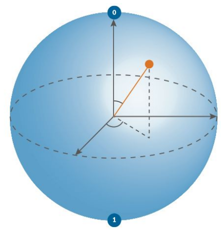
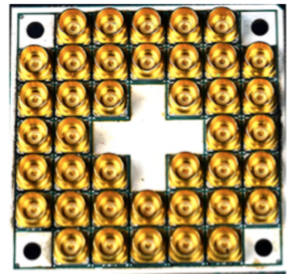
ECE 8XXX: Introduction to Quantum Systems (IQS)

Prerequisite: ECE 3056/6100 or equivalent + Linear algebra
(senior undergrad students are welcome to join)







Quantum computing promise exponential speedups for a class of important problems. Recent demonstrations from IBM, Intel, and Google have shown quantum computers ranging from 49 to 72 qubits. And, the number of qubits is expected to increase in the number of hundreds in the near future. Research in quantum computer spans a wide range of subjects, ranging from physical devices (ion trap, superconducting, spin etc.) to error-correction codes (surface code or Shor code) to system & architecture issues (memory/microarchitecture/IO) to compiler and tools (simulation and programming), to algorithms and applications. The goal of this course is to introduce ECE students to the different stacks in quantum computer systems and give them a chance to explore sub-problems in each domain. Quantum computer is a promising paradigm -- unfortunately, there is no course in ECE that can introduce the students to the full stack of quantum computing. The aim of this course to fill this gap and form a bridge between physics-engineering-mathematics that the quantum computing domain demands.

Text: The material for this course will be derived from the following texts and papers:

1. “Quantum Computing: A Gentle Introduction” by Eleanor Rieffel and Wolfgang Polak
2. “Elements of Quantum Computing: *History, Theories and Engineering Applications”* by Seiki Akama
3. "Quantum Computing for Computer Architects" Tzvetan S. Metodi, Arvin I. Faruque, Frederic T. Chong
4. Preskill, J. (2018). Quantum Computing in the NISQ era and beyond. *arXiv:1801.00862*.
5. Wendin, G. (2017). Quantum information processing with superconducting circuits: a review. *Reports on Progress in Physics*, *80*(10), 106001.
6. Svore, K. M., Aho, A. V., Cross, A. W., Chuang, I., & Markov, I. L. (2006). A layered software architecture for quantum computing design tools. *Computer*, (1), 74-83.
7. Jones, N. C., Van Meter, R., Fowler, A. G., McMahon, P. L., Kim, J., Ladd, T. D., & Yamamoto, Y. (2012). Layered architecture for quantum computing. *Physical Review X*
8. Papers from recent conferences: ISCA, MICRO, ASPLOS, PLDI etc.

Topical Outline

Quantum Computing

- Limits of Classical Computing
- Brief Intro to Quantum Mechanics
- Linear Algebra Primer
- Quantum Computing Models: Gate Model, and Quantum Turing Machine

Quantum Devices and Control Interfaces

- Superconducting Qubit Devices
- Ion-trap Qubit Devices
- Spin Qubit Devices
- Quantum Control
- Open vs Closed quantum systems and noise

Introduction to Quantum Algorithms

- Quantum Circuits
- Bernstein Vazirani Algorithm
- Quantum Fourier Transform
- Grover's Algorithm
- Quantum Chemistry applications (Ground State Estimation, Ising Model)

Near Term Quantum Systems

- Noisy Intermediate Quantum Computers (NISQ)
- IBM, and Rigetti Quantum Machines
- Quantum Assembly Language
- NISQ Compilers
- Qubit Allocation and Data mapping problems
- Quantum Simulators

Quantum Error Correction

- Classical and Quantum Noise Models
- Classical Error Correction, example codes
- Shor's Error Correction Code, Steane's Code, Concatenated Codes
- Introduction to Topological Codes (Surface Code)
- System Tradeoffs in Quantum Error Correction

Fault-Tolerant Quantum Systems

- Cryogenic Control Electronics
- Cryogenic CMOS and Superconducting Electronics
- Quantum Processors Microarchitecture
- Quantum Programming Language, Compilers and Resource Estimators
- System resource management problems - Magic State Distillation
- Scalable Error Correction and Decoding
- Advanced Topics in Fault Tolerance Protocol: EPR distribution, Logical Data Movement

Course Grading:

Mid-term: 20%
Three Assignments: 30%
Research Paper Reviews (4): 20%
Final Exam or Research Project (Report and Presentation): 30%

The will be a mix of traditional lectures plus discussion of research papers. The midterm will test knowledge of the theory portion of the lectures. The assignments will give the students an overview of working on typical problems in quantum computing (evaluating Bernstein Vazirani algorithm on real IBM-Q5 quantum computer, qubit allocation and routing algorithms, reliability models for quantum computers and techniques to mitigate errors). The assignments will also make the students familiar with the typical tools used in modeling quantum computers. The paper reviews and discussion will cover four seminal papers in the area of quantum computing. The students will be given the option of either having a final exam or do a research project. For the research project, the students will be expected to solve an open problem and conduct research that can potentially lead to a workshop/conference publication.

Educational Objectives:

As part of this course, students …

1. apply their knowledge of mathematics to analyze the computation model of quantum computing [1]
2. apply their knowledge of physics to understand the different devices that can be used as qubit and associated trade-offs [1]
3. demonstrate an ability to utilize basic laboratory equipment and procedures. [3]
4. formulate and solve complex problems in building quantum computer systems by applying principles of engineering [1]
5. recognize the ongoing need to acquire new knowledge by reading and understanding research papers and doing reviews [6]
6. apply the engineering design process to study quantum architectures that meet the constraints of time, cost and energy [2]

Educational Outcomes:

Upon successful completion of this course, students should be able to …

1. write assembly code for small quantum programs
2. perform experimental evaluations on the publicly available quantum computer
3. analyze qubit allocation and routing algorithms
4. read basic research papers in quantum computing and review them.

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