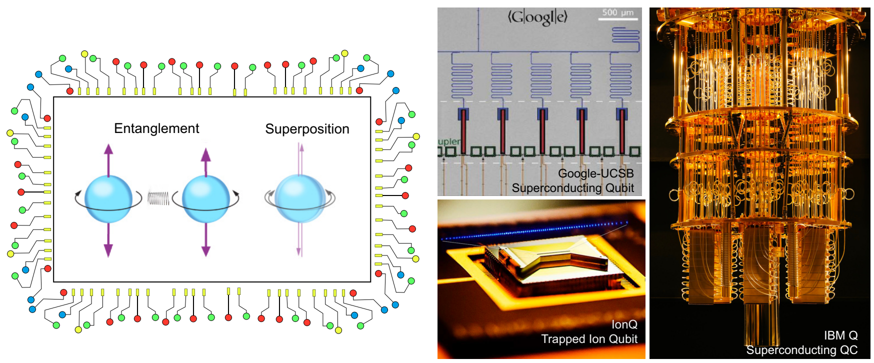
ECE 8863: Quantum Computing Devices and Hardware

Prerequisite: Undergraduate level understanding of quantum mechanics, solid state physics/devices (ECE 3030/3040 level), linear algebra (Senior undergraduate students are welcome to join.)



A quantum computer is built upon the quantum rather than classical nature of devices that can solve computational problems intractable on even the most powerful supercomputers , and on any future classical computers. Major technology companies including IBM, Google, Intel and start-ups such as Rigetti and IonQ are racing towards demonstration of quantum computers with an increasing number of entangled qubits. In the backdrop of massive investments in quantum computing in China and Europe, the US government has recently announced the National Quantum Information Act (NQIA) and the Quantum Computing Research Act (DoD). This course is focused on providing an engineering-oriented treatise of the fundamental building blocks of quantum computers–the quantum computing devices. The topics will include the physics of quantum computing, different quantum bit (qubit) technologies (ion trap/superconducting/semiconductor spin qubits), full hardware and system level aspects, the state-of-the-art, challenges and outlook of the paradigm. A primary outcome of the course will be to introduce graduate students from electrical and computer, physics, materials science and any other related disciplines to this field, to foster quantum research activities on campus, and to create a pipeline of highly skilled quantum engineers in the workforce.

Reference material: The course material for this course will be derived from different sources including but not limited to the following ones.

1. Nielsen MA, Chuang I. Quantum computation and quantum information. Cambridge University Press, 2002.
2. Rieffel, Eleanor G., and Wolfgang H. Polak. Quantum computing: A gentle introduction. MIT Press, 2011.
3. Feynman RP. Feynman lectures on computation. CRC Press; 2018 Jul 3.

Course syllabus and topical outline

- **Module 1: Quantum computing in a nutshell**

  ◇ The quantum world: Wave-particle duality and quantum mechanics

  ◇ Qubits (Quantum Bits): Bloch's sphere representation, superposition, entanglement, coherence, single qubit and multi-qubit systems

  ◇ An overview of quantum algorithms: Shor, Deutsch-Jozsa

  ◇ Metrics for a quantum computer: Single qubit and two-qubit operation error rates, interqubit connectivity, qubit count (scalability)

- **Module 2: Quantum computing with trapped ion qubits**

  ◇ An overview of the physics of trapped ion qubits

  ◇ Techniques of trapping ions

  ◇ The state-of-the-art, metrics, challenges and outlook

- **Module 3: Quantum computing with superconducting qubits**

  ◇ Overview of the physics of superconductors and Josephson junctions

  ◇ Superconducting qubits: transmon, fluxonium, hybrid

  ◇ The state-of-the-art, metrics, challenges and outlook

- **Module 4: Quantum computing with semiconductor spin qubits**

  ◇ An overview of spin physics

  ◇ Semiconductor spin qubits: optical and electrical gating

  ◇ The state-of-the-art, metrics, challenges and outlook

- **Module 5: Other qubit technologies**

  ◇ Neutral atom/diamond NV center/topological qubits/photonic qubits

  ◇ Comparison of different quantum computing technologies

- **Module 6: System level and hardware aspects**

  ◇ Input/Output and supporting peripherals; cooling and RF requirements; interconnects; scalability

  ◇ Quantum information processors: Gate based quantum computing, Quantum simulation and annealing and adiabatic quantum computing

  ◇ Analysis of full quantum information processing systems with ion trap, superconducting and semiconductor spin qubits

  ◇ An overview of quantum sensing

- **Module 7: Challenges, opportunities, outlook and reality check**

  ◇ Key players in quantum computing in the world

  ◇ Cloud based quantum computing (IBM and IonQ)

  ◇ Review of recent status reports, white papers and road-maps in quantum computing

Course grading and evaluation

1. Mid-term (1): 20%, assignments (3): 30%, research paper reviews (4): 20%, final exam or research project (report and presentation): 30%

2. 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 device technologies. The assignments will also make the students familiar with simple and basic calculations related to quantum devices operation and design(such as qubit error rates, frequencies etc.). 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.

Course objectives
As part of this course, students will

1. familiarize themselves with the fundamental principle of quantum computing devices and hardware.
2. apply their knowledge of device and quantum physics to understand the qubit technologies.
3. apply the engineering design process to study quantum computing hardwares that meet the constraints of time, cost and energy .

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

1. apply their knowledge of engineering to understand the advantages and challenges of different qubit technologies.
2. formulate and solve complex problems in building quantum computer systems by applying principles of quantum physics and technologies.
3. understand the state-of-the-art of quantum computing technologies, identify the challenges.
4. recognize the ongoing need to acquire new knowledge by reading and understanding research papers and doing reviews.

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