# CS8803 Syllabus: Introduction to Quantum Computing

## Instructor Information

| Instructor | Email | Office Hours & Meeting Link |
|---|---|---|
| Moin Qureshi | moin@gatech.edu | Tu 2-3pm on Zoom |
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## Overview :

Quantum computing promises exponential speedups for a class of important problems. Quantum computers with dozen(s) of qubits have already been demonstrated, and qubit counts expected to cross hundred in the next few years. Quantum Computing is an interdisciplinary field with topics ranging from physical devices (ion trap, superconducting, spin etc.) to error-correction codes (surface code or Shor code) to system & architecture (memory/microarchitecture) to compiler and tools (simulation and programming), to algorithms and applications. The goal of this course is to provide students in CS and ECE with the fundamental background on quantum computing and equip them with the skills to write code and optimize quantum programs on real quantum computers. This course will focus more on the "computing" aspects of quantum computing and will be cover the architecture, compiler, and applications of quantum computing for both the near-term (NISQ model of computation) and long-term (fault tolerant quantum computing).

## Objectives:

By the end of this course students will:
+ Become familiar with 1-qubit and 2-qubit gate operations and gain the ability to build simple quantum circuits
+ Become familiar with the concepts of superposition and entanglement and be able to analyze quantum state transformations
+ Understand quantum algorithms (Deutsch-Jozsa, Bernstein Vazirani, Grover, and Shor) and compare effectiveness versus classical algorithms
+ Understand the problem of noise and analyze the effectiveness of simple error correction codes
+ Become familiar with NISQ model of computation, and perform intelligent qubit mapping and error mitigation

**Text:** The material for this course will be derived from the following:

1. "Quantum Computing: A Gentle Introduction" by Eleanor Rieffel and Wolfgang Polak
2. Recent research papers from: ISCA, MICRO, ASPLOS etc.

## TOPICAL OUTLINE:

The course is divided into three parts:

- **A.** Basics of Quantum Computing (6 lectures, based on text-book material)
- **B.** Near-Term Quantum Computing (4 lectures, based on recent papers)
- **C.** Fault-Tolerant Quantum Computing (2 lectures, based on text-book & papers)

### A1. Superposition and Single Qubit

**Goal:** Analyze simple states of superposition and the effect of doing the measurement in different basis states.

**Topics:**

Superposition
Polarization of light
Single qubit notation
Measurement of Qubit
BB84 Quantum Key Dist
Bloch Sphere Notation

### A2. Quantum Gates and Circuits

**Goal:**
Build simple quantum circuits with single and two-qubit gates.

**Topics:**
Model of computation (movement on Bloch Sphere)
X, Y, Z, H gates
CNOT, Toffoli, Fredkin
SWAP gate
Simple circuits
Quantum Adder
Reversible circuits

### Tutorial on Evalution Infrastructure: QASM and IBM Machines (1-2 lectures)

Tutorial on how to use the IBM infrastructure to write quantum programs in QASM.
Setup for running quantum programs on IBM machines using simple quantum circuits.

### A3. Basics of Linear Algebra

**Goal:**
Equip students with the linear algebra background required for this course

**Topics:**
Dirac Notation
Vectors
Complex Conjugate & Norm
Analyzing Pauli gates

Analyzing Cascade of gates
Analyzing Two-qubit gates
Tensor Product (example)

### A.4: Entanglement

**Goal:**
Analyze quantum circuits with entanglement

**Topics:**
Entangled States
Testing for Entangled States
Bell Pair and Bell States
EPR Paradox & Bell Theorem
Conditional Instructions
Quantum Teleportation
Superdense Coding

### A.5: Simple Quantum Algorithms

**Goal:**
Analyze simple quantum algorithms and complexity

**Topics:**
Deutsch
Deutsch-Jozsa
Bernstein Vazirani
Grover

### A.6: Advanced Quantum Algorithms

**Goal:**
Analyze advanced quantum algorithms based on global properties like periodicity

**Topics:**
Simon's Algorithm
Period Finding
Shor's Algorithm
QFT (Basics)

## B1. Errors, Metrics and Benchmarking

**Goal:**
Discuss different modalities of error and effort to benchmark quantum computers

**Topics:**

Types of errors
Device Level Metrics
System Level Metrics
Benchmarking

## B2. NISQ Model of Computing

**Goal:**
Implement quantum programs in NISQ model of computing

**Topics:**
Current machines (5-50 qubit)
What is NISQ Model?
NISQ Metrics
Qubit Mapping Problem
Qubit Allocation Problem

## B.3 Error Mitigation Techniques for NISQ

**Goal:**
Analyze software-based techniques for reducing the error rate of NISQ

**Topics:**
Variability-Aware Mapping
Diversity-Aware Mapping
Reducing Measurement Errors
Reducing Idling Errors

## B.4 QAOA

**Goal:**
Become familiar with Quantum Approximate Optimization Algorithm

**Topics:**

Maxcut problem
Overview of QAOA
Optimizations for QAOA

**C.1 Errors and Error Correction**

**Goal:**
Analyze the effectiveness of simple error correction scheme

**Topics:**
Unique challenges in QEC
Shor's bit-flip code
Shor's phase-flip code
Shor 9-qubit code
Steane code
Concatenation code
Threshold theorem

**C.2 Surface Code and Error Decoding**

**Goal:**
Become familiar with Surface code and the latency constraints of error decoding

**Topics:**

Surface Code
Syndrome Extraction Cycle
Lookup Table Decoder
Scalable Decoder

**Course Grading:**

| | |
|---|---|
| Reviews | 5 x 2 pts = 10 pts |
| Knowledge Checks | 10x1=10 pts (10 best of 12) |
| Midterm | 20 pts |
| Final | 20 pts |
| Labs | 4 x 10pts = 40 pts |

The lectures will be a mix of textbook material and research papers. The midterm and the final exam 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 quantum computer, qubit allocation and routing algorithms, and error mitigation). The assignments will make the students familiar with the typical tools used in modeling quantum computers. The students will also review five recent papers in quantum computing.

**Office of Disability Statement:** https://disabilityservices.gatech.edu/

**Academic Honor Code:** http://www.policylibrary.gatech.edu/student-affairs/academic-honor-code

**Schedule**

| Week | Date | Content | Notes | KC (Due Mon) |
|---|---|---|---|---|
| 1 | 15-May | Lecture-0, Lecture-1, Setup | Setup QISKIT | |
| 2 | 22-May | Lecture-2, Lecture-3 | | KC-1 |
| 3 | 29-May | Lecture-4, Lecture-5 | Lab-1 due | KC-2, KC-3 |
| 4 | 5-Jun | Lecture-6 | | KC-4, KC-5 |
| 5 | 12-Jun | Midterm | Thu-Sun | KC-6 |
| 6 | 19-Jun | Lecture-7, Lecture-8 | Lab-2 due, R1 due | |
| 7 | 26-Jun | Lecture-9 | R2 due | KC-7, KC-8 |
| 8 | 3-Jul | Lecture-10 | Lab3-due, R3 due | KC-9 |
| 9 | 10-Jul | Lecture-11 | R4 due | KC-10 |
| 10 | 17-Jul | Lecture-12 | Lab4 due, R5 due | KC-11 |
| 11 | 24-Jul | Final Exam | July 27 - Aug 1 | KC-12 |