CS8803 Syllabus: Introduction to Quantum Computing

Instructor Information

Instructor	Email	Office Hours & Meeting Link
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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 4 pts = 20 pts
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.

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