ECE 8XXX: Introduction to Quantum Computing

Prerequisite: ECE3057/ECE6100 or equivalent + Linear Algebra

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 issues (memory/microarchitecture/IO) 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-Joza, 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 texts and papers:

1. "Quantum Computing: A Gentle Introduction" by Eleanor Rieffel and Wolfgang Polak

2. "Quantum Computing for Computer Architects" Tzvetan S. Metodi, Arvin I. Faruque, Frederic T. Chong

3. Preskill, J. (2018). Quantum Computing in the NISQ era and beyond. *arXiv:1801.00862*

4. Papers from recent conferences: ISCA, MICRO, HPCA, ASPLOS, PLDI etc.

TOPICAL OUTLINE:

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

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
(example AND gates)

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

Tutorial on how to use the IBM infrastructure to write quantum programs in QASM (Quantum Assembly) language.

Setup for running quantum programs on IBM machines. simple quantum circuits with single and two-qubit gates.

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)
Relative and Global Phase

Entanglement

Goal:
Analyze quantum circuits with entanglement

Topics:
Entangled States
Testing for Entangled States
Bell Pair and Bell States
EPR Paradox & Bell Theorem
Ekert 1991 QKD
Conditional Instructions
No Cloning Theorem
Quantum Teleportation
Superdense Coding

Simple Quantum Algorithms

Goal:
Analyze simple quantum algorithms and complexity

Topics:
Duetsch
Duetsch-Jozsa
Bernstein Vazirani
Simon
QFT

Advanced Quantum Algorithms (Fault Tolerant Quantum Computing)

Goal:
Analyze advanced quantum algorithms and complexity

Topics:
Shor’s Algorithm
Grover’s Algorithm

Errors and Error Correction

Goal:
Analyze the effectiveness of simple error correction scheme

Topics:
Types of errors
Unique challenges in QEC
Shor’s bit-flip code
Shor’s phase-flip code
Shor 9-qubit code
Steane code
Concatenation code
Stabilizer code
Threshold theorem (mention)

Fault Tolerant Quantum Computation

Goal:
Survey current research in the architecture of quantum computers

Topics:

Surface Code
Problem of decoding
Error Correction as Workload
QuEST and CryoDRAM
Magic State Distillation
Resource Estimation

NISQ Model of Computing

Goal:
Implement quantum programs in NISQ model of computing

Topics:
Current machines (5-50 qubit)
Why NISQ Model?
What is NISQ Model?
NISQ Metrics
Qubit Mapping Problem
NISQ Algorithms (VQE, QAOA)

Error Mitigation in NISQ Machines

Goal:
Analyze techniques for reducing the error rate of NISQ

Topics:
Variability-Aware Mapping
Reducing Measurement Errors
Diversity-Aware Mapping
Impact of Errors on Application

Advanced Topics (Latest/Ongoing Research)

Goal:
Discuss ongoing research topics in quantum computing

Topics:
Google Quantum Supremacy Paper
Using Compression to Push the Limits on Simulating Quantum Computers
Open-Pulse Model of Quantum Computing
Crosstalk noise and impact on emerging architectures

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.

Educational Objectives:

As part of this course, students …

1. apply their knowledge of mathematics to analyze quantum computing [1]
2. demonstrate an ability to utilize basic laboratory equipment and procedures. [3]
3. formulate and solve complex problems in building quantum computer systems by applying principles of engineering [1]
4. recognize the ongoing need to acquire new knowledge by reading and understanding research papers and doing reviews [6]
5. 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 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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