

# CS7400 (Online) Introduction to Quantum Computing

(Dated: Fall 2024)

## I. INSTRUCTOR INFORMATION

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## II. 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 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).

## III. 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.

## IV. 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

### 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)

### A4. 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

### **A5. Simple Quantum Algorithms**

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

**Topics:**

Deutsch  
Deutsch-Jozsa  
Bernstein Vazirani  
Grover

### **A6. 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

### **B3. 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

### **B4. QAOA**

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

**Topics:**

Maxcut problem  
 Overview of QAOA  
 Optimizations for QAOA

**C1. 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

**C2. 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

**V. COURSE GRADING**

Paper Reviews (PR)	5 pts
Knowledge Checks (KC)	5 pts (10 best of 12)
Problem Sets (PS)	15 pts
Midterm	15 pts
Final	15 pts
Labs	45 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 theories and typical tools used in modeling quantum computers. While we do encourage students to discuss, please keep in mind that your submission must be your own work and any resource used must be cited. The students will also review five recent papers in quantum computing.

**VI. LATE POLICY**

Each assignment, as defined and mentioned in Section V, is assigned a Due date-time and an Available Until date-time, as shown on its respective Canvas page. All dates and times are considered in Eastern Time. If you live in another timezone, please adjust your Canvas settings to correctly convert them to your local timezone. Your

submission for each assignment will be marked as Late after the Due date-time and before the Available Until date-time; this period is considered the grace period, and no penalty will be applied to submissions marked as Late. After the assigned Available Until date-time, an assignment will be closed, and no further submissions will be accepted. If no submission was made prior to the Available Until date-time, your assignment will be graded as 0. In case of an emergency, extension requests will be considered based on individual circumstances.

## VII. OFFICE OF DISABILITY STATEMENT

Please see <https://disabilityservices.gatech.edu/>.

## VIII. ACADEMIC HONOR CODE

Please see <http://www.policylibrary.gatech.edu/student-affairs/academic-honor-code>.

## IX. SCHEDULE

Week	Date	Content	Notes
1	19-Aug	Lecture-0, Lecture-1	Setup Qiskit
2	26-Aug	Lecture-2	
3	02-Sep	Lecture-3	PS-1 due
4	09-Sep	Lecture-4	Lab-1 due
5	16-Sep	Lecture-5	
6	23-Sep	Lecture-6	PS-2 due
7	30-Sep	Review	Lab-2 due
8	07-Oct	Midterm Exam	Thu-Sun
9	14-Oct	Lecture-7	PR-1 due
10	21-Oct	Lecture-8	PR-2 due
11	28-Oct	Lecture-9	PR-3, PS-3 due
12	04-Nov	Lecture-10	PR-4, Lab-3 due
13	11-Nov	Lecture-11	PR-5
14	18-Nov	Lecture-12	PS-4, Lab-4 due
15	25-Nov	Review	<i>Thanksgiving</i>
16	02-Dec	Final Exam	Thu-Sun

## X. DISCLAIMER

We reserve the right to modify the syllabus when it becomes necessary. In such cases, we will make notifications as soon as possible.