CS-4390/5390: Quantum Information Science

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Logistics

- Course Website: CS-4390/5390: Quantum Information Science
- Mode of Instruction: In-Person
- Class Schedule: Tuesday and Thursday 03:00PM - 04:20PM Mountain Time (MST)
- Location: Classroom Building C305
- Office hours: TBD
- Grading Breakdown:
  - Quizzes 30%
  - Labs and Implementations (40%)
  - Final Project and Presentations (30%)
  - Bonus Activities (5%)
- Contact: In addition to the office hour meeting, students are encouraged to ask all course-related questions on our *Microsoft Teams Channel* so that your peers can benefit from the answers. If you have a specific question that requires privacy, you may *email* directly.
- Academic accommodations: If you need an academic accommodation based on a disability, you should initiate the request with the Center for Accommodations and Support Services (CASS). The CASS will evaluate the request and recommend accommodations. Students should contact the CASS as soon as possible since timely notice is needed to coordinate accommodations.
- Honor code and Academic Integrity: Very very important. See Section 9.
- Audit Policy: See Section 10.

1 Course Overview

This course offers an in-depth introduction to Quantum Information Science, intended for upper-level undergraduate and graduate students in computer science, physics, electrical and computer engineering, or related fields. Due to the advanced material, a solid understanding of linear algebra, calculus, and probability and statistics is necessary.

We begin by examining the fundamental concepts of quantum mechanics relevant to information science, such as qubits, superposition, entanglement, and quantum gates. Students will learn to represent and manipulate quantum information mathematically and understand its physical interpretations. The course then explores key quantum algorithms, including Grover's algorithm for database search and Shor's algorithm for integer factorization, with practical implementations using tools like Qiskit. Furthermore, we explore topics such as quantum error correction methods, quantum hardware platforms, and quantum complexity theory.

In the latter part of the course, we focus on applications. We study quantum communication protocols, quantum networks, and quantum cryptography, including quantum key distribution protocols like BB84. The course also addresses the vulnerabilities of classical cryptography in the quantum era and introduces post-quantum cryptographic algorithms. We conclude with an introduction to quantum machine learning and a discussion of contemporary quantum technologies and their potential impact.

Why Quantum Information Science (QIS)?

Quantum Information Science sits at the forefront of technological innovation, with the potential to fundamentally transform computing, communication, and cryptography. As classical computing nears its physical and theoretical limits, quantum computing offers a new paradigm by utilizing quantum mechanical phenomena to perform computations beyond classical capabilities. Gaining expertise in Quantum Information Science enables students to contribute to this rapidly advancing field.

Advancements in quantum algorithms promise breakthroughs in solving complex problems in cryptography, optimization, and materials science that are currently intractable for classical computers. Quantum communication facilitates secure information transfer, which is vital for future cybersecurity. Proficiency in quantum error correction and hardware development is essential for building practical and scalable quantum computers.

The demand for professionals skilled in quantum technologies is growing swiftly in both academia and industry. By studying Quantum Information Science, students position themselves at the cutting edge of research and development, prepared to address challenges and drive innovation in a field with significant societal and technological impact.

2 Course Objectives

1. **Understand Fundamental Concepts and Mathematical Foundations**

- Comprehend the basic principles of quantum mechanics as they apply to information processing.
- Use mathematical tools like linear algebra and density matrices to represent and manipulate quantum information.

2. **Analyze and Implement Quantum Algorithms**
   - Study key quantum algorithms such as Grover's and Shor's, and understand their advantages over classical algorithms.
   - Learn about quantum error correction methods and their importance in preserving quantum information.
   - Gain insight into quantum hardware platforms and relevant computational complexity classes.
3. **Explore Quantum Communication and Cryptography**
   - Examine quantum communication protocols and the fundamentals of quantum networks.
   - Understand quantum cryptography, including the No-Cloning Theorem, and implement quantum cryptographic protocols.
   - Investigate the vulnerabilities of classical cryptography in the quantum era and explore post-quantum cryptographic algorithms.
4. **Introduce Advanced Topics in Quantum Information Science**
   - Learn about quantum machine learning concepts and their potential applications.
   - Discuss contemporary quantum technologies and their impact on science and industry.
5. **Develop Practical Skills through Hands-On Experience**
   - Participate in labs and projects that apply theoretical knowledge in practical settings.
   - Collaborate on group projects to investigate specific topics in quantum information science, integrating both theory and practice.

3 Course Learning Outcomes

By the end of this course, students will be able to:

1. **Understand fundamental quantum principles and mathematical methods**
   - Apply the principles of quantum mechanics to represent and manipulate quantum information.

- Use linear algebra and density matrices to describe and analyze quantum states.

2. **Implement and analyze quantum algorithms**
   - Implement quantum gates and circuits using quantum computing frameworks.
   - Develop and execute quantum algorithms such as Grover's and Shor's algorithms, comparing their performance with classical algorithms.
   - Explain quantum error correction codes and their role in preserving quantum information.
3. **Comprehend quantum hardware and computational complexity**
   - Describe different quantum hardware platforms.
   - Understand computational complexity classes relevant to quantum computing.
4. **Explore quantum communication and cryptography**
   - Evaluate quantum communication protocols and discuss quantum networks.
   - Implement quantum cryptographic protocols, including quantum key distribution schemes, and analyze their security features.
   - Assess the impact of quantum computing on classical cryptography and explore post-quantum cryptographic solutions.
5. **Engage with advanced topics and develop practical skills**
   - Understand quantum machine learning algorithms and discuss their potential applications.
   - Collaborate effectively on a group project, integrating theoretical concepts and practical skills in quantum information science.

4 Prerequisites

Students are expected to have the following backgrounds or equivalents:

- **Mathematics Pre-Requisites**:
  - Linear Algebra, Precalculus (MATH 1508), Calculus (MATH 1411 & MATH 1312), Discrete Mathematics (MATH 2300), Probability and Statistics (STAT 3320)

- **Computer Science Pre-Requisites**:
  - Programming (CS 1101, CS 3331, CS 3360), Data Structures and Algorithms (CS 2302, CS 2401)

- **Optional**:
  - Introduction to Cryptography, Introduction to Quantum Mechanics or Modern Physics, and Data Communication and Networking

5 Grading Policy

We will follow a standard UTEP grading policy. Grades in this course will be assigned based on the following scale:

- A: 90 – 100 %
- B: 80 – 89 %
- C: 70 – 79 %
- D: 60 – 69 %
- F: 0 – 60 %

6 Submission Policy

- **Deadlines**: All labs, assignments, and reports, must be submitted by the specified due date and time.
- **Late Submission and Penalties**:
  - 0-24 Hours Late: 10% deduction.
  - 24-48 Hours Late: 50% deduction.
  - 48+ Hours Late: 100% deduction.
- **Extensions**: Extensions may be granted for serious and extraordinary circumstances if requested before the deadline. Documentation may be required.
- **Technical Issues**: Technical difficulties are not valid reasons for late submissions. Plan ahead and submit early.

7 Course Syllabus

Table 1: Week-by-Week Course Outline with Detailed Topics and Lectures. Subject to revision and change.

Week	Contents
Thrust I: Foundations	
Week 1: Course Details, Review of Linear Algebra	
01/21/2025	Lecture 1: Course introduction, objectives, and fundamentals
01/23/2025	Lecture 2: Linear algebra for quantum systems
Week 2: Fundamentals of Quantum Mechanics	
01/28/2025	Lecture 1: Qubits, Superposition, Basics of quantum states and classical vs. quantum information
01/30/2025	Lecture 2: No-Cloning Theorem, Hilbert spaces, and multi-qubit systems
Week 3: Quantumness to Computer Science	
02/04/2025	Lecture 1: Quantum gates and quantum states
02/06/2025	Lecture 2: Quantum circuits and quantum operations
Week 4: IBM Qiskit	
02/11/2025	Lecture 1: Hello World! and Quantum Games
02/13/2025	Lecture 2: Quantum Information Science w/ Qiskit
Quiz 1: Foundations (100 points)	
Lab 1: Quantum Gates and Circuits (100 points)	
Thrust II: Theory	
Week 5: Density Operators	
02/18/2025	Lecture 1: Pure vs. Mixed States, Density Matrices
02/20/2025	Lecture 2: Partial Trace, Entanglement, and Quantum Measurements
Week 6: Quantum Algorithm I	
02/25/2025	Lecture 1: Grover's algorithm theory

02/27/2025	Lecture 2: Implementing Grover's algorithm
Quiz 2: Theory I (100 points)	
Lab 2: Implementing Grover's Algorithm (100 points)	

Week 7: Quantum Algorithms II	
03/04/2025	Lecture 1: Guest Lecture – Dr. Miralem Mehic
03/06/2025	Lecture 2: Shor's algorithm theory and impact on cryptography
Week 8 (03/11 and 03/13): Spring Break	
Week 9: Quantum Algorithm II	
03/18/2025	Lecture 1: Implementing Shor's algorithm
03/20/2025	Lecture 2: Guest Lecture – TBD
Quiz 3: Theory II (100 points)	

Lab 3: Implementing Shor's Algorithm (100 points)

Week 10: Quantum Error Correction	
03/25/2025	Lecture 1: Quantum errors and noise
03/27/2025	Lecture 2: Quantum error correction codes and fault tolerance
Week 11: Quantum Hardware and Complexity Theory	
04/01/2025	Lecture 1: Quantum hardware platforms
04/03/2025	Lecture 2: Quantum complexity theory (P, NP, BQP, QMA)
Quiz 4: Theory III (100 points)	

Thrust III: Applications	
Week 12: Quantum Communication	
04/08/2025	Lecture 1: Quantum communication protocols
04/10/2025	Lecture 2: Quantum networks and quantum internet
Project Proposal Presentation (Group)	

Week 13: Post Quantum Cryptography	
04/15/2025	Lecture 1: Introduction to PQC and vulnerabilities of classical cryptography
04/17/2025	Lecture 2: Implementing PQC algorithms

Quiz 5: Applications I (100 points)	

Week 14: Quantum Cryptography	
04/22/2025	Lecture 1: Introduction to Quantum Cryptography and the No-Cloning Theorem
04/24/2025	Lecture 2: Quantum Cryptographic Protocols and Applications
Lab 4: Quantum Cryptography Experiment (100 points)	

Week 15: Quantum Key Distribution	
04/29/2025	Lecture 1: Introduction to QKD and BB84 Protocol
05/01/2025	Lecture 2: Advanced QKD Protocols and Practical Implementations, and Thorlab kits
Quiz 6: Applications II (100 points)	
Lab 5: Quantum Key Distribution Experiment (100 points)	

Week 16: Quantum Machine Learning	
05/06/2025	Lecture 1: Introduction to QML and quantum-enhanced algorithms
05/08/2025	Lecture 2: Hybrid quantum-classical machine learning models

Final Project Presentation

8 Reference Resources

The course does not require any textbook.

Relevant books to the course (Optional):

- "Quantum Computation and Quantum Information," Michael A. Nielsen, Isaac L. Chuang.
- "Building Quantum Computers," Shayan Majidy, Christopher Wilson, and Raymond Laflamme."
- "Quantum Information Theory," Mark M. Wilde.
- "Quantum Computing Since Democritus," Scott Aaronson.

9 Honor Code and Academic Integrity

Permissive but strict. If unsure, please ask the course staff!

- **OK** to search for information and ask questions publicly about the systems we're studying.
  - Always cite all resources you reference, including papers, online articles, and any information obtained from AI tools.
  - When using AI tools, include a link to your tool's search history (e.g., share your ChatGPT workspace) and mention this in your reports, labs, and final projects.
  - If you engage in public discussions, such as on Reddit, include the link to the discussion.
- **NOT OK** to copy solutions directly from AI tools or other sources.
  - Solutions should be your original work, reflecting your understanding and analysis.
- **NOT OK** to ask someone else to complete your assignments, labs, or projects.
  - Academic integrity requires that all submitted work is your own.
- **OK** to discuss questions and ideas with classmates.
  - Collaborative learning is encouraged, but you must disclose your discussion partners in your submissions.
- **NOT OK** to copy solutions from classmates.
  - While discussion is permitted, all submitted work must be completed independently.
- **OK** to incorporate existing solutions as part of your projects or assignments.
  - Properly cite these solutions and clearly distinguish your contributions from those of others.
- **NOT OK** to present someone else's solution as your own.

  - Always attribute credit where it is due, and clearly identify your original work.
- **OK** to publish your final project after the course is over.
  - We encourage you to share your work with the broader community, contributing to the field's body of knowledge.
- **NOT OK** to post your assignment solutions online during or after the course.
  - This protects the integrity of the course for future students and maintains academic standards.

10 Audit Policy

We welcome auditing requests from anyone affiliated with UTEP. As an auditor, you will have access to all course lectures but will not receive grades for labs, homework, or final projects. Due to limited resources, we are unable to provide feedback on assignments or projects for auditors. If you are interested in auditing this course, please contact the Computer Science department to make the necessary arrangements.

Please note that external requests for auditing will not be considered, as the course is conducted in-person on campus.

All course materials, including lecture slides, detailed notes, assignments, and final project instructions, will be made publicly available on the course website for your reference.