CSCI-769 Topics in Theory (Quantum Computing Principles and Applications)

Lecture details

Lecture time/location:	Zoom Call - link on MyCourses
Instructor:	Dr. Ryan Vogt - United States Department of Defense/NSA
Email:	rhvvcs@rit.edu
Office Hours:	One Hour Before Each Class Session
Course GitHub (For Course Codes and Homework):	CSCI-769 Quantum Computing Principles And Applications

Course Description

This course provides a comprehensive introduction to quantum computing, blending foundational principles with hands-on experience. Designed for students with an interest in advanced computational technologies, the course begins with an overview of the transformative potential of quantum computing, the NISQ (Noisy Intermediate-Scale Quantum) era, and DiVincenzo's criteria for a functional quantum computer. Students will explore fundamental quantum mechanics concepts such as qubits, superposition, entanglement, and quantum measurement. Through an introduction to essential quantum gates and circuit models, they will understand the unique advantages of quantum computation over classical approaches.

Key quantum algorithms, including Deutsch-Jozsa, Grover's search, and Shor's factoring algorithm, are studied in depth, highlighting their computational implications and practical applications. Students will gain hands-on experience implementing these algorithms using Qiskit, fostering a practical understanding of quantum programming.

The course surveys a variety of quantum hardware platforms, including superconducting qubits, ion traps, photonics, topological models, and quantum annealers. Each platform's strengths, challenges, and practical considerations are analyzed, providing students with a holistic understanding of current quantum technologies. Additionally, the course addresses critical topics such as quantum error correction, fault tolerance, and managing noise in NISQ devices.

In the final weeks, students will undertake independent projects, selecting topics such as quantum algorithm implementation, an in-depth study of a quantum platform, or a novel research proposal. Projects are presented to the class, allowing students to showcase their findings through comprehensive reports and presentations.

By the end of the course, students will be equipped with the theoretical knowledge and practical skills to pursue further study or research in quantum computing, positioning them for opportunities in academia, industry, or government.

Grading Policy

Your overall grade in this course will be based on scores from around five homework tasks that include both theoretical and computational elements, as well as a final project. 75% of the grade is derived from homework assignments, while the remaining 25% is based on the final project.

Grade	Percentage Range
A	93 and above
A-	90 - 92
B+	87 - 89
B	83 - 86
B-	80 - 82
C+	77 - 79
C	73 - 76
C-	70 - 72
D	60 - 69
F	Below 60

Grading Breakdown:

- **Homework Assignments (5 total):** Every homework task will include a combination of theoretical and coding questions. Additionally, advanced bonus questions, designed as "mini-projects," provide an opportunity for students to gain a more profound insight into quantum computing and quantum mechanics. Each homework contributes **15% to the final grade**.
- **LaTeX**: If you haven't yet learned LaTeX, this course will serve as an excellent opportunity to get started. LaTeX is a powerful tool widely used for preparing STEM research documents, particularly for writing mathematical equations and formatting research papers. In fact, the vast majority of academic research papers in STEM fields are written using LaTeX.

  To begin, I recommend creating an account on Overleaf, an online LaTeX editor, using your RIT email: https://www.overleaf.com/. While it won't be mandatory to complete your homework assignments in LaTeX, I strongly encourage you to do so. To incentivize learning, I will award an additional 10 bonus points for homework submitted in LaTeX.

  This practice will also prepare you for the final project, where submitting the report in LaTeX will be a requirement (bonus points will not be offered for this). The goal is to help you become comfortable using LaTeX for "major accomplishments," a skill that will be invaluable if you pursue further education, publish research papers, or engage with the research community at large.
- **Final Project:** The final project is worth **25% of the final grade**.

Final Grade Calculation:

- The maximum possible score for a homework assignment is **160 points** (100 points from the 10 required questions + 50 bonus points + 10 bonus points for taking the time to write up your homework in LaTeX).
- Each homework contributes proportionally to the final grade, ensuring that:

$$\text{Homework Contribution} = \frac{\text{Total Earned Homework Points}}{500} \times 75\%$$

  where:
  - Total Earned Homework Points = Sum of all homework scores (up to 800 points, including bonus points).
- The final project contributes **25%** of the final grade. Its score is calculated as:

$$\text{Project Contribution} = \frac{\text{Final Project Score}}{100} \times 25\%$$

- The final grade is calculated as:

$$\text{Final Grade} = \text{Homework Contribution} + \text{Project Contribution}.$$

Final Project

Students will develop a quantum computing project, individually or in groups, demonstrating their understanding of a selected topic. Choose a final project that aligns with your interests and present it to the class at the end of the semester. While potential topics include quantum algorithms, hardware, cryptography, post-quantum cryptography or emerging quantum technologies like quantum sensing, communication, and radar, these are just examples. Students are encouraged to explore and select any project related to quantum technology that sparks their curiosity and passion.

Project Requirements:

- Submission of a project proposal by Week 7 for instructor approval.
- A final report, **typed up in LaTeX**, documenting methodology and findings.
- Presentation of the project to the class sometime in the weeks of 12-14.

Course Schedule

Weeks 1–6: Introduction to Quantum Computing

- **Week 1**: *Introduction to Quantum Computing, NISQ Era, and Superconducting Qubits*
  - Transformative potential of quantum computing.
  - High-level introduction to quantum vs. classical computation and foundational principles.
  - NISQ (Noisy Intermediate-Scale Quantum) Computing.
  - Superconducting Quantum Computers: Overview and criteria for an ideal functional quantum computer.
- **Week 2**: *Superposition, Entanglement, and Trapped Ion Qubits*
  - Quantum Bits (Qubits): Basics of qubits, superposition, and entanglement.
  - Ion Trap Quantum Computers: Principles of ion trap technology and its advantages for qubit coherence and manipulation.
- **Week 3**: *Quantum Circuits, Measurement, and Topological Qubits*
  - Building and simulating basic circuits in Qiskit, introduction to measurement and state collapse.
  - Topological Quantum Computing: Introduction to topological qubits, their theoretical basis, and the potential for fault tolerance.
- **Week 4**: *Universal Quantum Gate Sets and Photonic Qubits*
  - Overview of circuit-based quantum computing.
  - Photonics-Based Quantum Computing: Discussion on photonics as a platform for quantum information processing, focusing on advantages like room-temperature operation and high-speed photon transmission.
- **Weeks 5–6**: *Fault-Tolerant Quantum Computing, Quantum Error Correction Fundamentals, and Quantum Annealing*
  - Overview of quantum noise, bit-flip, and phase-flip errors.
  - Basic quantum error correction codes (e.g., repetition code) and fault tolerance.
  - Advanced error correction codes.
  - Quantum Annealing: Introduction to quantum annealing and its application to optimization problems, including an overview of D-Wave systems and how quantum annealing differs from gate-based quantum computing.

Weeks 7–11: Core Quantum Algorithms

- **Week 7**: *Deutsch-Jozsa Algorithm*
  - Concept of quantum algorithms with the Deutsch-Jozsa algorithm.
- **Weeks 8–9**: *Grover's Algorithm and Quantum Search Applications*
  - Exploration of Grover's algorithm for quantum search.
  - Hands-on with Qiskit to build and run quantum search algorithms.
- **Weeks 10–11**: *Shor's Algorithm and Quantum Computing Implications for Cryptography*
  - Study of Shor's algorithm for factoring, how it can be extended to solve the discrete log problem, and its impact on cryptography.
  - Introduction to modular arithmetic and implementation in Qiskit.

Weeks 12–14: Project Presentations

- **Weeks 12–14**: *Project Presentations and Course Conclusion*

- The main points of the project:
  * Students will develop a quantum computing project, individually or in groups, demonstrating their understanding of a selected topic. Choose a final project that aligns with your interests and present it to the class at the end of the semester. While potential topics include quantum algorithms, hardware, cryptography, post-quantum cryptography or emerging quantum technologies like quantum sensing, communication, and radar, these are just examples. Students are encouraged to explore and select any project related to quantum technology that sparks their curiosity and passion.
  * Original Research Proposal: A relevant topic centered on either a practical implementation or a theoretical exploration in quantum computing, designed to be thoroughly studied and completed within a 5-week timeframe.
- **Project Requirements**: Detailed documentation in a report (**typed up in LaTeX**) and presentation of their findings to the class.

Resources

- Nielsen, M. A., & Chuang, I. L. (2010). *Quantum Computation and Quantum Information: 10th Anniversary Edition*. Cambridge University Press.
- Von Neumann, J. (1955). *Mathematical Foundations of Quantum Mechanics*. (R. T. Beyer, Trans.). Princeton University Press.
- Mermin, N. David. *Quantum Computer Science*.
- Aaronson, Scott. *Quantum Computing Since Democritus*.
- Rieffel, Eleanor. *An Introduction to Quantum Computing for Non-Physicists*.
- Macauley Coggins. *Introduction to Quantum Computing with Qiskit*.
- James Weaver & Frank Harkins. *Qiskit Pocket Guide: Quantum Development with Qiskit*.

Academic Honesty

Academic honesty and integrity are foundational values of Rochester Institute of Technology (RIT). This course adheres strictly to RIT's Academic Honesty Policy, which requires that all submitted work represents your own understanding and effort.

Collaboration and Teamwork: Collaboration and working together to solve problems are highly encouraged in this course, as these practices foster deeper learning and reflect real-world scientific inquiry. Discussing concepts, brainstorming approaches, and seeking advice from peers are all valuable forms of collaboration. However, all submitted work must ultimately reflect your own understanding, phrasing, and coding.

Prohibited Actions: Blatant copying, plagiarism, taking credit for another student's work, or misrepresenting someone else's intellectual property as your own are serious violations of academic integrity and will not be tolerated. This includes, but is not limited to:

- Submitting work that is not your own or has been copied from another student, an online source without any intellectual input from yourself, or any other unauthorized material.
- Allowing another student to copy your work.
- Using unauthorized aids or resources to complete assignments.

Consequences: Instances of academic dishonesty will be handled according to RIT's Academic Honesty Policy. Possible consequences include a failing grade on the assignment, failure in the course, and further disciplinary action as outlined by the Institute.

By participating in this course, you agree to uphold the principles of academic integrity and contribute to a fair, respectful, and honest academic environment.