

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

### Lecture details

Lecture time/location: TBD  
Instructor: Dr. Ryan Vogt - United States Department of Defense/National Security Agency  
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Office Hours: 8:00-8:50 AM Monday, Wednesday, Friday

### 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. Approximately 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):** Each homework assignment will consist of 15 questions, a mixture of theory and coding. Students can choose to emphasize theory or practice, depending on their strengths. Each homework is worth **15% of the final grade**.
  - Students must complete at least 10 questions of their choice. Each of these 10 questions is worth **10 points**, for a total of **100 points**.
  - The remaining 5 questions are optional and worth **10 points each**, providing up to **50 bonus points**.
- **Final Project:** The final project is worth **25% of the final grade**.

#### Final Grade Calculation:

- The maximum possible score for a homework assignment is **150 points** (100 points from the 10 required questions + 50 bonus points).
- 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 750 points, including bonus points).
  - Maximum Possible Homework Points = 750 points (if all bonus points are earned).
- 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. The project can focus on:

- **Implementation and Analysis of a Quantum Algorithm:** Examples include Grover's or Shor's algorithm, with a deeper level of analysis or extension beyond what was covered in class or homework. Students may, and will be encouraged to, choose a quantum algorithm not mentioned throughout the course to study and implement in Qiskit.
- **In-Depth Exploration of a Quantum Platform or Topic:** A detailed examination of a specific platform, technology, or a novel concept not covered deeply during the course.
- **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:

- Submission of a project proposal by Week 9 for instructor approval.
- A final report, documenting methodology and findings.
- Presentation of the project to the class in Week 13 or 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*
  - Students may choose to:

- \* Implement and Analyze a Quantum Algorithm: Examples include Grover's or Shor's algorithm, with a deeper level of analysis or extension beyond what was covered in class or homework. Students may also choose a quantum algorithm not mentioned throughout the course to study and implement in Qiskit.
  - \* In-Depth Exploration of a Quantum Platform or Topic: Explore a specific platform, technology, or advanced concept not covered in-depth during the course.
  - \* 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 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.