ECE 792, MSE 791, PY 790 Course Syllabus

The Physics and Operation of Qubits TuTh 10:15-11:30 am

Course Description

This graduate-level course provides an in-depth exploration of the physics and operational principles of various qubit technologies, which are the fundamental building blocks of quantum computing. The course is designed to equip students with a comprehensive understanding of the different types of qubits, their underlying physics, and the challenges associated with their implementation and scaling.

Course Objectives/Goals

The primary objective of this course is to provide students with a comprehensive understanding of the physics and operational principles underlying various qubit technologies. By the end of this course, students will be able to explain and analyze the fundamental concepts and challenges associated with the main qubit technologies including semiconductor spin qubits, trapped-ion qubits, and superconducting qubits. Students will develop the ability to critically evaluate current research in qubit technologies, compare different qubit platforms, and assess their potential applications in quantum computing. The course aims to foster problem-solving skills by engaging students in practical exercises that bridge theoretical knowledge with real-world quantum computing scenarios. Additionally, students will gain insight into the cutting-edge advancements and future directions in qubit technology, preparing them for further research or professional work in the field of quantum information science. Through in-depth study of key review articles and current literature, students will also enhance their ability to interpret and synthesize complex scientific information, developing crucial skills for contributing to the rapidly evolving landscape of quantum technologies.

Learning Outcomes

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

- Demonstrate a deep understanding of the physical principles governing different types of qubits, including semiconductor spin qubits, trapped-ion qubits, and superconducting qubits.
- Analyze and compare the strengths, limitations, and operational challenges of various qubit technologies in the context of quantum computing applications.
- Evaluate current research literature in qubit technologies and articulate the significance of recent advancements in the field.
- Apply theoretical knowledge to solve problems related to qubit control, manipulation, and readout in different physical implementations.
- Explain the challenges associated with scaling qubit systems and discuss potential solutions proposed in current research.
- Assess the potential of different qubit platforms for practical quantum computing applications and quantum technologies.
- Develop and present a critical analysis of a specific qubit technology, including its underlying physics, recent progress, and future prospects.
- Demonstrate proficiency in interpreting and discussing complex scientific papers in the field of quantum information science.
- Propose potential research directions or experiments to address current challenges in qubit technology.

Course Structure

This course is designed to provide a comprehensive exploration of qubit physics and operation. We will begin with a broad survey of various qubit technologies. Following this overview, the course will be primarily divided into three main sections, each focusing on a key qubit technology that has shown significant promise in quantum computing research and development. The first main section will delve deeply into semiconductor spin qubits, exploring their physical principles, recent advancements, and potential applications. The second section will cover trapped-ion qubits, examining their unique properties, control mechanisms, and scaling challenges. The third section will focus on superconducting qubits, investigating their operational principles, various types, and recent breakthroughs in the field. Throughout these sections, we will analyze the fundamental physics, strengths and limitations of each technology, discuss current research challenges, and consider future prospects.

Course Policies

Class participation:

Participation in class discussions is an essential part of the learning process in this course. Although not explicitly graded, your contributions and insights will be evaluated and assessed to manage borderline grades (e.g., change B+ to A-, B- to B, etc.). While your participation grade is subjective, it will not be random or arbitrary. Your comments demonstrate some reflective thinking, and frequent quality comments are highly encouraged.

Computers and Communications Devices during class:

You will affect everyone's learning if your cell phone, laptop, etc. makes noise or is visually distracting during class. For this reason, you are asked to turn off your mobile devices and close your laptops during class unless you are taking notes on your laptop. You must turn the sound off so that you do not disrupt other students' learning.

Recording of the class:

The lectures may be recorded by students for personal use, but may not be further copied or distributed in any form without the written consent of the instructor.

Quiz Policy:

This course includes regular quizzes as part of the assessment. To accommodate unforeseen circumstances, the lowest graded quiz will be automatically dropped for all students. However, there are no make-up quizzes offered for missed assessments, with the sole exception being medical reasons. If a student misses a quiz due to illness, they must provide an official letter from a medical clinic confirming their inability to attend class on the specific date. No other form of evidence will be accepted to verify illness. It's important to note that schedule conflicts such as job interviews, conference attendance, or other exams are not considered valid reasons for waiving a quiz. Students are expected to manage their schedules accordingly to participate in all quizzes.

Instructors

Daryoosh Vashaee (dvashae) - *Instructor*
Email: dvashae@ncsu.edu
Phone: 9195159599
Office Location: 451 MRC or Online with an appointment
Office Hours: Tu 12:00 pm – 1:00 pm In-person or via Zoom at https://ncsu.zoom.us/my/daryoosh
These hours are subject to change, and the instructor will make every effort to provide advance notice; however, unavoidable appointments may necessitate last-minute adjustments. Office hours are designed for the convenience of students, and they are encouraged to take advantage of this time for assistance or discussion.

Course Meetings

Lecture

Days: TuTh
Time: Tu 10:15 am – 11:30 am
Campus: Centennial
Location: TBD
This meeting is required.

Final Exam

Day: TBD
Time: TBD
Campus: Centennial
Location: TBD

Course Materials

Lecture Notes:

Lecture slides will be provided to the students.

Textbooks:

For semiconductor spin qubits:

1. Review article: Hanson, Ronald, Leo P. Kouwenhoven, Jason R. Petta, Seigo Tarucha, and Lieven MK Vandersypen. "Spins in few-electron quantum dots." *Reviews of modern physics* 79, no. 4 (2007): 1217-1265.
2. Review article: Chatterjee, Anasua, Paul Stevenson, Silvano De Franceschi, Andrea Morello, Nathalie P. de Leon, and Ferdinand Kuemmeth. "Semiconductor qubits in practice." *Nature Reviews Physics* 3, no. 3 (2021): 157-177.
3. Review article: Burkard, Guido, Thaddeus D. Ladd, Andrew Pan, John M. Nichol, and Jason R. Petta. "Semiconductor spin qubits." *Reviews of Modern Physics* 95, no. 2 (2023): 025003.

For trapped-ion qubits:

1. Review article: Bruzewicz, Colin D., John Chiaverini, Robert McConnell, and Jeremy M. Sage. "Trapped-ion quantum computing: Progress and challenges." Applied Physics Reviews 6, no. 2 (2019).

For superconducting qubits:

1. Review article: Kjaergaard, Morten, Mollie E. Schwartz, Jochen Braumüller, Philip Krantz, Joel I-J. Wang, Simon Gustavsson, and William D. Oliver. "Superconducting qubits: Current state of play." Annual Review of Condensed Matter Physics 11, no. 1 (2020): 369-395.
2. Review article: Kjaergaard, Morten, Mollie E. Schwartz, Jochen Braumüller, Philip Krantz, Joel I-J. Wang, Simon Gustavsson, and William D. Oliver. "Superconducting qubits: Current state of play." *Annual Review of Condensed Matter Physics* 11, no. 1 (2020): 369-395.

General overview (covering all three technologies):

1. Textbook: Devoret, Michel H., Benjamin Huard, Robert Schoelkopf, and Leticia F. Cugliandolo, eds. Quantum machines: measurement and control of engineered quantum systems. Vol. 96. Oxford University Press, USA, 2014.
2. Review article: Alfieri, Adam, Surendra B. Anantharaman, Huiqin Zhang, and Deep Jariwala. "Nanomaterials for quantum information science and engineering." Advanced Materials 35, no. 27 (2023): 2109621.

Requisites and Restrictions

Prerequisites

None.

Co-requisites

None.

Restrictions

None.

While there are no specific prerequisites for this course, students must be familiar with quantum mechanics and solid-state physics. They should be comfortable with fundamental concepts, including wave functions, Schrödinger's equation, spin, and entanglement. Additionally, a working knowledge of solid-state devices is essential, as the course will focus on the physics of various qubit implementations in solid-state systems. Familiarity with fundamental concepts in condensed matter physics, such as band theory, semiconductor physics, and superconductivity, will be beneficial. While not strictly required, prior exposure to quantum information theory and basic quantum computing concepts will enhance students' ability to contextualize the hardware discussions within the broader field of quantum technologies. Students unsure about their preparedness for this course are encouraged to consult with the instructor before enrolling. The course is designed for graduate students in electrical engineering, materials science and engineering, and physics, or related fields with a strong background in quantum physics and materials science.

General Education Program (GEP) Information

GEP Category

This course does not fulfill a General Education Program category.

GEP Co-requisites

This course does not fulfill a General Education Program co-requisite.

Transportation

This course will not require students to provide their own transportation. Non-scheduled class time for field trips or out-of-class activities is NOT required for this class.

Safety & Risk Assumptions

None.

Grading

Component	Weight	Details
Quiz & HW	**20**	Quizzes and HW are given throughout the course to assess ongoing understanding. All quizzes are closed book and closed notes, with no formula sheets allowed. While simple calculators are permitted, laptops, tablets, and other electronic devices are prohibited during quizzes.
Midterm exam	**30**	It is a closed book and closed notes exam, with no formula sheets permitted. Graphing calculators are not allowed; however, students may use a basic, non-graphing calculator for computations if needed.
Paper review & presentation	**20**	Students will select a topic related to the course content, subject to instructor approval. They will then conduct an in-depth study of the chosen topic and present their findings.
Final exam	**30**	Like the midterm, it is closed book and closed notes, with no formula sheets allowed. Graphing calculators are prohibited, but students may use a simple, non-graphing calculator for basic calculations if necessary.

Letter Grades

This course uses Standard NCSU Letter Grading:

97	≤	A+	≤	100		73	≤	C	<	77
93	≤	A	<	97		70	≤	C-	<	73
90	≤	A-	<	93		67	≤	D+	<	70
87	≤	B+	<	90		63	≤	D	<	67
83	≤	B	<	87		60	≤	D-	<	63
80	≤	B-	<	83		0	≤	F	<	60
77	≤	C+	<	80						

Requirements for Auditors (AU)

Information about and requirements for auditing a course can be found at http://policies.ncsu.edu/regulation/reg-02-20-04.

Policies on Incomplete Grades

If an extended deadline is not authorized by the Graduate School, an unfinished, incomplete grade will automatically change to an F after either (a) the end of the next regular semester in which the student is enrolled (not including summer sessions), or (b) by the end of 12 months if the student is not enrolled, whichever is shorter. Incompletes that change to F will count as an attempted course on transcripts. The burden of fulfilling an incomplete grade is the responsibility of the student. The university policy on incomplete grades is located at http://policies.ncsu.edu/regulation/reg-02-50-03. Additional information relative to incomplete grades for graduate students can be found in the Graduate Administrative Handbook in Section 3.18.F at http://www.fis.ncsu.edu/grad_publicns/handbook/

Academic Integrity

Students are required to comply with the university policy on academic integrity found in the Code of Student Conduct found at http://policies.ncsu.edu/policy/pol-11-35-01

All assignments will be screened for plagiarism and academic integrity. Copying another student's assignment or computer program, turning in an assignment that is identical or very similar to others' work, or receiving help on assignments without permission of the instructor is a violation of academic integrity and will be treated strictly by NCSU Policy and Procedures. Violations will result in your being sanctioned, including receiving a failing grade, receiving a notation of a violation of academic integrity on your transcript (F!), and being suspended from the University.

Honor Pledge

Your signature on any test or assignment indicates, "I have neither given nor received unauthorized aid on this test or assignment."

Late Assignments

Late assignments are NOT acceptable.

Electronically-Hosted Course Components

There are no electronically-hosted components for this course.

Accommodations for Disabilities

Reasonable accommodations will be made for students with verifiable disabilities. In order to take advantage of available accommodations, students must register with the Disability Services Office at Suite 2221, Student Health Center, Campus Box 7509, 919-515-7653. For more information on NC State's policy on working with students with disabilities, please see the Academic Accommodations for Students with Disabilities Regulation (REG 02.20.01).

NC. State University Policies, Regulations, and Rules (PRR)

Students are responsible for reviewing the PRRs, which pertain to their course rights and responsibilities. These include: http://policies.ncsu.edu/policy/pol-04-25-05 (Equal Opportunity and Non-Discrimination Policy Statement), http://oied.ncsu.edu/oied/policies.php (Office for Institutional Equity and Diversity), http://policies.ncsu.edu/policy/pol-11-35-01 (Code of Student Conduct), and http://policies.ncsu.edu/regulation/reg-02-50-03 (Grades and Grade Point Average)

NC State University provides equality of opportunity in education and employment for all students and employees. Accordingly, NC State affirms its commitment to maintaining a work environment for all employees and an academic environment for all students that is free from all forms of discrimination. Discrimination based on race, color, religion, creed, sex, national origin, age, disability, veteran status, or sexual orientation is a violation of state and federal law and/or NC State University policy and will not be tolerated. Harassment of any person (either in the form of quid pro quo or creation of a hostile environment) based on race, color, religion, creed, sex, national origin, age, disability, veteran status, or sexual orientation also is a violation of state and federal law and/or NC State University policy and will not be tolerated. Retaliation against any person who complains about discrimination is also prohibited. Any person who feels that he or she has been the subject of prohibited discrimination, harassment, or retaliation should contact the Office for Equal Opportunity (OEO) at 919-515-3148.