PHY 3650 Quantum Information Processing

Spring 2024

University of Central Florida

Pre-requisites: PHY 2049/C, 2049/L; MAC 2313 or MAS 3105; or instructor's consent.

Regular meeting times and venue: Tuesdays and Thursdays, 10:30 am – 11:50 am, CSB 1 (Classroom building 1) room 113.

Course modality: P (face-to-face)

Instructor: Dr. Eduardo Mucciolo (mucciolo@ucf.edu)

Office: PSB (Physical Sciences building) room 457

Office hours: Friday 10:00 – 11:00 am and 4:00 – 5:00 pm

Overview: This course aims to bring the fundamentals of quantum information processing to undergraduates without requiring a formal background in quantum mechanics as pre-requisite. Quantum information processing, which includes quantum computation, quantum communications, and quantum sensing, is a rapidly developing interdisciplinary area that may have far-reaching technological implications soon. There is a growing effort from academia, the federal government, and the private sector to push for fundamental and applied research in this area, with the goal to develop new algorithms and hardware and to apply quantum solutions to problems in a variety of fields, from materials science to telecommunications to finances and biomedical research. There is also growing demand for a labor force well trained in quantum information. This course provides as steppingstone in this direction for students from a variety of majors, balancing rigor with generality. Students should expect a challenging but rewarding course.

This is a self-contained course. It does not rely on any previous knowledge of quantum mechanics. It combines lectures with discussions and some hands-on (programming) activities. Some experience with programming, especially with Python, will be useful in this course, but is not a requirement. Some familiarity with matrices, vectors, and linear algebra is recommended for a better experience.

Learning Outcomes: Students who successfully go through this course will be able to:

(1) understand and employ fundamental concepts and methods from quantum mechanics relevant to quantum information processing.
(2) understand the basic elements of quantum information processing, such as qubits, classical and quantum gates, circuits, measurements, entangled states and product states.
(3) understand the workings of foundational quantum algorithms.
(4) be knowledgeable of models of quantum computing other than the circuit model.
(5) understand the concept of decoherence, its implications to quantum information processing, and its mitigation.
(6) understand the fundamentals of quantum key distribution.
(7) be knowledgeable of physical realizations of qubits.
(8) be able to do some basic programming of a quantum computer.

Course Content:

1. **Introduction**: what is quantum information, where did it come from, why is it so important?
2. **The basics of quantum phenomena**: particles, waves, energy levels, measurements, uncertainty, superposition, interference, entanglement; postulates of quantum mechanics.
3. **The language of quantum mechanics**: a linear algebra primer; probabilities; Dirac notation; Hilbert spaces.
4. **Qubits**: one, two, many; Bloch sphere, operators, observables; entanglement; EPR, Bell states.
5. **Programming quantum computers**: programming languages; Qiskit; open-source platforms.
6. **Basics of quantum information**: no-cloning theorem, quantum teleportation, superdense coding.
7. **Quantum circuits and foundational quantum algorithms**: gates; universality; Deutsch-Josza, Grover (amplitude amplification and database search), Shor (order finding and semi-prime factoring); variational; applications.
8. **Other approaches to quantum computing**: adiabatic, variational, topological.
9. **Decoherence and quantum error correction**: single-qubit errors, relaxation times, damped Rabi oscillations; Steane code, 5- and 7-qubit codes; fault tolerance and threshold theorem.
10. **Quantum cryptography and quantum communication**: basics of cryptography; quantum key exchange protocols; channels, entropy.
11. **Physical realizations of qubits**: superconductor junctions, ion traps, impurities/defects/color centers, nuclear spins, photonic systems, etc.

Important Dates:

Start of classes: Tuesday, January 9.
Homework assignments: due every two weeks: January 22, February 5 and 19, March 4 and 25, April 8 (any changes to these dates will be communicated with reasonable advance)
Mid-term exam: February 27
Spring break: March 18 – 22
Final project paper due: April 12
Final project presentations: April 18 (last day of classes)
Final exam: TBD

Homework assignments: six in total, due every two weeks, always on Mondays. They consist mostly of conceptual questions and quantitative problems, which may require analytical and/or numerical computations to be solved. They are designed to take 4 to 6 hours each to be completed and will be posted on Webcourses. Solutions will be available after grading is completed.

Homework consultation policy: Students can exchange ideas with their peers about problems and questions in the assignments but must develop their own solutions and answers. Failure to comply with this policy may result in sanctions, ranging from a zero score to reporting to the SCAI office, which may result in more serious sanctions.

Final project: a turn-in paper on a topic chosen by the students with prior approval from the instructor. The topic must be chosen by the end of 13^{th} week. Groups of up to 3 students are allowed to work together on a single paper. The paper should have at least 5 pages and no more than 15 pages, single-spaced, font 11, letter size, 1-inch margins, and be handed to the instructor in electronic format (latex editing highly recommended). References and bibliography, when consulted and used, must be acknowledged and listed. Students are free to consult any source but need to write their own text. All papers will be reviewed electronically for plagiarism before graded. If the paper is found to have any part of it plagiarized (including the lack of appropriate referencing), a zero score will be given, ensued by reporting to the SCAI office. Only papers who passed the plagiarism scrutiny will be allowed to be presented. Each group will have 15 minutes to make a presentation of their final project during regular class time.

Mid-term exam: The exam is planned to take place during regular class time. Textbooks and other materials may be consulted, but all answers and solutions must be developed by the student.

Final exam: Like the mid-term exam. It will only cover material not tested in the mid-term exam. The content and format will be communicated to students a week prior to the exam period. Textbooks and other materials may be consulted as well, but answers and solutions must be developed individually by the student.

Cheating: If a student is deemed to have cheated in any exam or assignment, they will receive a zero score and will be reported to the SCAI office.

Make-up policies: This course will follow UCF, the College of Sciences, and the Department of Physics make-up policies and procedures, including those regarding participation in university-sanctioned activities and religious holidays (see below). In addition to these policies, students who know that they will miss a homework assignment deadline need to communicate it to the instructor with reasonable advance, when possible. The instructor reserves the right to reduce the score of the student's homework assignment by 10% for every day passed the due date when the assignment is handed in late. The instructor also requires significant cause and documentation for allowing make-up exams. There is no make-up for the final project paper.

Attendance: It is expected for every class meeting and is part of the course grade composition.

Lectures: They will be primarily expositions of concepts and ideas, and explanations of formulations and methodologies, but will also include discussions.

Office hours: The instructor will be available to students at least two hours per week on pre-determined weekdays. Office hours will be face-to-face; video conferencing may be used if conditions require it. Students are encouraged to exchange emails with the instructor via Webcourses for a quicker response when questions arise. Webcourses will be the primary channel for electronic communication, but students may request individual meetings with the instructor, who will try to accommodate them to the best of his ability.

Grade Breakdown Policy:

Attendance and participation: 5%
Homework: 20%
Mid-term exam: 22.5%
Final project: 30%
Final exam: 22.5%

Grade Scale:

A: 100 – 90, B: 89 – 75, C: 74 – 60, D: 59 – 50, F: 49 – 0.

All grades will be posted in Webcourses in a timely way. The instructor will only use Webcourses email or in-person meetings to discuss a student's grade. FERPA rules will be strictly followed.

Textbook and Supporting Materials

We will not adopt or strictly follow any textbook in this course. Notes and slides prepared by the instructor will be posted on Webcourses following their use in class. Therefore, students are not required to purchase any textbook. The instructor will strive to identify additional free resources during the course and will share them with students.

There is an ever-growing plethora of books on quantum information processing, to a point that it is nearly impossible to provide a comprehensive list. There are many online resources in this area. Students are encouraged to consult these sources, according to their interests and preferential format or style of presentation. For those who would like to dig deeper into the course contents or would like to have textbook-level/format supplementary materials to read, here is a suggested list:

- *A First Introduction to Quantum Computing and Information*. Author: B. Zygelman (Springer, 2018). This book is freely available online for UCF students via the UCF Library's Springer Collection.

- *Quantum Computer Science, an Introduction*. Author: N. D. Mermin (Cambridge University Press, 2007). The target audience of this book is computer scientists.

- *Quantum Processes Systems, and Information*. Authors: B. Schumacher and M. Westmoreland (Cambridge University Press, 2010). This book is a good introduction for physics majors who will take Wave Mechanics.

- *An Introduction to Quantum Computing*. Authors: P. Kaye, R. Laflamme, and M. Mosca (Oxford University Press, 2007). A very good reference, accessible to scientists and engineers, but focused on quantum computing only.

- *Quantum Computation and Quantum Information*. Authors: M. L. Nielsen and I. L. Chuang (Cambridge University Press, 2010). The most comprehensive textbook on quantum information processing, but it is getting old fast.

- *Learn Quantum Computing with Python and IBM Quantum Experience*. Author: R. Loredo (Packt Publishing, 2020). Guide to using IBM Quantum Experience, but it is already a bit out of date.

- *Approaching Quantum Computing*. Authors: D. C. Marinescu and G. M. Marinescu (Pearson, 2004). A comprehensive review written by a former UCF professor.

Tentative Schedule: (The instructor reserves the right to modify it according to the course progress)

- Week 1 (Jan 9, 11): introduction; the basics of quantum phenomena.
- Week 2 (Jan 16, 18): the language of quantum mechanics.
- Week 3 (Jan 23, 25): qubits.
- Week 4 (Jan 30, Feb 1): basics of quantum information; programming quantum computers
- Week 5 (Feb 6, 8): programming quantum computers (cont.); quantum circuits
- Week 6 (Feb 13, 15): quantum circuits (cont.); foundational quantum algorithms.
- Week 7 (Feb 20, 22): foundational quantum algorithms (cont.).
- Week 8 (Feb 27, Feb 29): *mid-term exam*; other approaches to quantum computing.
- Week 9 (Mar 5, 7): other approaches to quantum computing (cont.).
- Week 10 (Mar 12, 14): decoherence and quantum error correction.
- Week 11 (Mar 26, 28): quantum cryptography and quantum communications.
- Week 12 (Apr 2, 4): physical realizations of qubits.
- Week 13 (Apr 9, 11): physical realizations of qubits (cont.).
- Week 14 (Apr 16, 18): catch up time; final project presentations.
- Week 15 (Apr 23, 25): final exam (TBD).

UCF Rules of Conduct

Students in this course should familiarize themselves with UCF's Rules of Conduct at https://scai.sdes.ucf.edu/student-rules-of-conduct/

as there are several prohibitions that students need to be aware of, including unauthorized assistance, communications to others during exams, commercial use of academic materials, falsifying or misrepresenting the student's own academic work, plagiarism, etc.

Students in this course should also familiarize themselves with the procedures for academic misconduct in UCF's student handbook, *The Golden Rule*: https://goldenrule.sdes.ucf.edu/

Accessibility

The University of Central Florida is committed to providing access and inclusion for all persons with disabilities. Students with disabilities who need access to course content due to course design limitations should contact the professor as soon as possible. Students should also connect with Student Accessibility Services (SAS) <http://sas.sdes.ucf.edu/> (Ferrell Commons 185, sas@ucf.edu, phone 407-823-2371). For students connected with SAS, a Course Accessibility Letter may be created and sent to professors, which informs faculty of potential course access and accommodations that might be necessary and reasonable. Determining reasonable access and accommodations requires consideration of the course design, course learning objectives and the individual academic and course barriers experienced by the student. Further conversation with SAS, faculty and the student may be warranted to ensure an accessible course experience.

Campus Safety

Emergencies on campus are rare, but if one should arise during class, everyone needs to work together. Students should be aware of their surroundings and familiar with some basic safety and security concepts:

- In case of an emergency, dial 911 for assistance.
- Every UCF classroom contains an emergency procedure guide posted on a wall near the door. Students should make a note of the guide's physical location and review the online version at <http://emergency.ucf.edu/emergency_guide.html>.
- Students should know the evacuation routes from each of their classrooms and have a plan for finding safety in case of an emergency.
- If there is a medical emergency during class, students may need to access a first-aid kit or AED (Automated External Defibrillator). To learn where those are located, see <https://ehs.ucf.edu/automated-external-defibrillator-aed-locations>.
- To stay informed about emergency situations, students can sign up to receive UCF text alerts by going to <https://my.ucf.edu> and logging in. Click on "Student Self Service" located on the left side of the screen in the toolbar, scroll down to the blue "Personal Information" heading on the Student Center screen, click on "UCF Alert", fill out the information, including e-mail address, cell phone number, and cell phone provider, click "Apply" to save the changes, and then click "OK."
- Students with special needs related to emergency situations should speak with their instructors outside of class.
- To learn about how to manage an active-shooter situation on campus or elsewhere, consider viewing this video (<https://youtu.be/NIKYajEx4pk>).

Deployed Active-Duty Military

Students: Students who are deployed active-duty military and/or National Guard personnel and require accommodation should contact their instructors as soon as possible after the semester begins and/or they after receive notification of deployment to make related arrangements.

Make-Up Assignments for Authorized University Events of Co-curricular Activities

Students who represent the university in an authorized event or activity (for example, student-athletes) and who are unable to meet a course deadline due to a conflict with that event must provide the instructor with documentation in advance to arrange a make-up. No penalty will be applied. For more information, see the UCF policy at https://policies.ucf.edu/documents/4-401.pdf

Religious Observance

Students must notify their instructor in advance if they intend to miss class for a religious observance. For more information, see the UCF policy at https://regulations.ucf.edu/chapter5/documents/5.020ReligiousObservancesFINALJan19.pdf

Accessibility

Students with disabilities should speak with their instructor and should contact sas@ucf.edu to discuss specific accommodations for this course.

Diversity and Inclusion

UCF considers the diversity of its students, faculty, and staff to be a strength and critical to its educational mission. We expect every member of the university community to contribute to an inclusive and respectful culture for all in its classrooms, work environments, and at campus events. Dimensions of diversity can include sex, race, age, national origin, ethnicity, gender identity and expression, intellectual and physical ability, sexual orientation, income, faith and non-faith perspectives, socio-economic class, political ideology, education, primary language, family status, military experience, cognitive style, and communication style. The individual intersection of these experiences and characteristics must be valued in our community.

If you or someone you know has been harassed or assaulted, you can find resources available to support the victim, including confidential resources and information concerning reporting options at https://letsbeclear.ucf.edu and http://cares.sdes.ucf.edu/.

If there are aspects of the design, instruction, and/or experiences within this course that result in barriers to your inclusion or accurate assessment of achievement, please notify the instructor as soon as possible and/or contact Student Accessibility Services.