PHYS 150 / CSE 109
Quantum Computing

Peter Young

Spring quarter 2024

"*I think I can safely say that nobody understands quantum mechanics.*"
(R. Feynman)

"*Those who are not shocked by quantum mechanics cannot have understood it.*"
(Attributed to Niels Bohr.)

Instructor: Peter Young, office ISB 220, e-mail: petery@ucsc.edu

Location and Time: Tuesdays and Thursdays 3:20–4:55 pm, in Physical Sciences 114.

TA: Kuroush Allameh, email: kallameh@ucsc.edu

TA Discussion Section: Mondays 5:20 pm in Thimann 391.

Office Hours: I will have both an in-person office hour and a remote office hour using Zoom.

In person: Tuesdays after class, 5:15–6:15 pm. in Interdisciplinary Sciences Building 220.
Zoom: Wednesdays, 7:00-8:00 pm.

Overview The quantum world is fundamentally different from the classical world, as indicated by the above quotes. An important consequence is that, for certain problems, computations can be done more efficiently if the information is processed according to quantum, rather than classical, rules. The topic of quantum computing will therefore interest both physics majors and computer science majors, as well as students in other disciplines. The course will cover the necessary quantum mechanics background, including some aspects not always taught in undergraduate physics classes such as entanglement. Students will study famous quantum algorithms such as Shor's for factoring integers, which is used in encryption, and Grover's for searching an unstructured database. They will also learn about quantum error correction, which appears at first to be impossible, but which *can* be done and changes the field of quantum computing from one which would be completely impossible to realize experimentally to one which, though very difficult, *may* be feasible at some future time. The two most important (and also most challenging) topics that we will study are Shor's algorithm and quantum error correction.

Prerequisites
A knowledge of linear algebra, including eigenvalues and eigenvectors, from either Physics 116A or Math 21 or AMS 10. Also familiarity with complex numbers. No previous experience of quantum mechanics is required since all the necessary quantum mechanics will be covered in the course. Junior or senior standing is required.

Books
The required text is an online book that I have written for this course. It is available for free at:

https://young.physics.ucsc.edu/150/phys_150_all.pdf.

Other useful books are

- *Introduction to Quantum Physics and Information Processing* by Radhika Vathsan. This is the closest book in content and level to the present course.
- *Quantum Computer Science* by N. David Mermin. An somewhat idiosyncratic presentation by a well-known physicist which includes some material not in many other texts.
- *Quantum Computation and Quantum Information* by Michael A. Nielsen and Isaac L. Chuang. This is a monumental classic containing a huge amount of material at an advanced level.
- *Quantum Computing Explained* by David McMahon. Has lots of worked examples.
- *Quantum Computing; A Gentle Introduction* by Eleanor Rieffel and Wolfgang Polak. A more advanced text.

These are available on reserve in the Science Library. The link to them is here.

Approximate course schedule

Lecture dates	Topic
Week 1	Why is quantum different? Linear algebra, matrices, eigenvalues, operators.
Week 2	Postulates of quantum mechanics, uncertainty principle, measurements.
Week 3	Entanglement, entanglement entropy, Bell's theorem, EPR experiment.
Week 4	Classical gates, reversible computing, quantum gates.
Week 5	The Deutsch, Deutsch-Josza, Bernstein-Vazirani, and Simon algorithms.
Week 6	Factoring, breaking RSA encryption, period finding, intro. to Shor's algorithm.
Week 7	More on Shor's Algorithm, continued fractions, the Grover Algorithm.
Week 8	Quantum Error Correction: stabilizer formalism, Shors 9-qubit code.
Week 9	Other Quantum Error Correction codes. Quantum Cryptography
Week 10	Teleportation, Adiabatic Quantum Computing.

The material covered will be everything in the required text except:

- The appendices in Chapters 15 and 16. These involve the Fast Fourier Transform (FFT), which is a wonder of classical computer science but is not part of the course. The appendices in Ch. 16 discuss the connection between the FFT and the Quantum Fourier Transform (QFT), the latter of which is a major part of Shor's algorithm. This connection is of interest, but again is not part of the course.
- Chapter 5, the density matrix. With regret I will omit this topic for lack of time. The material is not necessary for the rest of the course, but is essential for more advanced treatments, particularly of quantum error correction. I therefore recommend that motivated students look at this chapter for their own interest.

Homework
There will be around seven howework assignments. I expect that most or all of them will be due on Thursdays at midnight.

Grading
Performance in the class will be decided on the basis of midterm and final exams, and homework assignments, as follows:

final	40%
midterm	20%
homework	40%

The exams will be in class and closed book. The weekly homework assignments will consist of problems based on the lectures and related concepts, and require the students to understand *fully* the material that is covered in the lectures. Typed up solutions to the homework problems will be available to registered students after the submission deadline. Especially if you are having trouble with the homework, I suggest that you study the posted solutions carefully.

You can get help with the course, both lecture material and homework, from the TA discussion section and the instructor office hours.

Exam Dates
Midterm: **Tuesday, May 7, 3:20–4:55 pm**, (Tuesday lecture of week 6),
Final: **Monday, June 10, 8:00–11:00 am** (sorry, not my doing!).
You must take the exams at these times.

Academic Integrity
All work in the homework assignments and examinations should be the student's own. For the homework assignments, students may discuss the problems with each other and consult other sources. However, direct copying of another student's work, or from another source like ChatGPT, is not permitted. A violation of this policy will result in an F grade for the course. Examinations will be closed book, but you can bring in one sheet of notes on which you can write whatever you like. No electronics can be used during the exams so phones must be *switched off*.

Recordings
All lectures will be recorded and available to registered students on the YuJa systems shortly after the end of each lecture. Nonetheless, in-person attendance at lectures is strongly encouraged.