Proposed Syllabus for Physics 345 Spring 2021 (course will be entirely virtual)

"Introduction to Quantum Information Processing and Communication"

Instructor: Steven Girvin

Course Description:

This course is intended for undergraduate physics, chemistry, engineering, computer science, statistics and data science, and mathematics majors seeking an introduction to quantum information science. There is now a second quantum revolution underway and a world-wide race to build powerful new types of computers based on quantum principles, and to develop new techniques for encrypted communication whose security is guaranteed by the laws of quantum mechanics. The approach of this course to these topics will strip away much of the traditional physics details to focus on the information content of quantum systems, the nature of measurement, and why the true randomness of certain measurement results can be a feature rather than a bug. We will learn what it means for a quantum bit ('qubit') to be simultaneously 0 and 1 (in some sense). We will learn about quantum entanglement and the associated 'spooky action at a distance' that convinced Einstein that the quantum theory must be wrong. Ironically, this bizarre effect is now used on a daily basis to prove that quantum mechanics is indeed correct and used as a routine engineering test to make sure that quantum computers are working properly and are truly quantum. Specific topics to be covered in this course include: the mathematical representation of quantum states as complex vectors, the superposition principle, entanglement and Bell inequalities, quantum gates and algorithms for quantum computers, quantum error correction, dense coding, teleportation, and secure quantum communication. In this course you will learn enough of the basics to be able to do problem sets based on programming and operating publicly-accessible cloud-based quantum computers. See for example: https://www.ibm.com/quantum-computing/ .

Pre-requisites

The only prerequisites for this course are familiarity with complex numbers and the basics of linear algebra (matrices, determinants, eigenvectors and eigenvalues). Prior exposure to basic probability and statistics is useful but not required. A prior course in quantum mechanics will also be useful but is not required.

Homework will be assigned weekly. Late homework will in general **not** be accepted. Exceptions only with approval of the instructor **in advance**.

Required textbooks:
There will be no required textbook, but Professor Girvin will supply extensive course notes.

Recommended textbooks:
Quantum Computer Systems, Yongshan Ding, Frederic T. Chong, free electronic access provided by the Yale University Library at this link (use VPN) **DOI:** 10.2200/S01014ED1V01Y202005CAC051

Quantum Mechanics: The Theoretical Minimum, by Leonard Susskind and Art Friedman, ISBN:

978-0465062904 ($15, paperback). The introductory pedagogical chapters are excellent.

Quantum Systems, Processes and Information, by Benjamin Schumacher and Michael Westmoreland, ISBN: 9780521875349 ($40-100, depending on format).

Basic Training in Mathematics, by R. Shankar, ISBN: 9780306450365 (approx. $70, new)

Other useful texts for the seriously interested:

Quantum Computation and Quantum Information, by Michael Nielsen and Isaac Chuang, ISBN-10: 9781107002173 (approx. $75, new) is the standard graduate-level reference book in the field but is much more sophisticated than will be needed for this course.

The Higher Education Opportunity Act requires us to inform you of textbook prices for each course. If the cost of the texts is a financial burden for you, please contact the instructor to arrange loan of a textbook from the Physics Department.

Other reading material: A folder with useful reading material on quantum information science will be placed in CANVAS. Additional class notes and other reading material will be deposited there from time to time during the semester.

Teaching Fellows: TBD
The TFs will grade the homework and will hold a weekly section, time TBD.

Undergraduate Peer Tutors: TBD
The course peer tutors will hold weekly homework help sessions, time and place TBD.

Office Hours: **TBD** Please take advantage of the regular office hours that the instructor, the peer tutors and the TFs will hold.

Class schedule: **TBD**
Exceptions: **TBD**

Grading Formula:

Homework:	25%	You may work together on homework but must write it up separately and state with whom you worked.
Midterm:	25%	
Individual Project:	25%	Small project and written report (ca. 5 pages) exploring a special topic.
Final Exam:	25%	

Academic Integrity:

All students are expected to be familiar with Yale's Academic Integrity Policies. The Poorvu Center for Teaching and Learning is a good resource:

https://poorvucenter.yale.edu/writing/wr-instructor-resources/addressing-academic-integrity-and-plagiarism

As our course takes place online, I recognize that new challenges to participation and study may arise. I encourage students to contact me or another member of our course's instructional staff with any concerns they may have. Our efforts to establish new habits and work together will benefit from your ongoing commitment to academic integrity. We all gain from each other's commitment to honest work and full participation in course practices. As a reminder, Yale College maintains firm policies on academic dishonesty of any sort. Please review the syllabus and my latest updates for information about course policies and expectations.

Approximate Outline of Topics

- Introduction to the Second Quantum Revolution
- Overview of basic quantum phenomena, particles, waves, interference, quantized energy levels, measurements
- Stern-Gerlach experiment, spins, two-level quantum systems, qubits
- Representing quantum states as complex vectors (Hilbert space)
- Superposition states, Dirac bra-ket notation,
- Operators, observables, Bloch Sphere
- Distinguishability of states
- Representation of multi-qubit states as direct products
- Entanglement, EPR, Bell inequalities, CHSH inequality, GHZ states
- Causality and the no-signaling condition on 'spooky action at a distance'
- No cloning theorem, quantum teleportation, quantum dense coding
- Quantum information processing, quantum circuits
- Programming the IBM Q
- Basic Quantum Algorithms, Deutsch-Josza, Grover Search, etc.
- Quantum error correction codes
- Quantum Encryption and Communication

Useful Links:

Yale Physics Dept. undergraduate program, society of physics students, etc.
https://physics.yale.edu/academics/undergraduate-studies (Links to an external site.)

Women in Physics at Yale: https://womeninphysics.sites.yale.edu/ (Links to an external site.)
(Contacts from last year's P260 class: sami.alves@yale.edu helena.lyng-olsen@yale.edu)

WIQI: Women in Quantum Information Luncheon
https://quantuminstitute.yale.edu/event/women-quantum-information-wiqi-lunch

Conference for Undergraduate Women in Physics
https://www.aps.org/programs/women/cuwip/

3blue1brown: a great website with highly visual tutorials on math and physics (including linear algebra, vectors, error correction codes and differential equations)
https://www.youtube.com/channel/UCYO_jab_esuFRV4b17AJtAw/featured

Help Professor Girvin reach 7 million views!
Quantum Computing Expert Explains One Concept in 5 Levels of Difficulty | Wired Magazine

What is a Quantum Computer? Link to non-technical video at:
http://quantum.yale.edu/#research

"Progress and Prospects for the Second Quantum Revolution," a one-hour colloquium giving an overview of the field and aimed at undergraduates. [NEED TO ADD LINK]

Professor Girvin's Research Page with links to various videos
https://girvin.sites.yale.edu/

Co-Design Center for Quantum Advantage (A national quantum information science center led by Professor Girvin) https://www.bnl.gov/quantumcenter/