Catalog Description: PHYS 3911 / 7310 Quantum Information Science and Engineering (3): This survey course will introduce students to the new world of quantum information, quantum communication, and quantum computing. The course is intended for advanced undergraduates and beginning graduate students in physics, engineering, and mathematics. Topics will include: Quantum states, operators, and linear algebra; Bits and qubits; Ensembles and density operators; Unitary transformations; Gates and circuits; Information and entropy; POVM measurement; Multipartite systems; Bell inequality, Bell states, and non-locality; Measures of entanglement and quantum multipartite correlations; Quantum communication and cryptography; Teleportation; Superdense coding; Quantum noise and error correction; Classical and quantum computational complexity; Quantum algorithms: Deutsch-Jozsa, Grover, Shor; DiVincenzo criteria; Physical realizations of quantum computers: trapped ions, solid state qubits; Quantum optics and quantum internet; Topological quantum computation; Quantum metrology; Quantum biology.

Designation: This course is an elective for students in physics and engineering physics.

Prerequisites: PHYS 2350 or equivalent; MATH 2210 or 2240 or equivalent


Specific Aims: 1. Students will be able to apply principles of quantum mechanics to problems in quantum information processing, quantum communication, and quantum computation.
2. Students will be able to solve problems involving multipartite quantum systems and entanglement.
3. Students will be able to evaluate advantages and disadvantages of different physical realization of quantum computers.
4. Students will be able to solve problems involving quantum communication and teleportation.
5. Students will be able to analyze the workings of quantum key distribution and of several quantum algorithms, including quantum search and quantum Fourier transform.
6. Students will investigate and report on contemporary applications of quantum principles in 21st century science and engineering.

Topics: 1. Quantum states, operators, transformations and gates, circuits, projective and POVM measurement;
2. Multipartite systems, entanglement, nonlocality, Bell states, Bell inequalities;
3. Quantum communication, teleportation, superdense coding, quantum cryptography;
4. Classical and quantum computational complexity;
5. Quantum algorithms: Deutsch-Jozsa, Grover, Shor;
6. Physical realizations of quantum computers, DiVincenzo criteria;
7. Classical and quantum error correction;
8. Quantum information and entropy, quantum metrology, quantum biology.

Class Schedule: MWF 12:00-12:50 PM Boggs 239

Program Outcomes: The most strongly addressed program outcomes are:
(35%) [a] an ability to apply knowledge of mathematics, science and engineering
(35%) [e] an ability to identify, formulate, and solve engineering problems
(15%) [g] an ability to communicate effectively
(15%) [j] a knowledge of contemporary issues

Criterion 5: (a) and (b)

Prepared by: Lev Kaplan, PhD
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PHYS 3911 / 7310
Quantum Information Science and Engineering
Fall 2010

Professor: Lev Kaplan
Lectures: MWF 12-12:50 in Boggs 239
Course website: tulane.blackboard.com [for web links, assignment schedule, course documents, solutions, grades, …]

Office: 5046 Percival Stern Hall
Office hours: Tentatively Monday 2-3, or by appointment
Please stop by and say hello – I am always happy to see you
Email: lkaplan@tulane.edu [A great way to ask a question or arrange an appointment]
Telephone: 504-862-3176 (x3176) [Leave a message if I’m not there or better yet try email]

Textbook: Nielsen and Chuang, Quantum Computation and Quantum Information
(errata: http://www.squint.org/qci/)

Welcome to Quantum Information Science and Engineering at Tulane University!

1. General Course Information, Objectives, and Requirements:
Quantum information is a relatively new and strongly interdisciplinary field, which lies at the intersection of quantum physics, mathematics, information theory, computer science, and engineering. In this overview course, we will explore how ideas from these different disciplines are coming together to produce exciting ideas for new technologies. In particular, we will examine several examples of how the weird properties of quantum mechanics (specifically superposition and entanglement) can be used to perform information processing tasks, including secure communication, teleportation, and ultra-fast computing.

The key prerequisites are a familiarity with modern physics at the sophomore level (PHYS 235) and some mathematical maturity, including a basic understanding of linear algebra (vectors, matrices, basis transformations, inner products, tensor products, etc). More advanced topics in physics and mathematics, as well as ideas from classical information theory or the theory of computational complexity, will be introduced as needed. It is expected that students in the course will come from a variety of disciplinary backgrounds, and I will be happy to help you fill in gaps in your knowledge as they arise.

2. Possibly Useful Online References:
John Preskill's lecture notes at Caltech http://www.theory.caltech.edu/people/preskill/ph219/#lecture
Kaye, Laflamme, and Mosca, An Introduction to Quantum Computing (ebook through Tulane library website)
Vedral, Introduction to Quantum Information Science (ebook through Tulane library website)
3. Guidelines for Success:

You should expect to spend at least 6 hours per week outside of class in order to be successful in this course. This is consistent with general university guidelines, which recommend at least two hours of outside preparation time for every hour of lecture. Students with a less strong background (or those who love the subject and wish to excel in it) may want to put in more hours. If you are having difficulties and may need extra help, please let me know early, and do not fall behind!

Do all your readings in advance. Attend class regularly and arrive on time. If you must miss a class, it is your responsibility to get good notes from a colleague. Class participation is strongly encouraged. If you have a question, please do not be afraid to ask it. Students who are actively engaged in class learn much better than those who listen passively to the instructor's explanations.

Start your assignments early so that if you get stuck, you can seek help from the instructor or from a colleague.

4. 3911/7310 enrollment:

This course is cross-listed as an undergraduate-level and graduate-level class, with common lectures. Students taking the course at the 7310 level will be required to complete longer and more challenging homework assignments. In addition, I will have higher expectations for the final presentations/projects submitted by 7310 level students (see below).

5. Grading:

Homework Assignments:  25%
Midterm Exam: Friday, Oct 8 (to be confirmed): 20%
Team Papers and Presentations (last week of class):  25%
Comprehensive Final Exam:  30% (Monday, Dec 13, 8am-noon)

6. Homework Assignments:

A homework assignment will be due in class approximately every other week. Assignments may include exercises from the textbook, or problems taken from other sources. If you get stuck, you are very welcome and encouraged to discuss problems with your classmates or with me, and to consult any resources you wish for a better understanding of the material, but the write-up of the solutions must be your own. Late assignments may be accepted at the instructor's discretion, with a severe penalty. Start early!

7. Midterm and Final Exam:

If you miss an exam without prior permission (based on serious illness, family emergency, or similar circumstances), you will receive a grade of zero for the exam. [Make-up exams given in extraordinary circumstances may not follow the format or the difficulty level of the original exam.] The exams will emphasize broad conceptual understanding, and may include material from lectures, homework assignments, guest lectures, and student presentations. Parts of the exams may consist of short essay questions. You will be allowed to bring one double-sided sheet of notes to each exam. More specific information will be provided prior to the date of each exam.
8. Final Project/Presentation:

25% of your course grade will be based on a team report and presentation. Each team will consist of two students (or three with the instructor’s permission). You will investigate a topic of your choice not covered in lecture, produce a written report, and present your findings to the class in a 20-minute presentation during the last week of class. This is your chance to apply and extend what you have learned, and to educate others as well. You will have a lot of freedom in choosing a subject that interests you, as long as it is related to quantum information, broadly construed. I will provide you in advance with a list of possible topics, but you may also come up with a topic on your own, e.g. by consulting some of the online resources listed on the first page of the syllabus, or browsing [http://arxiv.org/archive/quant-ph](http://arxiv.org/archive/quant-ph). PHYs 7310 students are strongly encouraged to select more advanced topics. Let me know early what topic you’re interested in, so I can offer you feedback, confirm that the topic has not already been reserved by another group, and suggest useful references.

By Nov 1, you will confirm your choice of topic by sending me the composition of your two-student team, the report title, a one-paragraph abstract, and your preferred presentation dates. I will then schedule the presentations. Finally, an electronic copy of your report will be due by email on the last day of class.

9. Guest Lectures:

Occasionally, guest lecturers, including members of the Tulane faculty, may be invited to share with our class their particular expertise in some area of quantum information theory. These special lectures will broaden your understanding of the relevant mathematics, science, and engineering, and expose you to new areas of the field from the viewpoint of an active practitioner. Material covered in the special guest lectures may be included on the final exam.

10. Team Study:

Team study is strongly encouraged, and is a habit that will benefit you in all your other courses as well. You are especially encouraged to consult with your colleagues in the class when you get stuck or encounter difficulties with the coursework, as peer-to-peer learning will enhance your understanding of the material and make study more enjoyable (in those instances where you are the one offering assistance and also in those instances where you are seeking out assistance). Please note that the peer-to-peer learning I recommend is in addition to, and not a substitute for, the assistance that I personally will be more than happy to provide whenever you have questions (during class, after class, during office hours, or by appointment).

11. Professional Conduct:

As Tulane students, you are expected at all times to uphold high ethical and professional standards, as described in the “Code of Academic Conduct”. Cheating on the exams or plagiarism on your assignments will not be tolerated, and may be punished by failure in the exam or assignment, failure in the course, academic probation, and/or expulsion. You are also expected always to treat your classmates with respect, and you have the right to be treated with fairness, respect, and consideration by me. Disruptive and unprofessional behavior, such as talking in class or packing up your books before class has ended, disrespects everyone else who is trying to learn, and such behavior will not be accepted.
12. Readings

Assigned readings associated with each subject covered will come from the textbook (NC) or other sources. You are expected to complete the relevant reading before the topic is covered in class, so that you can ask questions and participate actively in the discussion. Some readings are already noted in the tentative outline below; more information will be provided in class and on blackboard as the course progresses.

13. Tentative Course Outline:

_We will not have time to cover all interesting topics in quantum information. Some topics may be added and others omitted or rearranged, at the instructor’s discretion and depending on student interest and time constraints. Changes to this outline, along with assignment due dates, will be announced in class and on the course website._

0. General Overview: Quantum Computation and Quantum Information (NC 1.1)

1. Quantum Mechanics
   - Superposition Principle, Qubits, Bloch Sphere, Multi-Qubit States (NC 1.2)
   - Gates, Circuits, No Cloning Theorem, Measurement (NC 1.3)
   - Bell States, Quantifying Entanglement (NC 1.3)
   - Application: Teleportation (NC 1.3)
   - Stern-Gerlach Experiment (NC 1.5)
   - Review of Basic Linear Algebra: Vectors, Linear Operators (NC 2.1)
   - Formal Postulates of QM, Projective and POVM Measurement (NC 2.2)
   - Application: Superdense Coding (NC 2.3)
   - Ensembles, Density Matrices (NC 2.4, 2.5)
   - EPR Correlations, No Hidden Variables, Bell Inequalities (NC 2.6)

2. Quantum Circuits
   - Single-Qubit Gates: Rotations, Hadamard Gate (NC 4.2)
   - Multi-Qubit Gates: CNOT, Controlled Unitary, Toffoli, Fredkin (NC 4.3)
   - Measurement in Quantum Circuits (NC 4.4)
   - Universal Gates (NC 4.5)

3. Quantum Computation and Algorithms
   - Classical vs Quantum Computation, Parallelism, Deutsch’s Algorithm (NC 1.4)
   - Turing Machines, Universality, Computational Complexity Classes (NC 3.1, 3.2)
   - Feynman: Simulating Quantum Evolution (NC 4.7)
   - Classical and Quantum Fourier Transform (NC 5.1)
   - Application: Shor’s Quantum Factoring Algorithm (NC 5.3)
   - Grover’s Quantum Search Algorithm (NC 6.1)

4. Quantum Noise and Quantum Error Correction
   - Classical Noise (NC 8.1)
   - Examples of Quantum Noise, Decoherence: Bit Flip, Phase Flip (NC 8.3)
   - Quantum Error Correction, Shor Code (NC 10.1, 10.2)

5. Quantum Information
   - Shannon Entropy, Von Neumann Entropy (NC 11.1, 11.2)
   - Quantum Cryptography (NC 12.6)
6. Physical Implementations of Quantum Computers
   DiVincenzo Criteria, Decoherence (NC 7.1, 7.2)
   Optical Quantum Computing, Phase Shifters, Beam Splitters (NC 7.4)
   Ion Trap Quantum Computing (NC 7.6)
   Solid State Quantum Computing: Quantum Dots, Josephson Qubits, Flux Qubits
   Topological Quantum Computing

7. Additional Topics (Time Permitting)
   Quantum Metrology
   Quantum Biology

14. About me:

   My research in the area of quantum information currently centers on linear optical quantum computation (LOQC). More generally, my interests involve wave physics in complicated geometries (from ocean waves to electron waves). This field is known as quantum chaos, and if you want to know more about it, just ask, or take a look at http://www.tulane.edu/~lkaplan. I was born in Latvia, grew up in New Jersey, did my undergraduate studies at the University of Pennsylvania, and my graduate work at Harvard University (on particle theory). Prior to coming to Tulane, I worked on nuclear theory at the University of Washington in Seattle. I strongly encourage you to stop by my office to talk about physics, Tulane, questions, concerns, suggestions, or anything else that may be on your mind.