Signal Processing Tour of Quantum Computing

ECE 592–100 (also ECE 492-054, CSC 495-054, and CSC 591-054)
Spring 2024

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Teaching assistant: None.

Course Text: The course borrows material from various sources, and there is no single source. The following may be useful at times.

- Nielsen and Chuang, Quantum Computing and Quantum Information, 2000.
- Proakis and Manlakis, Digital Signal Processing – Principles, Algorithms, and Applications, 1992 or later editions.

Some of you may want to download electronic versions of these books.

Prerequesites:

- As suggested by the course's name, it will be advantageous for students to be familiar with signal processing or quantum computing. However, seeing that the number of students who have both backgrounds is limited, we will cover these materials quickly during the first half of the course.
- It is advisable (more than helpful, but not quite required) for students to be familiar with linear algebra (e.g., Math 305 or 405), and probability and statistics (e.g., ST 371).
- Programming proficiency, for example in Matlab or Python, may be helpful. The specific language is less important.
- It will be helpful (but not required) for students to be familiar with linear systems (ECE 301), undergraduate signal processing basics (ECE 410/421), mathematical transforms such as Fourier, and group theory (Math 407).

Course purpose: ECE 592–100 (Signal Processing Tour of Quantum Computing) will develop some well-known algorithms in quantum computing, especially those using the quantum Hadamard and Fourier transforms, where insights will come from a signal processing angle. Specific topics covered will include:

1. Motivation and Introduction.
2. Mathematical basics: complex numbers, linear algebra, tensor products.
3. Signal processing basics: discrete time signals and systems, discrete time Fourier transforms, frequency interpretation of linear time invariant systems.
4. Quantum computing basics: state spaces, quantum evolution, measurement, qubits, single qubit gates, multi-qubit gates, entanglement. Deutsch's algorithm.
5. Hadamard transform: finding XOR function patterns, Deutsch-Jozsa algorithm, Bernstein-Vazirani algorithm.
6. Fourier transforms: Fast Fourier transform (classical FFT), quantum Fourier transform (QFT), quantum phase estimation, classical spectral estimation, noisy spectral estimation.

Course Objectives: By the end of the semester, the student should be able to:

- Apply linear algebra in discussing and analyzing quantum computing, including usage of the bra-ket Dirac notation.
- Apply signal processing concepts such as convolution and Fourier transforms to analyze the interaction between signals and systems in either the time or frequency domain.
- Analyze quantum circuits, and be able to describe the evolution of a quantum state using linear algebra.
- Demonstrate command of quantum algorithms that utilize the Hadamard transform, for example Deutch-Jozsa.
- Formulate classical spectral estimation and quantum phase estimation.

Policies and Procedures: Academic integrity is important in ECE 592, because many of you will be designing various computational systems in several years. If you cut corners in your future professional work, it could lead to lawsuits, you could be fired, and in extreme cases people could be injured or die. (If these comments seem far fetched, recall that multiple autonomous car makers have had to explain to the public why their vehicles crashed.)

Students should refer to the University policy on academic integrity. Here are some specific expectations we have.

- When working on homeworks (you are encouraged to submit in pairs), students can certainly work together and submit together; each student should make sure that they understand different aspects of the problems being worked through, and that the assignment helped them grasp concepts covered in class.
- We expect your mini projects to include a survey of related techniques and papers you may have gone through. These works should be referenced with a citation.[1]

[1] If students are unsure how to cite, Dr. Baron will be glad to post examples on the course webpage.

- Our tests (3 quizzes and a final exam) will likely be administered in class. When working on tests, no cooperation or "collaboration" between students is allowed. It is likely that tests will be open notes, and graphical calculators will be allowed as an aide, but computers will not be allowed. **By submitting the test, you will be acknowledging that you completed the work on your own without the help of others in any capacity.** Any such aid would be unauthorized and a violation of the academic integrity policy.

All cases of academic misconduct will be submitted to the Office of Student Conduct; the recommended penalty will be a failing grade for the entire course.

Homework: We expect homeworks due during the semester every 1–2 weeks. Students will submit homework individually or in pairs. Assignments and the schedule for submitting them will be posted on the course web site. Keep in mind that homework will be 40–50% of the grade (depending on whether the student is enrolled in an undergradiate or graduate section; details below).

Mini projects: The *mini project* will involve a topic that individuals or pairs of students choose to work on. The project may involve reading a paper and presenting the main ideas to the entire class, or perhaps working on some quantum algorithm on a physical quantum computer; a superb project will involve novel work by the group, and ideally would result in publication. The project will also require the individual or group to submit a short report; the formats required for the report and presentation will be specified during the semester. All the students will be providing feedback (including the grade) on each other's presentations. Overall, the objective of the project is to give students a personalized learning experience. Projects will be worth 10% in the graduate sections; students enrolled in undergraduate sections may opt to work on a project for extra credit.

Homeworks and projects should be submitted electronically via Moodle. Assignments and the schedule for submitting them will be posted on the course web site.

Late submissions: Unless you received permission in advance (see below), homeworks and projects should be turned in electronically by midnight on the due date. Late submissions will immediately be penalized 50%; after 24 hours, no credit will be given.

This is the important part. If you let me know of something well in advance, it is easy for me to be flexible. Requesting to submit something late 2–3 days ahead of the deadline is reasonable, but doing so the morning it's due isn't. As a guiding principle, the nicer you are to the course staff, the nicer they're likely to be to you. Exceptions (permitting late submissions without advance notice) will only be made in emergency situations such as medical problems.

Programming: It is possible that the homeworks will involve some programming. When working on your projects, possible programming is topic-dependent. We suggest to use Matlab and/or Python; other software platforms can be used. A free Matlab download is available on the EOS website:

`http://www.eos.ncsu.edu/software/downloads/`

And a link to a tutorial on Python:

`https://docs.python.org/3/tutorial/`

Tests: We will have 3 quizzes and a final exam. Details about the test schedule will be published on the course webpage. The tests will be open-book, open-notes. See comments about intellectual integrity on page 2. (The aforementioned guiding principle also applies here. Students who are taking multiple courses with tests scheduled at inconvenient times should consult with Dr. Baron early on during the semester. In contrast, special circumstances such as a student going to a conference will be handled with greater flexibility.)

Extra credit: Extra credit of up to 2–3% will be allowed. Extra credit will be allocated based on factors such as class participation, feedback about assignments, attendance of office hours, and overall contributions to the course. Details about how much extra credit is allocated to different activities will not be published. Note, however, that Dr. Baron has typically allocated roughly 1% extra credit for typical students. The bottom line is that you are encouraged to contribute to a pleasant course experience!

Grading:
For graduate sections, the following grade structure will be used.

Homework	40 %
Mini project	10%
Quizzes	30% (10% each)
Final exam	20%
Extra credit	3%

For undergraduate students, there is no need to submit the mini project. However, undergraduate students are welcome to submit projects, in which case the project grade will be assigned up to 2% extra credit. (For example, an undergraduate with a 90% grade on the project will receive 1.8% extra credit.) Note that the total extra credit will still be capped at 3%, including a possible contribution from the mini project.

Homework	50 %
Quizzes	30% (10% each)
Final exam	20%
Extra credit	3%

Weighted averages of 90, 80, and 70 will guarantee *minimal* letter grades of A-, B-, and C-, respectively.

Instructors' commitment: You can expect your instructor to be courteous, punctual, well organized, and prepared for class activities; to answer questions clearly and in a non-negative fashion; to be available during office hours or to notify you beforehand if they are unable to keep them; and to grade uniformly and consistently according to the posted guidelines.

Disabled students: North Carolina State University is subject to the Department of Health, Education, and Welfare regulations implementing Section 504 of the Rehabilitation Act of 1973. Section 504 provides that: "No otherwise qualified handicapped individual in the United States ... shall, solely by reason of his handicap be excluded from participation in, be denied the benefits of, or be subjected to discrimination under any program or activity re-

ceiving Federal financial assistance." This regulation includes students with hearing, visual, motor, or learning disabilities and states that colleges and universities must make "reasonable adjustments" to ensure that academic requirements are not discriminatory. Modifications may require rescheduling classes from inaccessible to accessible buildings, providing access to auxiliary aids such as tape recorders, special lab equipment, or other services such as readers, note takers, or interpreters. It further requires that exams actually evaluate students' progress and achievement rather than reflect their impaired skills. This may require oral or taped tests, readers, scribes, separate testing rooms, or extension of time limits.

Schedule:
A detailed tentative schedule appears on the course webpage. As we progress through the semester, the schedule will be updated periodically. The final exam is scheduled by the university for April 26, 2024, 12-2:30 PM.

Class Evaluations: Online class evaluations will be available for students to complete; this will happen toward the end of the semester. Students will receive an email message directing them to a website where they can login using their Unity ID and complete evaluations. All evaluations are confidential; instructors will never know how any one student responded to any question, and students will never know the ratings for any particular instructors.

Final comments: Informally, as a relatively new course, please take ownership not just over your studies, but also view yourself as a contributor to the development of the course. Do not hesitate to provide Prof. Baron with feedback. The ideal situation at the end of the semester is if your overall impression of the course is favorable, and we identify how to further improve it in future years.