UNIT 0

INTRO TO QUANTUM COMPUTATION

TCS QUBIT X QUBIT INITIATIVE

Introduction

Welcome to The Coding School's Intro to Quantum Computation course! We are very excited to have you here and want to begin by telling you a little about the course. Quantum computing is a growing research field, which makes use of cutting-edge technology and lies at the very boundary of human knowledge!

By taking this course, you will be learning concepts that many students do not get exposed to until well into their undergraduate or even graduate education, in college. If you are interested in math, computer science, electrical engineering, or physics, you will soon find that quantum computation lies right at the intersection of all these fields! However, if you are more interested in fields like biology, chemistry, or economics, fret not! Quantum computing has major applications in all these disciplines, which we will also explore over the course of this class. Regardless of whether or not you want to become a quantum engineer, we believe that this class will be invaluable towards your STEM education. In order to even begin describing what a quantum computer is, we will need to build a strong foundation in linear algebra and probability, master complex numbers, learn a little about quantum mechanics, and familiarize ourselves with normal computation stacks and structure. These are all extremely important tools to have in your skill-set and are very broadly applicable.

In the next few sections, we provide a course syllabus, including course logistics, a lecture calendar, and a table of contents for the course textbook. We also provide a high-level overview of each of the units of the textbook, so you can get a sense of the content we will cover as well as the learning expectations.

Finally, make sure to do the homework! Trust us, it's a fun assignment...

Course Logistics

Lecture Calendar

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- Lesson #4: The Density Matrix

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- Lesson #4: Quantum Measurement
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- Lesson #3: VQE (Variational Quantum Eigensolvers)
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- Lesson #5: Quantum Phase Estimation

- Lesson #6: HHL Algorithm
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- Lesson #4: Further Readings
- Lesson #5: Concluding Thoughts - The Prospects of Quantum Computation

Textbook Unit Overviews

UNIT #1: Limits of Classical Computation

In this unit we aim to provide students with a background in "classical" computation (non-quantum, normal computing). We introduce the notion of the Turing Machine and explain Boolean logic. We define the term "algorithm" and teach students how to assess the resources required by an algorithm (both time and memory), through Big-O-Notation. Using this skill, students should be able to see how classical computation can be limited, given finite resources. We then provide a brief overview of the hardware of classical computers, specifically transistors. Through discussion of Moore's Law and quantum advantage, we explain why there is interest in developing quantum computers.

Objectives: The student will be familiar the classical with classical algorithms and feel comfortable finding the runtime of simple programs. The student should understand the motivation for building quantum computers.

UNIT #2: Math Foundations

In this unit we aim to build the math foundations (specifically in linear algebra and probability) necessary for the rest of the course. It is critical that students master the content of this unit, so as not to struggle later in the course.
Objectives: The student has a strong understanding of math concepts generally seen in high school, specifically trigonometry, Cartesian coordinates, and polar/spherical coordinates. The student is comfortable with complex numbers, both in the real-imaginary plane geometric view, as well as in algebraic manipulation (i.e. Euler's equation). The student is able to represent a system of equations in terms of vectors and matrices. The student is comfortable with the notion of a vector space and basic vector and matrix operations (i.e. transpose and inner product). The student is extremely comfortable with matrix and vector multiplication, as well as determining the shapes of matrices and vectors after manipulation. The student has a firm understanding of what a discrete probability distribution and random variable is, can relate real world to mathematical statistical descriptions, and can calculate important properties of random variables (i.e. expectation). Finally, the student should not be intimidated by mathematical notation such as summations.

UNIT #3: Advanced Math Concepts Applied

In this unit we build upon the math introduced in unit #2, but dive deeper into aspects related to (and introduce notation for) quantum computation. Throughout the unit, we motivate why the math is useful and necessary to describe the physics to come. We begin by going over Bra-Ket (Dirac) notation, which will be critical throughout the remainder of the course, for effectively describing quantum systems and algorithms. We then take a second look at vector spaces, specifically focusing on the Hilbert space. This is a more technical section and if students don't fully grasp it, that is OK. Hopefully, if anything, it will give them more linear algebra practice. They should, however, have a solid understanding of the tensor product. We additionally introduce students to the notion of eigenvalues and eigenvectors, computationally and geometrically. We also describe particular types of matrices and matrix properties that are important to quantum computation (i.e. Hermitian and unitary). We conclude with an optional unit on the Fourier Transform. If students are struggling with the math, the Fourier Transform section can be skipped and is only necessary for the advanced quantum algorithms portion of the course.

Objectives: The student has a strong foundation in linear algebra and probability, with comfort in application, especially in the context of quantum mechanics.

UNIT #4: Introduction to Quantum Mechanics

In this unit we aim to provide a primarily conceptual introduction to many of the weird phenomena observed in quantum mechanics. We begin with an overview of the experimental basis for quantum mechanics, specifically discussing the double slit experiment, photoelectric effect, and Stern-Gerlach experiments. We then go through the fundamental postulates of quantum mechanics and formulate quantum mechanics mathematically. We conclude with an in-depth discussion of entanglement and composite systems, as well as a lesson on density matrices.

Objectives: The student should be able to explain what superposition and entanglement are. They should also be able to see why quantum mechanics is weird and how it differs from classical mechanics. The student should be comfortable with the notion of a wavefunction and the fundamental postulates of QM.

UNIT #5: Introduction to Quantum Information

In this unit, students will be introduced to the most fundamental, yet arguably most important concepts in quantum information. They will not only learn about the physical and abstract meaning of a qubit, but how a qubit's state can be transformed using quantum gates. Combinations of these gates can be used to run quantum algorithms, which students will be introduced to via the circuit model interpretation. Finally students will be introduced to some of the weirdness of working with quantum states through the introduction of quantum measurement and some of the challenges it creates. There is an optional lesson on the adiabatic model of quantum computation, so that students are exposed to an alternate model of quantum computation.

Objectives: The student should be able to explain what a qubit is and how quantum gates transform the qubit state to run quantum algorithms. Students should be able to explain the process of running a quantum algorithm, from state preparation to unitary transformation to quantum measurement.

UNIT #6: Introduction to Quantum Information Protocols & Processing

In this unit, we will learn about our first quantum algorithm, Deutsch-Josza! We will also cover other interesting aspects of quantum information processing, such as a simple quantum key distribution protocol (BB84), superdense coding, and quantum teleportation.

Objectives: The student should understand how quantum algorithms are formulated and advantageous to classical algorithms. Furthermore, the student should understand how quantum information processing differs from classical information processing.

UNIT #7: How to Assess and Build a Quantum Computer

In this unit, students will be exposed to experimental aspects of quantum computation. They will begin with a lesson on noise and its characterization at the single qubit level, through an in-depth discussion of T1 and T2. Then, students will learn how quantum devices/systems are characterized as a whole, through discussions of tomography and benchmarking techniques such as quantum volume. Student will next learn about current competing experimental efforts for constructing a quantum computer. They will learn about the differences between and respective benefits of NMR, superconducting, trapped ion, photonics, neatural atoms, and nitrogen-vacancy based computing methods (this will be a high-level discussion given students' limited physics background). Finally, the unit will conclude with a discussion of the quantum computing stack, via a comparison to a classical computing stack. It will go through everything from the qubit to quantum compilers, all the way to the quantum cloud.

Objectives: The student should have a high-level understanding of the different aspects of experimental quantum computation. They should understand that there are experimental limitations, such as noise, which make achieving theoretical results challenging.

UNIT #8: Advanced Quantum Algorithms

This will be a challenging, theoretical section that walks through some of the most important algorithms in the history of quantum information. Students will learn about algorithms that can be used for optimization, phase estimation, database search, and RSA decryption.

Objectives: This is a very challenging unit and students are not expected to understand all the algorithms in full. The main goal is that students can explain the use of each of quantum algorithm and its advantage over classical counterparts. Bonus points if the student can follow all the math and/or implement the algorithm on a quantum computer/simulator!

UNIT #9: Course Wrap-Up

In this unit, we will wrap up the course by highlighting some cool, current research in the domains of quantum algorithms and quantum implementations. We will also highlight some of the corporate work being done and provide further readings for students interested in exploring beyond the TCS curriculum. We will conclude some words on the potential use cases and importance of quantum computers in upcoming decades.

Objectives: The student should be aware of opportunities in quantum computing outside of TCS and have resources to explore it further. They should also be able to recognize the importance and applicability of the skills they learned throughout the course, beyond the field of quantum computation alone.

Homework

Watch this YouTube video and get hyped!

`https://www.youtube.com/watch?v=JhHMJCUmq28`