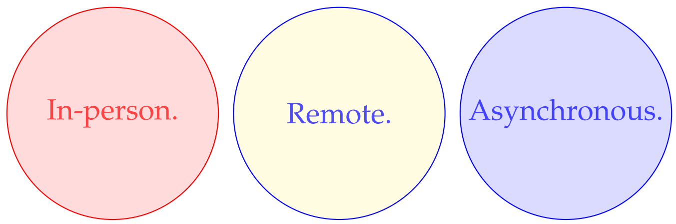

CSCI-C 290: Programming Quantum Computers

Primary Instructor: Adrian German
Teaching Assistant: Arpan Ojha

6W2 Summer 2022
(June 21 - July 29)

E-mail: `dgerman@indiana.edu`	Web: **www.cs.indiana.edu/classes/c290-quantum/**
Office Hours: 10:30-11:30am (daily) also, by appointment	Class Hours: MTWRF 8:45-10:00am
Office: Luddy Hall 2010	Class Room: Myles Brand Hall (I) 109

Take this class because the area of quantum information science and technology (QIST) is experiencing a severe shortage of talent (workforce). Traditional engineers and computer scientists are especially in demand now across this field and that trend will only accelerate. The potential implications are broad; quantum technology may eventually underlie a whole new technological infrastructure much as the semiconductor revolution changed everything in the second half of the last century. A technological ecosystem is currently being shaped by massive public and private investment in North America, Asia and Europe. With this growth there has been a steady demand for QIST talent. You don't need an advanced degree; but you need to speak the language. QIST spans physics, CSCI, mathematics, engineering, chemistry, and materials science. Take this class to learn the basics. This class is only offered in summer.

Course Description

Quantum mechanics is more than a physical theory of nature. It is a quantitative philosophy that provides us with a set of general, overarching principles that describe the innermost workings of our world at its most fundamental level. There are two aspects of quantum mechanics: the "machinery" and the "spook". The machinery, epitomized by the Schrödinger equation and its various methods of solution, allows us to propagate the quantum state of a system deterministically forward in time. This aspect of quantum mechanics is not particularly "quantum"; we find it in similar form in all classical field theories. The "spook" are all those aspects of quantum mechanics that do not have a classical analogue, not even in principle. This part of quantum mechanics is connected with the theory of measurement and its implications.

Surprisingly, starting in the mid 1970s and early 1980s, questions about the foundations of quantum mechanics led to direct technological advances and applications, culminating in the possibility of quantum computing, a qualitatively new way of data processing that promises to be orders of magnitudes faster and more efficient than any "classical" computer could ever hope to be. Today, quantum computers exist, access to them via the cloud is affordable, university and industry-developed education is increasing, and government funding was approved to further research and focus on needed workforce development. The conceptual basis for the new quantum technology consists of (a) superposition, (b) entanglement, and (c) quantum measurement (i.e., the collapse of the wave function). In connection with matter, these concepts simply do not exist in the classical description of our world and are not used in any of the "classical" machines and appliances around us. Thus, quantum technology is not just better, it is different.

This is a course for all those who wish to become literate and articulate in the new field of quantum information science and engineering with a focus on quantum computing.

This is also a Bridge to Quantum STEM course that can be used as a Boot Camp by any undergraduate interested in Indiana University's new[1] accelerated Masters' program in Quantum Science and Engineering[2] (a new, multi-disciplinary research program offering a research-intensive MS degree culminating with an industry internship and a research project; the new program is designed around tracks which thread as needed through business, chemistry, cognitive science, computer science (CS), economics, engineering, linguistics, mathematics, and physics to bridge students with a broad distribution of previous training into QIS-related opportunities. It is part of our vision to meet the emerging and challenging need for cross-disciplinary QISE training.)

Required Materials

- Complete materials for this course will be made available to enrolled students via Canvas.

Prerequisites/Corequisites

Genuine interest is the only true prerequisite; everything else will be introduced (and developed) on "as needed" basis. Specifically, prior familiarity with quantum mechanics, probabilities, complex numbers and/or linear algebra is welcome but not required. Likewise a programming background in Python or Java is useful but also not regarded as essential.

Course Objectives

The purpose of the course is to build an operational awareness about state of the art quantum technologies in students taking the class. To that effect generous assistance will be provided in working all the exercises assigned as homework. We'll introduce an elementary rewriting system that has been shown to accurately describe the functional aspects of quantum gates at a level accessible by students in middle school (sixth-grade and older). We also have planned trips in to the Physics (Optics) lab to demonstrate simple quantum algorithms (e.g., Deutsch-Josza) experimentally, via Mach-Zender interferometers[3]. For those students that want to pursue the accelerated MS in QISE program the promise is that they will be able to function with confidence and competence in the first course of the program (based on the new book by Ekert[4] and Osgood).

[1] news.iu.edu/stories/2020/08/iu/inside/14-6-new-degrees-receive-approval-from-trustees.html
[2] quantumstrategyinstitute.com/2021/10/26/roadmap-to-quantum-engineering/
[3] Click here for similar materials from the Institute for Quantum Computation Schrödinger's Class
[4] https://qubit.guide/

Course Structure

Class Structure

The class will meet daily in a lab (I109) from 8:45-10:00am (EDT). Students do not need to be on campus to be enrolled and receive credit for this class. All lectures will be broadcast (and recorded) via Zoom following a "hybrid" course delivery modality perfected in our Spring 2022 classes (C322, A310, A348/A548 and H212). Both the primary instructor and the teaching assistant will be available daily in person or via Zoom for office hours. This class (or a variation thereof) will be mandatory for incoming students in the MS in QIS program. These students will be able to take this class (or test out of it) every summer prior to starting the program in earnest, whether they are on campus or are yet to arrive on campus.

Prospective MS in QIS students are (and will also be) encouraged to take this C290 class, online or in person, before applying to the program. Time is scheduled in the Physics lab for elementary quantum algorithms demonstrations and for several other hands-on Physics experiments. On the Computer Science side we will be using emulators in Java, Python, Q# along with access in the cloud to genuine quantum computers via the Amazon Braket SDK, or IBM Q. The rewriting system developed by Terry Rudolph will be used in class. We have lectures on the hardware of quantum computers, especially on the various qubit modalities. The class will be available to both HS teachers and advanced HS students.

Assessments

There will be daily assignments, a midterm (on July 8) and a final exam (on July 29). There is no class project, only a midterm and a final (along with daily, written assignments).

This is a class offered by the Computer Science Department (IU SICE CSCI) that is sponsored by the Indiana University Quantum Science and Engineering Center (IU QSEc[5]). The center has recently entered in a powerful coalition with Purdue University, Notre Dame and IUPUI to create the first Quantum Industry-University Cooperative Research Center in the nation[6]. This will allow us to discuss potential projects of interest to industry and internships.

Grading Policy

The typical IUB grading scale will be used[7]. Grades will never be curved, instead unlimited make-ups will be allowed (within the time constraints imposed by the structure of the 6W2 Summer 2022 semester). Any make-up work will only ever make it easier to obtain a certain letter grade (highest score is kept). The grade will count the assessments using the following proportions:

- **20%** of your grade will be determined by attendance and in-class participation.
- **25%** of your grade will be determined by daily written assignments
- **20%** of your grade will be determined by weekly programming assignments
- **15%** of your grade will be determined by the midterm exam
- **20%** of your grade will be determined by the final exam

Working in groups is permitted (encouraged, even) but please acknowledge your collaborators.

[5] https://qsec.sitehost.iu.edu/research/history/
[6] https://news.iu.edu/stories/2021/07/iu/08-center-for-quantum-technologies.html
[7] https://kb.iu.edu/d/azij

Course Policies

During Class

We are meeting once a day in a lab environment (I109). That means you will have a (Windows) computer in front of you. You are welcome to bring your laptop to class. You are expected to follow along on your computer and to participate in class. You are encouraged and allowed to ask questions at any time. If you are called upon you need to share an opinion on the spot. The rule (in class) is that nobody is ever responsible for an incomplete or incorrectly formulated thought; that becomes the responsibility of everybody else (including the instructors). However, any accurate or correct response received deserves (and will get) credit. Class meetings are recorded. If you are attending in person (in I109) you need to be able to join the Zoom session at any time. If you need assistance during class time you need to share your screen so we can address that issue and discuss and (re)solve it.

Attendance Policy

Attendance is expected in all lecture and lab sections. Valid excuses for absence will be accepted before class. In extenuating circumstances, valid excuses with proof will be accepted after class. For every class missed the participation grade will be dropped 1 point. However, attendance can be easily made up in office hours (or via Zoom).

Policies on Incomplete Grades and Late Assignments

Late assignments will be accepted, in person (they need to be defended briefly) or via Zoom.

The IU Policy on the Grade of Incomplete is available here[8]

Academic Integrity and Honesty

Students are required to comply with the university policy on academic integrity[9]

Accommodations for Disabilities

Reasonable accommodations will be made for students with verifiable disabilities[10]. In order to take advantage of available accommodations, students must register with the IUB Disability Services for Students (DSS) Office located at Wells Library W302, 1320 E. Tenth Street, Bloomington, IN 47405. Please call DSS at 812.855.7578 or send an email to `iubdss@indiana.edu` to schedule an appointment or for further assistance.

Schedule and Weekly Learning Goals

Schedule is tentative and subject to change. Learning goals below should be viewed as key concepts you should grasp after each week, and also as a study guide before each exam, and at the end of the semester. Exams are cumulative. The applications in the second half of the semester tend to build on the concepts in the first half of the semester though, so it is still important to at least review those concepts throughout the semester. Topics are listed in order in which they will be addressed; however they may occur naturally, and repeatedly, in our class, both prior (or after) the time of their appearance in the list below.

Week 01, 06/20 - 06/24: Introduction (class actually starts on Tue, Jun 21)

- A Taste of Quantum Mechanics
- Probabilities and Complex Numbers
- The Basics of Linear Algebra

[8] https://bulletins.iu.edu/iub/college/2017-2018/policies/academic-policies/incomplete.shtml
[9] https://college.indiana.edu/student-portal/undergraduate-students/academic-integrity.html
[10] https://studentaffairs.indiana.edu/student-support/disability-services/get-help/accommodations/

Week 02, 06/27 - 07/01: Physics and Computation

- Rewriting Systems
- Reversible Computation
- Qubits and Quantum Gates
- Working with Single Qubits

Week 03, 07/04 - 07/08: Early Quantum Algorithms

- Working with Multiple Qubits
- Entanglement and Bell's Experiment
- Quantum Circuits and Teleportation
- Midterm Exam

Week 04, 07/11 - 07/15: Quantum Algorithms (continued)

- The Deutsch-Josza Algorithm
- Quantum Factoring (Shor's Algorithm)
- Quantum Search (Grover's Algorithm)
- Continuous Quantum Systems and Spins

Week 05, 07/18 - 07/22: Quantum Hardware

- Building Blocks of a Quantum Computer
- Qubit Modalities (NV Center, Superconducting, etc.)
- Topological Quantum Computing
- Quantum Compiling. Microarchitectures.

Week 06, 07/25 - 07/29: Quantum Communication and Control

- The Quantum-Classical Interface
- The Quantum Internet
- Quantum Cryptography
- Quantum Error Mitigation and Control
- Final Exam

Your Instructors

How feasible/plausible is it to put together a course like the one we're advertising here? It turns out that some quantum mechanics concepts are needed to understand **why** you do certain steps. Also, complex algebra is required to understand **how** you do these steps. Finally, some computer scientist skills are needed to know **where** to apply all of this.

This is not a course in quantum physics although the language of qubits and gates provides a perfect way to introduce the concepts of quantum physics since it allows for a rigorous exploration of the conceptual foundations and paradoxical features of quantum physics without the complicated formalism of infinite dimensional Hilbert spaces.

A quantum algorithm is unlike any you have seen so far. Its structure reflects the tension between the exponential "private workspace" of an n-qubit system and the mere n bits that can be obtained through measurement. The input to a quantum algorithm consists of n classical bits, and the output also consists of n classical bits. It is while the quantum system is not being watched that the quantum effects take over and we have the benefit of Nature working exponentially hard on our behalf.

Throughout this course we aim to provide a working introduction to the topic by showing that everything follows from, and is consistent with the postulates of the modern quantum theory.

In preparation for designing this course over the last three years we have taken (registered for, taken and passed with high scores) a large number of existing certificate programs in quantum information science and engineering. Most of them are structured by emphasis in five distinct modules: (a) fundamentals, (b) materials, (c) sensing, (d) communication and (e) computing. We think these modules will be readily recognizable in this class (with the exception of sensing, to which we only refer occasionally, and for which we presently offer this recent review[11]).

We introduce everything only when (and as) needed. The one persistent goal we had in mind was for the course to remain as much as possible consistent and logically compatible with the most popular and successful industry certification programs available today such as: the two programs in Quantum Computing Fundamentals and Quantum Computing Realities offered by MIT (xPRO); the certificate in Quantum Engineering from the University of Chicago and the Chicago Quantum Exchange; the many courses and certificates available on EdX from QuTech at the Technical University of Delft; the two courses on Quantum Mechanics for Scientists and Engineers offered by David Miller (Stanford University); the three courses in Quantum Mechanics (PHYS-253) and Quantum Mechanics for Everyone (PHYX-008), offered by James Freericks (Georgetown University) and the CS 191 course at UC Berkeley taught by Umesh Vazirani. Our class offers comparable, compatible instruction using high-quality, original materials developed specifically to achieve the integration of ideas and concepts from those and many other sources.

Adrian German[12] is a Senior Lecturer in Computer Science and Acting Manager for the IU Quantum Science and Engineering center. At IU Bloomington he is the recipient of several teaching awards at the departmental and university level. His interests include learner-sighted teaching practices and maker-centered learning. He is the organizer of several successful symposia and conference workshops and has had presentations at various national and international conferences (SIGCSE, SIGITE, ITiCSE, ISSOTL, FIE, ECEL, and others). In 2021 he served as Chair for the Technical Advisory Committee (TAC) on Workforce Development in the Quantum Economic Development Consortium (QED-C) a broad national group of stakeholders from industry, academia, national labs and professional organizations that aims to enable and grow the US quantum industry and its associated supply chain[13].

Arpan Ojha is a Graduate Student in our (SICE) Data Science program. His interests are Quantum Computing, Deep Learning and Computer Vision. He has experience in Cybersecurity, Software Development and Robotics. He completed his Bachelor's Degree in Physics with a minor in Electrical and Communication Engineering. His thesis studied expansion dynamics of ultra-cold atoms from Mott insulators to super-fluid phase. He is currently assisting with C322 (Object-Oriented Software Methods). Arpan is a dedicated teacher has an extensive background in quantum mechanics and engineering, and is a very accomplished individual. He aims to develop efficient quantum computing pipelines that improve businesses.

[11] https://www.classcentral.com/report/review-quantum-mechanics/

[12] https://ieeexplore.ieee.org/stamp/stamp.jsp?tp=&arnumber=9733176

[13] QED-C was established with support from NIST as part of the federal strategy for advancing QIST as per the National Quantum Initiative Act in 2018.