Quantum Boot Camp*

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Abstract

Quantum mechanics is transforming the way we compute and communicate today, and it will change the technological landscape of tomorrow. Although today's quantum computers are noisy, intermediate-scale devices, the theory behind them is solid. Recent, accelerated breakthroughs in the field have led to a documented lack of talent in the quantum industry. High school programs continue to stay away from quantum physics, but the idea behind quantum computing is to embrace the bizarre quantum world, rather than fight it. Inspired by the many recent educational initiatives worldwide and the increased expertise on campus we propose the development of a dual purpose MOOC on the Quantum, both for outreach (to HS students and teachers alike) and as an entry point to our new one year intensive MS degree in QIS.

Contents

*In the sense of Basic Training, Apprenticeship, Clinic and/or Workshop.

1 What is this about?

The laws of quantum mechanics were formulated about a hundred years ago, replacing the classical laws of Newton and Maxwell. Since then, quantum mechanics has been applied remarkably successfully to understand a very wide range of observations and systems. The success of the laws of quantum mechanics in predicting and explaining essentially all the known physical phenomena is astounding. However, in spite of the great success, it remains a mysterious theory and the concepts of wave-particle duality, complementarity, the probabilistic nature of measurement, quantum interference, and quantum entanglement are still hotly discussed. It is not just the remarkable success in explaining all the known phenomena that makes quantum mechanics a fascinating subject. What is truly amazing is that, even today, a mere knowledge of the basic postulates can lead to startling new ideas and devices. For example, just the knowledge of the principle of complementarity can lead to perfectly secure communication systems, or the understanding of a beam splitter for a single photon can lead to a highly counterintuitive communication protocol with no particle present in the transmission channel, or the resource of quantum entanglement can lead to novel quantum computing algorithms. Therefore it becomes possible to convey not only the foundations of quantum mechanics but also some mind-boggling applications, such as in quantum communication and quantum compting, with just elementary knowledge of basic physics and mathematics.

With this background it is interesting to ask whether it is possible to convey the basic concepts of quantum mechanics and its amazing range of applications to someone (possibly just out of high-school, and) with a limited knowledge of physics and mathematics.

2 Why is it important?

A quick survey of recent, worldwide initiatives seems relevant in this regard:

- The Institute for Quantum Computation at the University of Waterloo runs "Schrödinger's class: learn how to teach quantum in your high-school class" a recurring workshop[1] for high-school teachers.
- At Texas A&M University M. Suhail Zubairy's Quantum Mechanics course is aimed at, and designed for, incoming college students before they take the usual Mechanics and Electricity and Magnetism courses. His lecture notes were published as a book by Oxford University Press in July 2020.
- Terry Rudolph[2] is a Professor of Quantum Mechanics at the Imperial College London, and one of the founders of PsiQ[3]. His 2017 book teaches the basic elements of quantum mechanics(e.g., nonlocality, entanglement)

[1] `https://uwaterloo.ca/institute-for-quantum-computing/programs/schrodingers-class`
[2] `https://www.imperial.ac.uk/people/t.rudolph`
[3] `https://www.ft.com/content/afc27836-9383-11e9-aea1-2b1d33ac3271`

and quantum computation to ”students who know only arithmetic [and are willing to use simple drawings in the process]”.

- Additional books documenting successful high-school programs have come out in recent years from: Valerio Scarani (at the Centre for Quantum Technologies of the National University of Singapore); Yuly Billig (Carleton University, in Ottawa, Ontario, Canada).

- Since 2017 when IBM first started providing remote access to their quantum computers via the cloud a plethora of online platforms[4] have become available, backed up by both major companies and upcoming startups (e.g., Amazon, Honeywell, IonQ, Microsoft, Rigetti, Xanadu, Google).

- Every major IT publisher (O'Reilly, Packt, Manning, Apress, The Pragmatic Bookshelf, etc.) has had a quantum computing title out in the last 12-15 months. The online[5] Qiskit textbook was used in this summer's IBM Global Qiskit Summer School (5,000 students worldwide[6] enrolled in Crowdcast delivered lectures with 2,000 students in labs).

- Increased demand for workforce development led to a slew of certification programs now being offered online: MIT's xPRO, Keio University in Japan, the University of Chicago started one last week, Microsoft has partenered with Brilliant[7] and AlphabetX and TU Delft, in Holland, UC Berkeley and many others have active courses on EdX[8].

The EdX platform, as a matter of fact, deserves a special mention. It has evolved in the last few years into the platform of choice worldwide for MOOCs and remote, online classes that also offer blended learning. IU has a few graduate programs[9] on it, as do most of other[10] universities in the country. So the main takeaway is that recent progress has been very fast (supported by a sound scientific body of knowledge and technological breakthroughs at many levels[11]) in an area of industry that promises to have a major disruptive impact globally.

[4] `https://qosf.org/learn_quantum/`

[5] `https://qiskit.org/textbook/preface.html`

[6] The crucial aspect that made it possible was the Discord platform. It's basically where we lived during those 10 days; the dynamics between students and even the level of support from appointed teaching assistants (called, if I remember well, mentors) was beyond incredible.

[7] `http://[...]/microsoft-brilliant-team-up-to-offer-quantum-curriculum`

[8] `https://www.edx.org/`

[9] `https://www.edx.org/masters/online-master-in-accounting-indiana-university`

[10] `https://www.edx.org/masters/online-master-science-computer-science-utaustinx`

[11] Aashish Clerk during office hours, two days ago, at the Chicago Quantum Engineering Certification Program: “people thought about the physics of squeezed states, this area that Alex talked about, back in the '80s, when there was an entire community of people during quantum optics, and there was a lot of beautiful theory worked out, not a ton of experiments, and then it became some sort of lore that whatever you did as a physicist you should not work on squeezing, because if you were going to do that, it was going to end your career. And some of us are living proof that that advice was wrong. And the fact that there are experiments now, and a growing number of systems, tells me that there are still interesting applications out there to be discovered. And as a matter of fact there's now a company in Canada, Xanadu, that is doing quantum computation just using squeezed states of light.”

3 What's the plan?

Our focus is learning how to exploit the laws of quantum mechanics in order to compute. For the most part, we'll be concerned with the structures of quantum mechanics that are useful to that end. We'll spend much of our time in the early stages learning the relevant laws of quantum mechanics, while keeping close to the framework defined by classical computing. By the end we'll understand the nature of quantum computing and the reason for which[12] scientists think it will lead to speedups on a variety of important problems.

3.1 The Course Content

We're going to organize the course into a learning sequence of four broad units where the first two units listed below will in fact be offered together:

3.1.1 Introduction to Quantum Mechanics and Its Applications

Unlike a classical bit that can be in only one of two states, a qubit has both an amplitude and a phase. A qubit, therefore, can have as many data points as you can partition the surface of a (Bloch) sphere, allowing for a superposition state. Looking at a superposition state changes it, and this is a resource for information security. Entanglement allows sharing information even without a physical connection. This allows scaling for computing, communication through teleportation and precise sensing.

3.1.2 Introduction to Platforms and Materials

How does one build such systems? Photons, semiconductor spins, cold atoms, trapped ions, superconducting circuits: All these systems are being aggressively pursued by the industry We, furthermore, may be able to harness the investment[13] in material developments pursued by the nano-electronics industry for the quantum technologies.

3.1.3 Quantum Sensing and Metrology

What is a quantum sensor? One can use a quantum object to measure a physical (either classical or quantum) object. A quantum object is characterized by quantized energy levels (e.g. quantum harmonic oscillator). Example measurements include electronic, magnetic or vibrational states. One can also make use

[12]To whatever extent we can map and mold our computational problems onto quantum objects, we'll be able to use it to our advantage. If a problem has an inherent quantum aspect to it, then we can expect a speedup.

[13]National Quantum Initiative Act allocating \$1.25B for 5 years to establish national centers by DOE, DoD, NIST and NSF. The Quantum Economic Development Consortium (QED-C) was also established in the spirit of Sematech which brought many competing companies to work together to solve technical challenges within a noncompetitive environment. The QED-C was launched in a similar vein to bring the industry together and create roadmaps for quantum technologies.

of quantum coherence (i.e. wavelike spatial or temporal superposition states) to measure a physical quantity. Finally one can make use of quantum entanglement to improve the sensitivity or precision of a measurement, beyond what is possible classically. The learning objectives for this unit can be summarized as follows: to communicate the advantages of QIS on sensing and metrology and the fundamental limits associated with quantum measurements; to create an appreciation for the quantum states that can be leveraged in quantum sensing and metrology; to build an understanding of the current state-of-the-art in quantum sensing technologies and to have a working understanding of key use cases and future applications for quantum sensing and metrology, including biological sensors, atomic clocks, and solid state systems.

Some of the focus areas include: time keeping[14], force sensing[15], imaging[16]– from nanoscale to astronomical, and frequency counting[17] There are many different quantum limits to sensing from measuring different things to amplifying quantum signals. All these limits are context dependent. These limits come from two aspects: backaction (measuring disturbs) and quantum noise (cannot be overcome).

3.1.4 Quantum Communications

With each improvement in quantum networks we can unlock new technologies.

Stages of quantum networks from difficult to easy in descending order:

Quantum computing	Network quantum computing, blind quantum computing
Hybrid quantum interface	Long-base line quantum telescopes, network of clocks
Quantum memory	Entanglement purification and quantum repeaters
Entanglement generation	Device independent QKD, quantum teleportation and superdense coding
Prepare and measure	Quantum key distribution

Quantum networks can do: secure communication; secure quantum computing in the cloud; clock synchronization & quantum sensors. Quantum networks exist[18]. We need quantum repeaters to overcome the exponential decay of photons within fibers. We have been using repeaters to transmit information for

[14]These clocks are so accurate that if they ran over the age of the universe, they would be off by only a second. They are used for GPS, time tagging (high frequency trading etc.)

[15]Use Bose-Einstein condensates to probe gravity (general relativity tests, gravitational waves, high energy physics, dark matter etc.). Ultraprecise measurement of gravitation, electric, magnetic fields can be used for detecting underground resources for example.

[16]Precision measurement of time, deep space, gravity is possible. Within the industry, pharmaceutical development, hard drive diagnosis, neurological imaging, satellite imaging are all possible applications.

[17]Some examples include counting the moon cycles, or building clocks (it counts how many times the pendulum oscillates). Most accurate clocks are made out of atoms (Cesium atom's hyperfine levels).

[18]In 2017 Chinese scientists have smashed the quantum entanglement distance record. Transmitting information through entangled photons had previously only been possible up

millennia – the principle is to amplify and duplicate the signal. But in quantum mechanics we cannot duplicate quantum states due to No-Cloning Theorem. Realistically we have loss errors, and operation errors (channel decoherence, memory errors, etc.).

Learning objectives for this unit: build a working understanding for the applications of quantum communication and cryptography; have an appreciation for the principles and applications of quantum key distributions (QKD); grasp the concept of entanglement and applications of quantum teleportation and super-dense coding; understand the concept of, and need for, the quantum repeaters and other technological hurdles in the development of quantum networks; have an appreciation for additional engineering and physics issues of quantum communication, including materials and devices, entanglement sources and their engineering concerns, and quantum photonics; state-of-the-art quantum communications and future perspectives.

3.1.5 Quantum Computing

Quantum computers have the ability to perform some computations using exponentially fewer states than classical computers. This violates a well-known hypothesis in computing theory sometimes called the Strong Church-Turing thesis, which roughly asserts that if a computation can be performed efficiently by any means then a classical computer can also perform it efficiently.

An early barrier to the development and viability of quantum computing was the no-cloning theorem discovered in 1982 by William Wootters, Wojciech Zurek, and Dennis Dieks, which states that it is impossible to create a guaranteed identical copy of any quantum system. This prevents use of classical error correction techniques for quantum algorithms, since such techniques rely on making backup copies of states as templates to fix errors. Without error correction, thermal fluctuations and other sources of noise cause quantum systems to decohere and lose information. In 1995, however, Peter Shor and Andrew Steane discovered a method of quantum error correction that circumvents this problem. Since 1994, a number of quantum algorithms that demonstrate dramatic speedup over classical algorithms have been discovered.

Learning objectives: understand fundamentals of quantum computing; have an appreciation for challenges in scaling up quantum systems for different platforms and qubit modalities; have an understanding of key concepts in quantum computing, such as quantum measurement superposition and entanglement, gates, and error correction; grasp software concepts and algorithm use cases such as Grover's algorithm and in quantum chemistry, such as VQE and DFT.

Learning sequence proposed is: classical computation, reversible and quantum computation; qubits, teleportation, superposition, entanglement; quantum circuits; quantum algorithms (Deutsch-Josza, Bernstein-Vazirani, Grover, Shor); quantum hardware (ion traps, superconducting qubits, photonics and

to about 100 km (62 mi), but using the Micius satellite launched in August 2016, information has effectively been teleported as far as 1,200 km (746 mi).

anyons[19]); quantum communication and quantum cryptography (the quantum internet); post-quantum cryptography; NISQ realities: noise, error correction and mitigation; probabilities (for Quantum Bayesianism) and basic complexity theory (P, NP, BQP etc); VQE, DFT, QAOA, emulation/simulation and applications in quantum chemistry (just the basics). Borrowing the terminology from GenEd and N&M we aim for this preliminary stage (this unit as well as the entire Quantum Boot Camp) to be complete but at a level between literate and articulate (i.e., right in the zone of proximal development between the two).

3.2 The Course Development Process

The recommended time to create a MOOC on the EdX platform is 6-8 months[20].

Before we start we need to assemble a team of teaching assistants, teaching fellows or undergraduate volunteers to help with creating the course (and maybe administer a pilot). We will also need volunteers to help moderate discussion forums and with debugging and testing the courseware. Occasional access to campus resources, such as video specialists or instructional designers, is also likely, and therefore, foreseeable. An online course alternates short videos with exercises and benefits from a modular structure. The course must be designed as an overall experience and we carefully need to plan our course goals.

Here's a timeline of the steps we will take:

September-December 2020	Recruit teaching fellows
Starting in January 2021 -	Getting the word out: advertise
January - June 2021	Create course content
May - June 2021	Prepare the course for delivery
June - July 2021	Run course pilot
August 2021	Course delivery for Fall 2021

4 What's the budget?

I'm already working (through UROC) with three students this semester. One of the students is a freshman and has no prior experience programming and the research aspect of the project is to determine whether the student can acquire a working knowledge of concepts and algorithms on the quantum side without prior exposure to the traditional elements of computation.

Course content will be developed in EdX Studio (the course authoring tool in EdX). Courses delivered via the EdX platform have built in analytics. Opportunities for blended learning are significant, in the sense that once the course is ready students can take it whether they're on campus or off-campus (possibly

[19] Very recent Majorana fermions paper: `https://arxiv.org/pdf/2009.07590.pdf`

[20] This, of course, is influenced by a number of factors but as a ballpark figure should work well as a reasonable first approximation.

overseas). Teaching fellows will be trained in EdX authoring tools and will help create, edit and maintain the course content (mainly a collection of carefully structured quizzes in the manner used by ZyBooks and/or VitalSource).

We (CSCI) are normally budgeting $2,000 per undergraduate instructor working 10 hours/week during a Fall or Spring semester. We should recruit and hire 4 (four) undergraduate teaching fellows to help with course development and pay them at the same rate. We then recruit a focus group of 20 (twenty) interested students, with the right background, from all over the world[21] and pay them to take the pilot. Each student participating in the pilot gets $200 (essentially $50 per unit taken) and a certificate (if they pass). Teaching fellows act as TAs during the pilot (one per unit) and get paid $300 for monitoring the discussion boards and $300 for office hours via Zoom, one hour each, and held prior to the midterm and the final.

We are going to ask some of the faculty in the Indiana University Quantum Science and Engineering Center to help record short videos that would set the stage for the active learning items that will form the bread and butter of the course materials. They will also vet (audit/oversee) the exercises that we already have and help author new custom items/exercises as well.

We also budget travel expenses for the four teaching fellows since the intention is to write an experience report or a research paper and submit it to a conference like SIGCSE or ITiCSE and go and present it in person.

Teaching Fellows	$4 \times \$2,000 = \$8,000$
Focus Group	$20 \times \$200 = \$4,000$
Pilot TAs	$4 \times (\$300 + \$300) = \$2,400$
Travel	$4 \times \$700 = \$2,800$
Total	$\$17,200$

5 How do we assess success?

Quantum computing is a growing field at the intersection of physics and computer science. A recent[22] paper by a group of researchers from the Fermi Lab highlights a successfully trialed quantum computing course for high school students between the ages of 15 and 18 years old. The paper claims that "t[he] course bridges the gap between popular science articles and advanced undergraduate textbooks. Conceptual ideas in the text are reinforced with active learning techniques, such as interactive problem sets and simulation-based labs at various levels." Our aim is to confirm (or, simply, check) their findings and, if possible, improve and expand on them.

A second goal is to use the materials developed as a probing instrument into the thinking of the students in an attempt to determine a set of threshold concepts and bottlenecks in the student population. These are different type

[21] Apply basic NSF REU process/strategy here.
[22] https://arxiv.org/pdf/2004.07206.pdf

of concepts working at different levels (bottlenecks are relative concepts, while threshold concepts are more absolute in nature) but they can both decisively inform subsequent versions of the course. As a matter of fact one major goal of this project is to determine if the increased availability of interactive tools for quantum computing has an effect (and if so what exactly) on the ability of students to better relate to quantum mechanical concepts. ← important

6 Why are we qualified to develop this?

We anticipate we can rely on the following faculty from the IU Quantum Science and Engineering Center[23] to assist

- Prof. Amr Sabry, Computer Science
- Prof. Gerardo Ortiz, Physics
- Prof. Mike Snow, Physics
- Prof. Julia Plavnik, Mathematics
- Prof. Srinivasan Iyengar, Chemistry

The list of faculty assisting with, and interested in, this development is much longer since last week the Academic Affairs and Quality Committee of the Indiana Commission of Higher Education approved our QIS accelerated MS degree program for expedited handling, and so it will be considered by the full ICHE very soon, hopefully on October 8. This is the last stage before we can start offering the course in Fall 2021. The Quantum Boot Camp described here would be a very meaningful introductory stage to that program.

We have first hand experience of all the major existing quantum science and engineering certificate programs, such as:

- MIT xPRO (two programs, four courses)
- Keio University, Japan
- Technical Unversity Delft, Holland (two courses)
- UC Berkeley (the Vazirani course)
- IBM Qiskit 2020 Global Summer School
- University of Chicago Quantum Engineering Certificate

In addition the PI on this proposal has a professional certificate from EdX in online and blended course development.

[23] `https://qsec.sitehost.iu.edu/`