

Experience Teaching Quantum Computing

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Abstract

There is a quantum computing race among the tech giants Google, IBM, and Microsoft, including to a lesser extent Amazon and China's Alibaba. Governments, particularly America and China, are funding work in the area with the concern that quantum computers may soon crack current encryption methods, giving the country that gets there first a major advantage. There are currently about 100 universities worldwide with some activity in quantum computing. Considerable funding is also available and the 2019 U.S. National Quantum Initiative Act authorized \$1.2 billion funding over the next 5-10 years. This paper shares the positive experience of Pace University in teaching quantum computing and encourages other schools to join us in this revolutionary step forward for computing. The paper discusses our experiences teaching a graduate-level quantum computing course, teaching the projects component of the course that develops problems to be solved on IBM's Q Experience quantum computing simulator, and teaching quantum computing modules in high schools.

Introduction

There is a quantum computing race among the tech giants Google, IBM, and Microsoft, including to a lesser extent Amazon and China's Alibaba. IBM emphasizes heavy usage on their Q Experience quantum simulator with more than 90,000 users who have run 5,000 experiments and published 110 papers.

Governments, particularly America and China, are funding work in the area with the concern that quantum-computers may soon become large enough (about 200 qubits) and with sufficient coherence to crack current encryption methods, specifically RSA, giving the country that gets there first a major advantage by being able to decipher competitor's communications (The Economist, 2018). At the 2019 Consumer Electronics Show, IBM announced for sale – or, more accurately, calculation time on it -- the IBM Q System One, the world's first commercial quantum computer (IBM, 2019d).

According to the Quantum Computing Report (Fink, 2019), there are currently 91 universities worldwide with some activity in quantum computing. None of these universities currently offers a degree specifically in quantum computing, rather making it an elective course, or at most a specialization in their established physics or mathematics programs. Some universities are planning future investment in the area – for example, the McMahon Lab at Cornell University which emphasizes quantum computation, will officially begin operation in July 2019. In MIT News, a recent article interviewed William Oliver, the principal investigator in both the Engineering Quantum Systems Group at MIT and the Quantum Information and Integrated Nanosystems Group at MIT Lincoln Laboratory. He noted that MIT's quantum computing effort was being inhibited by a shortage of quantum knowledge workers (Leddy, 2019).

The University of Wisconsin is introducing a new Master's program in Physics-Quantum Computing in the fall of 2019. MIT, in addition to its extensive course offering, has a program called xPRO, for online learning, that includes quantum computing units. The University of Maryland has established the Joint Quantum Institute to work with the National Institute of Standards and Technology which is "dedicated to the goals of controlling and exploiting quantum systems" (U of Maryland, 2018). The University of Oregon offers a course subtitled "Quantum Mechanics for Everyone" (U of Oregon, 2017) providing an accessible introduction to quantum phenomena. The following major universities offer courses in quantum computing: MIT, USC, U Michigan, Caltech, Cornell, Harvard, Stanford, UC Berkeley, U Maryland, U Massachusetts, U Minnesota, U New Mexico, U Oregon, Pace, U Pennsylvania, U Rochester, U Virginia, Virginia Polytechnic, and Washington University at St. Louis.

Considerable funding is now available in this area. In the U.S. in January 2019, the National Quantum Initiative Act, authorizing \$1.2 billion in investment over the next 5-10 years, was signed into law, and is being organized now into different areas that researchers can apply to for funding in quantum computing (Rep Smith, 2019). An overview of funding opportunities can be found in Appendix A.

This paper shares the positive experience of Pace University in teaching quantum computing at the PhD, Master's, and High School levels, and encourages other schools to step forward and join us in this revolutionary step forward for computing. In the following sections, this paper discusses our experiences teaching the theory of quantum computing in our graduate-level course, teaching the projects component of the graduate course that involves developing problems to be coded and solved on IBM's Q Experience quantum computing simulator, teaching quantum computing modules in high schools, and constructing a simple experimental apparatus to demonstrate some of the nonintuitive behavior of quantum systems.

Teaching a Graduate Course in Quantum Computing

Developed in the fall of 2017, a quantum computing course was offered in the spring of 2018 and again in the spring of 2019 for Computer Science PhD and advanced Master of Science students. This high-

level computing course demonstrates that our computing school provides a leading-edge computing technology education to our students. Three faculty members have been teaching this one-semester, graduate-level course in quantum computing for the last two years. The course meets for three hours weekly, in the evening so working students can attend, for a total of 14 weeks over the semester. Two of the instructors, seasoned faculty members with a strong background in mathematics, cover the theory and background material. The third instructor, an adjunct from IBM, handles the student projects concerned mainly with finding interesting problems and creating code to run the problem solutions on quantum computing simulators, primarily the IBM Q Experience. For the first offering of the course, the text *Quantum Computation and Quantum Information* (Nielsen & Chuang, 2010) was employed. However, we felt that the text did not do a good job of introducing mathematical terminology, so for the second offering of the course we used the text *Quantum Computing: A Gentle Introduction* (Rieffel & Polak, 2014). Furthermore, realizing the need for additional math instruction, for this second offering we held separate weekly hour-long sessions of math instruction. Also, since solving problems is an important aspect of teaching the course we adopted, as an auxiliary text, *Problems and Solutions in Quantum Computing and Quantum Information* (Steeb & Hardy, 2018). For the project work in the second offering we used the text *Mastering Quantum Computing with IBM QX* (Moran, 2019).

The course provides the students with an introduction to the theory and practice of quantum computing. Topics covered include quantum computing circuits, particularly quantum gates, and comparison with classical computing gates and circuits; quantum algorithms; mathematical models of quantum computation; quantum error correcting techniques; and quantum cryptography. We also spend a half day during the semester visiting the IBM T.J. Watson Research Center to see actual quantum computers and hear related presentations.

Ten to twenty students take the course – the majority are PhD in Computer Science (CS) students with a few advanced CS Masters students. Assessment is based on the project work and student presentations 40%, midterm exam 20%, and final exam 40%. The final exam also serves as a qualifying exam for the PhD students. The learning objectives of the course are:

- . Learn the background material in computer science, mathematics, and physics necessary to comprehend quantum computing.
- . Understand quantum computing circuits, particularly quantum gates, and comparison with classical computing gates and circuits.
- . Understand quantum Fourier transform and its applications.
- . Understand quantum search algorithms.
- . Understand the physical realization of quantum computers.
- . Understand quantum operations, quantum noise, and quantum error correction.
- . Understand quantum information theory and its comparison to Shannon's entropy and traditional information theory.
- . Understand in detail the central results of quantum computing.
- . Develop a working understanding of the fundamental tools and design methods of quantum computing.
- . Develop expertise in writing programming code for quantum computers.

Teaching the Projects Component of the Graduate Course

The quantum computing graduate course has student projects that utilize hands-on labs with simplified quantum program development, live code executions and student projects performed using IBM's Quantum Experience Platform with access to real Quantum Computers. During the first year we used 5 and 20 Qubit computers within IBM Research Labs in Yorktown, NY and Austin, TX locations. This year we are using the IBM Cloud to connect to the IBM Q Network with additional live quantum computers in Tokyo, Japan; Melbourne, Australia; and Santa Cruz De Tenerife Area, Spain.

We used multiple Quantum Computing Science Kits to teach students quantum computing technology. The objective was to help the students to gain practical experience via lab exercises and to develop projects to solve relevant and practical problems using quantum computing algorithm and programs. Details of the QC Science Kits can be found in Appendix B. While initially we used Watson Studio within IBM Cloud, we later deployed a simplified shared development platform based on integrated JupyterHub/JupyterLab virtual machine running within a public cloud service. Details of JupyterHub can be found in Appendix C.

The projects involved three types of problems that were coded using Quantum Computing Assembler Language (QASM) and Python. The programs were then run on quantum computing simulators or actual quantum computers. The first type of problems were well defined quantum computing experiments, including the following:

- .Placing qubits in super positions and implementing quantum entanglement
- .Implementing "Alice and Bob" example for quantum teleportation, transmitting a qubit's state using two classical bits □ Implemented "Alice and Bob" scenario for superdense coding, where two classical bits are transmitted using one qubit
- .Experiments with 3, 4, and 5 qubit Fourier transforms

The second type of problems were optimizations. We introduced a number of classic quantum computing algorithms and their actual implementation during the graduate classes. Quantum computing can provide solutions to a series of problems that are computationally intensive using classical computers, such as solutions to NP-Hard and NP-Complete Problems (NP: non-deterministic polynomial time). While classic computers use bitwise computations, quantum computers perform unitary transformations on the states of qubits. Using the principles of superposition, entanglement, and quantum parallelism, quantum computers enable implementation of algorithms and computational solutions that were previously not feasible on classic computers. Some of the classic quantum computing optimization solutions demonstrated within the class include:

- .Quantum approximate optimization to solve efficiently the classic "Travelling Salesman Problem"
- .Grover's Search Algorithm, to solve NP-Complete problem to find the actual solution from a large number of possible candidate combinations.
- .Implement simplified quantum programs to solve the Abelian hidden subgroup type problems with a focus on two special cases: Simon's and Shor's algorithms.

The third type addressed practical problems using quantum computing:

- .Financial Portfolio Optimization, such as retirement investments, using Variational Quantum Eigensolver (VQE) to find optimal solution to allocate investment dollars across funds.
- .Investigate using quantum computing classifiers to optimize computation using kernel methods applied to machine learning projects. Classification methods requiring feature extractions from complex

data can lead to complex kernel computations. These computations cannot be solved efficiently on classical computers. Applied medical image processing with feature extraction and features based classification is common problem. We reviewed an IBM Qiskit tutorial for images-based cancer detection area of applicability: https://github.com/Qiskit/qiskit-tutorials/tree/master/qiskit/aqua/artificial_intelligence

Traffic optimization prototypes aimed to find the best route for drivers within New York City.

As a direct result of what they learned in this course, four papers by students were published at outside conferences. (Westfall, 2018, 2019)(Barabasi, 2019)(Kamruzzaman, 2019).

Teaching High School Students

PhD candidate Avery Leider was impressed by a discussion by a mathematician working on the creation of the IBM Q Quantum Computation Center for commercial clients, which will open in Poughkeepsie, New York in 2019 (Howland, 2019). That mathematician said that the best student to learn quantum computing would not be a PhD or Master's student, but rather a high school student because they are more open to the unusual ideas of quantum computing.

Inspired by that conversation, Avery designed her PhD proposal around the idea of teaching quantum computing to high school students. She developed a curriculum and tested it by teaching quantum computing for five days (January 7 – 11, 2019) in the 12th grade Brooklyn, NY STEAM Center class of high school teacher Damiano Mastrandrea, Pace alumnus MS CS '18. Damiano had observed the first quantum computing course for PhD students during his last semester at Pace and wanted a version of the course for his high school students. The focus was on short lectures followed by hands-on programming utilizing the IBM Q Experience Composer interface to run quantum programs both on the simulator and on the actual machine. For teaching the theory, we found helpful material in *Quantum Computing for High School Students* (Billig, 2018). The module on quantum computing consisted of five days of class.

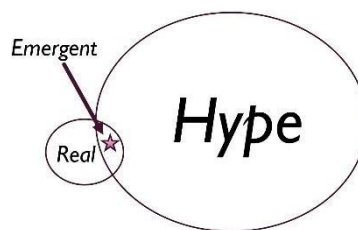


Figure 1: The emergence of Quantum Computing

Day 1 covered the visualization of a quantum bit (“qubit”), introduction to the $|\text{ket}\rangle$ notation for vectors in quantum computing, explanation of gates, and an introduction to matrix notation for kets, or vectors, and gates.

Discussion followed about the explosive growth in the science behind quantum computing and the hyperbole in the popular literature about its capabilities. Even excluding the hyperbole, the real discoveries are so advanced and amazing that they border on the fantastic. See Figure 1

An introduction to the concept of measurement was included in this first day. The pre-measurement state, when the quantum computing program is running and the qubit is in a quantum state, was contrasted with the post-measurement state, when the qubits are measured and the quantum waveform collapses and is read as either 0 or 1.

Also covered was the pre-paradigm status of quantum computing. If this was settled science, with a common vision, everyone would use the same terms and same equations. It is such a new science that notations are not standard, and even the order one reads the results – the zeros and ones – of a quantum program are not standard. So flexibility is necessary.

The hands-on portion utilized the IBM Composer, which required all students to register with the IBM Q Experience. The layout of the Composer (Figure 2) was reviewed and the method for selecting whether to run the program on the simulator or on one of the real quantum computers that IBM has made available was explained (Figure 3).

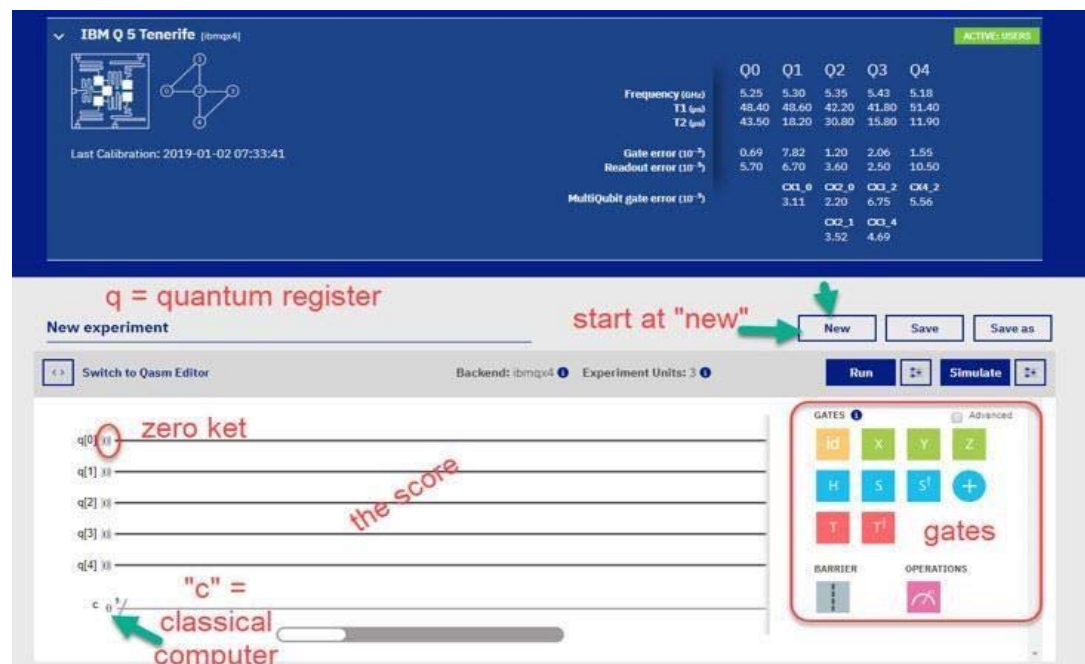


Figure 2: annotated user interface of the IBM Composer

The quantum registers with the qubits in them are listed on the left side, initialized with zero kets, $|0\rangle$, which is the ground state of a qubit. The qubits are also depicted in relationship to each other on the actual quantum circuit chip in the diagrams of the upper left hand side, see Figure 4. The gate selection menu on the lower right hand side is where the programmer chooses the gate they need and drags it onto the appropriate wire in 'the score'. The selection buttons, for running the program on either the simulator or the actual quantum computing machine are on the right hand side above the gate selection area. The system on which to run the program is selected after the program has been built, named, and saved.

After this orientation, the students went hands-on. The students ran programs demonstrating the X gate which is the quantum equivalent to the classical NOT gate. If the qubit is in a ground state with value 0, then putting it through an X gate flips it into the 1 state, the activation state, and vice versa. Students reviewed the results – the zeros and ones – which were read from right to left, as if they were Chinese characters. Also important was the understanding that the results in a quantum program are delivered in probabilities. Quantum programming does not deliver exact results, so each quantum program is run many times in order to give a probability distribution. On a simulator, a program might be run 100 times to give a good result, whereas on the real machine, it may take 1,024 or more executions to give a reasonable distribution.



Figure 3: Click “Run” for a quantum computer or “Simulate” for the simulator.

Day 2 covered superposition and entanglement. To understand the diagrams illustrating superposition, they had to be introduced to the Greek symbol psi, Ψ , as superposition can be shown as a psi Ψ $|\text{ket}\rangle$ (to show all of the possibilities, psi Ψ , of a vector $|\text{ket}\rangle$, in superposition: the psi-ket is depicted as $|\Psi\rangle$). The $|\Psi\rangle$ vector can move in multiple dimensions, which is hard to describe and hard to show in an illustration. Superposition is created by applying a Hadamard (H) gate to a qubit.

After superposition was firmly understood, entanglement was explored. Entanglement means that two or more qubits have formed a relationship. The entanglement is created by the program applying an H gate to the one qubit and then a Controlled-Not (CNOT) gate to two qubits. The qubit that had the H gate applied is the control qubit and the second qubit is the target qubit. They can be separated by large distances, yet always remain entangled with one another – if one is changed by a new gate, the other changes instantly in the same way. At this point the students protested that this would violate the law of physics that nothing can have a velocity greater than the speed of light (c). It was explained that there is no violation because there message noting that the change occurred is still limited by c .

The hands-on portion of the class was to make 6 CNOT connections in the IBM Composer, use X gates (X gates flip values from zero to one and one to zero), to predict their answers, and run the program. To do this, the students had to study the diagram that accompanies the programming interface of the Composer, to identify legitimate paths for entanglement of qubits, see Figure 4. A legitimate path of qubit entanglement goes from qubit 1 to qubit 0 or 2 or from qubit 3 to qubit 4 or 2. An attempt to put a CNOT gate between other combinations of qubits, such as between 1 and 3, will not be allowed and in the Composer, the disappearance of the incorrect CNOT from the program.



Figure 4: Five Qubit IBM Quantum Computer

Day 3 covered Grover’s Algorithm. This is an important search algorithm with great potential to help many industries. It is a uniquely quantum algorithm, not found using classical computers. To understand Grover’s Algorithm, the high school students first had to review the action of the H gate plus the CNOT gate in entanglement, and then understand the pattern of the gates – the two circuits formed by gates – that form the two parts of the Grover’s Algorithm. The first part is the Oracle that highlights the item being searched for. The second part is the Amplifier, which boosts the value of the highlighted result.

At low signal, the right answer does not clearly show in the probabilities distributions. After amplification the right answer is apparent.

There is an IBM tutorial at the Q experience that demonstrates Grover's Algorithm on their real world working IBM computer. However, the program failed, with the error message "You can't put a gate there" and the turnkey setup revealing a program missing its most essential components – the CNOT gates of entanglement, leaving orphaned H gates. The program was run on the quantum computer, but the results did not provide a valid solution to the problem. The students were grouped into troubleshooting teams to find and fix the problem. This was the most engaging part of the instruction, as the students, having only two days of quantum computing, got a chance to troubleshoot a real quantum computing program. The first team to solve the puzzle did so in 20 minutes, while the last of 5 teams solved it in 40 minutes. The answer was to look at the IBM circuit board diagram for the IBM computer that the program was being run on. Every quantum computing program has to take into consideration the exact construction of the specific individual IBM computer's unique hardware when making CNOT connections. Some connections are not physically possible. The author of the IBM tutorial on Grover's Algorithm must have used a different computer configuration. Once the problem was found, the students had to add back the CNOT gates that had been omitted, and then rerun the program. The troubleshooting process encouraged active participation of the students with a lot of animated discussion of how to solve the problem. Because of the time spent troubleshooting the problem and fixing it, the objective of Grover's Algorithm was neglected. This omission was revealed during review the following day.

Day 4 returned to the subjects of Superposition and Entanglement. Review of Superposition included the Bloch Sphere as an illustration of a qubit, and the $|\Psi\rangle$ vector within that sphere with its nearly infinite possibilities between zero and one. There was a brief introduction to the Bell States as the primary examples of entanglement.

A hands-on exercise followed that tested executing one superposition and its results – which are 50% one and 50% zero. Then the students tried two Hadamard gates in a row. Because the Hadamard gate is its own inverse, the second gate undoes the action the first gate and returns the input to its original state. The result was not one, but close to one, demonstrating that there is randomness in quantum computing. There was open discussion about how entanglement, as utilized in a quantum computer, can be used to solve problems.

A general survey introduction then discussed the few quantum algorithms available, such as Grover's Algorithm and Shor's Algorithm. The discussion of Shor's algorithm went into RSA encryption briefly, as Shor's algorithm may be used to factor the product of two primes, which is central to RSA encryption. This was followed by a lighthearted discussion of Schrodinger's cat and a search for images of Schrodinger's cat that each team shared with the class.

On **Day 5**, the students were split into teams and each team was given one day's worth of PowerPoint slides from the instructor. This was an exercise they were familiar with, and they called it the "Jigsaw Puzzle". They reworked the PowerPoint slides into their own slides. Then each team presented their slides to the class. This was a good opportunity for them to demonstrate and reinforce what they learned and for the instructor to get ideas on how to improve the class. Also on Day 5 the students completed a survey and ranked topics of most interest (Figure 5).

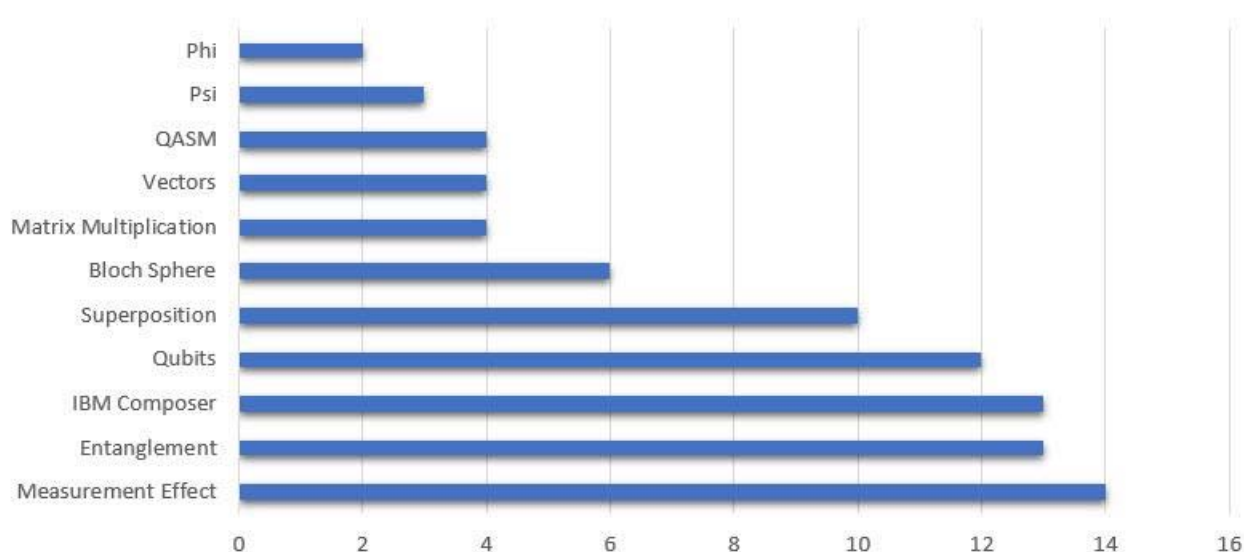


Figure 5. Topics the students found most interesting.

Each day, two assistant teachers supported the instruction by capturing student questions, compiling and displaying them on PowerPoint slides. The questions were answered at pauses in the instruction with the students being offered the opportunity to answer their classmate's questions first, with encouragement and clarification provided by the instructor. The student questions show a remarkable understanding of quantum computing in a very short amount of time, and also show that there were misunderstandings caused by an awkward use of an analogy of sound waves and quantum mechanics waves. These are two different kinds of waveforms that are not related, but that share similarities in the mathematics used to understand them. The opportunity to review the ideas understood by the students in front of them helped straighten out some of these misunderstandings.

Demonstration of Nonintuitive Behavior of Quantum Systems

Quantum computing is a beautiful combination of quantum physics, computer science, and information theory. Qubits (quantum bits) are the fundamental units of information in quantum computing, as bits are fundamental units in classical computing. Just as there are many ways to realize classical bits, there are many ways to realize qubits, and polarized photons are a possible realization of qubits. Here we describe a simple experimental apparatus constructed to demonstrate some of the nonintuitive behavior of quantum systems, in this case of systems involving polarized photons. This experiment was described by Rieffel & Polak (2014) to illustrate the behavior of polarized photons and they specify the minimal equipment required as a laser pointer and three polarized filters (polaroids) available from any camera supply store (Figure 6, top). Because it is difficult to have students hold the laser pointer, three filters, and the screen, we found it more convenient to use a laboratory rack to hold these items (Figure 6, bottom).

The demonstration is conducted as follows.

- .Remove all items from the rack except the laser pointer and the screen

- .Shine the laser beam of light on the projection screen

- .Place polaroid A between the light source and the screen to show a reduced light intensity reaching the screen, and rotate it to filter horizontally so that only horizontally polarized photons pass through the filter

- .Place polaroid C between polaroid A and the projection screen and rotate it initially to also filter horizontally to show the maximum unreduced light on the screen
- .Slowly rotate polaroid C to show that the light hitting the screen is reduced until the light is completely blocked when polaroid C filters vertically to block the horizontally polarized photons allowed through polaroid A
- .Finally, insert polaroid B between polaroids A and C, and rotate B slowly to allow light to pass and hit the screen

Because the insertion of polaroid B surprisingly increases the light intensity on the screen, the polaroids cannot be acting as simple sieves. Although the results of this experiment can be explained classically in terms of waves, the same experiment can be performed with more sophisticated equipment using a single-photon emitter to yield the same results which can only be explained with quantum mechanics. And it is not just light but many other quantum phenomena that behaves in this peculiar way.

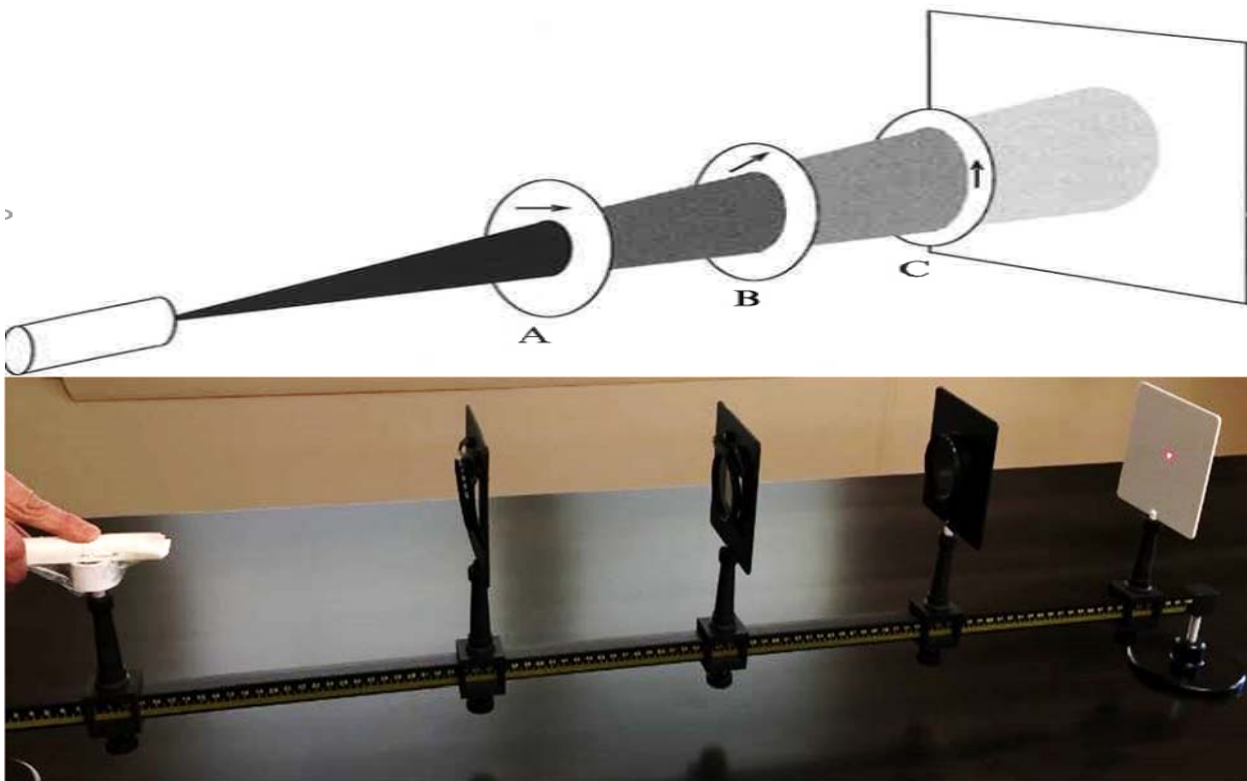


Figure 6. Rieffel & Polak (2014) textbook figure (top) and Pace University apparatus (bottom).

Conclusions

Because of the quantum computing race among the tech giants and the realization that computers may soon crack current encryption methods giving the country that gets there first a major advantage, there is a growing need to teach quantum computing technology at all levels of education from high schools through graduate schools. There are currently many universities worldwide with some activity in quan-

tum computing and considerable government funding is available. This paper shares the positive experience of Pace University in teaching quantum computing and encourages other schools to join us in this revolutionary step forward for computing.

In this paper, we have discussed our experiences teaching a graduate-level quantum computing course that includes the development of problems that can be solved on IBM's Q Experience quantum computing simulator, teaching quantum computing modules in high schools, and how to construct an experimental apparatus to demonstrate some of the nonintuitive behavior of quantum systems. We also anticipate offering an undergraduate course in quantum computing in the near future. Teaching quantum computing is an area rich with opportunity for growth, for funding from the federal government, and for employment for our students. It may also strengthen our nation's economic future. Quantum physics is a challenging subject, but the quantum computing that uses it, does not have to be difficult to teach.

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Appendix A - Overview of Funding Opportunities

A two-page overview of Federal Quantum Information Science was published by the Congressional Research Service in July 2018 (Congressional Research Service, 2018). It is a snapshot of federal efforts at that time, and includes views on international efforts. It is a good starting point for understanding federal efforts in the area of quantum computing. A more detailed overview is the National Strategic Overview for Quantum Information Science, published in September, 2018, by the Subcommittee on Quantum Information Science, under the Committee on Science of the National Science and Technology Council (Executive Office of the President of the United States, 2019). Also in September, 2018, the Department of Energy announced \$218 million funding for efforts in Quantum Information Science. The DOE's Office of Science has three program offices for Advanced Scientific Computing Research, Basic Energy Sciences, and High Energy Physics awarding grants. The ASCR lists award opportunities on its Funding Opportunities web page (DOE, 2018).

The National Science Foundation has been active in awarding quantum research grants for some time. In September 2018, the NSF announced awards in two efforts with the awards going to twenty-seven US universities.

- \$25 million for exploratory quantum research as part of the Research Advanced by Interdisciplinary Science and Engineering (RAISE)-Transformational Advances in Quantum Systems (TAQS) effort.
- \$6 million for quantum research and technology development as part of the RAISE-Engineering Quantum Integrated Platforms for Quantum Communication (EQuIP) effort.

The NSF promotes 10 Big Ideas, research areas deemed critical for US technological leadership. The NSF has plans in 2019 to invest \$30 million in each Big Idea. Quantum Leap is one of these 10 Big Ideas. The Quantum Leap web page (NSF, 2018) describes the effort as "Exploiting quantum mechanics to observe, manipulate, and control the behavior of particles and energy at atomic and subatomic scales, resulting in next-generation technologies for sensing, computing, modeling, and communicating."

In response to the National Strategic Overview, on December 11, 2018, the NSF issued a Request For Information, with responses due January 25, 2019, asking for "...information from the research and development community around quantum information science (QIS) to inform the subcommittee as the Government develops potential means of addressing specific policy recommendations."

Specific questions contained in the RFI (RFI, 2018) are indicative of the government's desire to be guided by the quantum community as it tries to encourage the development of quantum computing.

In a December 20, 2018 article in Forbes, Alex Knapp wrote about the new National Quantum Initiative Act (Knapp, 2018), "On Wednesday, the House of Representatives voted 348-11 to adopt a bill aimed

at accelerating the development of quantum computing. The bill, dubbed the National Quantum Initiative Act, passed the Senate last week unanimously, and President Trump is expected to sign the legislation, which will add the U.S. to the mix of powers such as China and the EU that are pursuing their own coordinated strategies to accelerate this technology."

On December 21, 2018, H.R.6227, the National Quantum Initiative Act, became law (Rep Smith, 2019). The bill defines "quantum information science" as the storage, transmission, manipulation, or measurement of information that is encoded in systems that can only be described by the laws of quantum physics. It directs the National Science Foundation to award grants for Centers of Quantum Research and Education. A search for NSF grants begins on the NSF web site's Funding page (NSF, 2019). From there, the "Browse Funding Opportunities A-Z" link will access a list of quantum computing funding possibilities:

- **Q-AMASE-i** - Enabling Quantum Leap: Convergent Accelerated Discovery Foundries for Quantum Materials Science, Engineering and Information (Q-AMASE-i)
- **QCIS-FF** - NSF Quantum Computing & Information Science Faculty Fellows (QCIS-FF)
- **QII** - Enabling Quantum Leap: Quantum Idea Incubator for Transformational Advances in Quantum Systems (QII - TAQS)
- **QLCI** - Quantum Leap Challenge Institutes (QLCI)
- **Quantum** (general)
- CISE-MPS Interdisciplinary Faculty Program in Quantum Information Science
- Enabling Quantum Leap: Convergent Accelerated Discovery Foundries for Quantum Materials Science, Engineering and Information (Q-AMASE-i)
- Enabling Quantum Leap: Quantum Idea Incubator for Transformational Advances in Quantum Systems (QII - TAQS)
- Ideas Lab: Practical Fully-Connected Quantum Computer Challenge (PFCQC)
- NSF Quantum Computing & Information Science Faculty Fellows (QCIS-FF)
- Quantum Information Science
- Quantum Leap Challenge Institutes (QLCI)

Each of these links will access further information about the research opportunity, including specific requirements, amounts, and dates. There is also a "Find Funding" link which provides a keyword search facility. On February 17, 2019, the word "quantum" returned 37 active funding programs. One would expect that in the coming months, the National Quantum Initiative Act will add to the funding opportunities already available for quantum computing research. The federal websites should be closely monitored for these opportunities.

Appendix B - QC Science Kits

These QC Science Kits include:

- IBM contributed and moderated community project Quantum Information Science Kit (QisKit) available at <https://github.com/qiskit>
- Quantum Toolbox in Python (QuTIP) moderated by QuSTaR (www.qustar.org)
- Investigated Rigetti's SDK package, with focus on its Python pyQuil package and Quantum Virtual
- Machine (QVM), which is an open-source implementation of simulator as a quantum abstract machine (QAM) using classical computer hardware.

In addition to Quantum Computers, we used multiple Quantum Computing simulators provided by IBM:

- The 32-qubit IBMQ-QASM-Simulator via IBM Cloud

- Custom deployed HPC-Quantum-Simulator and made it available for students with the goal to help them avoid job-queue wait times for having their code be processed by IBMQ devices. We have custom implemented this simulator using a large-size virtual machine, available 24/7 for students use.
- Local simulators available within QisKit, such as simplified traditional simulator and the experimental release of the QisKit Aer high-performance simulator framework

Appendix C - JupyterHub

The benefits of JupyterHub type deployment of the teaching environment were the following:

- Leveraged enhanced IDE using JupyterLAB and a number of extensions, such as Google Drive, Github and other plugins.
- We have pre-installed multiple Quantum Computing Science Kits, such as QisKit, QuTIP and others.
- We have pre-installed additional required python libraries, such as matplotlib draw, latex draw, IBMQ provider, PDF exporters and other circuit visualization add-ons.
- Simplified faculty's work to assist and help students with their Jupyter notebooks, python programs and code artifacts. This platform empowered students become self-sufficient with QC science kits, creating quantum circuits and developing programs for implementing specialized algorithm in context of the studied class topics.

Appendix D - IBM Composer

The benefits of IBM Composer used with the high school teaching environment were the following:

- IBM Composer is all on the web, so it took only the one step of having the high school technical support security policy decision maker to make the URL available. The students could get hands-on with the tool right away after IBM registration, which took only minutes.
- IBM Composer includes descriptions of the gates, includes QASM, and includes a diagram of the arrangement of the qubits in the quantum computer being programmed. The User Interface is intuitive, at least, to a high school student. Well-placed error messages, such as a reminder to save the program before running it, pop-up to assist.
- Quantum programs written in IBM Composer can be run on either real quantum computers or on the simulator. Sometimes at periods of high traffic, the real quantum computers delayed giving their results by a few hours or a day. Also, on common programs (such as those following the online IBM Composer tutorials), an option to accept the results of previous identical code that was run on the quantum computer, that is still in cache, will be offered. Simulator results are instantly delivered. For the classes given to the high school students, running the programs on the real machine were limited to where it made a significant difference in the results. The simulator also offers a range of configuration options and that can be designed by the student to try different ideas.