Teaching Quantum Computer Engineering: Practical Exercises Using the IBM Quantum Experience

Shellee Dyer

Dr Shellee Dyer is currently an assistant professor of electrical and computer engineering at Weber State University. Prior to that appointment, she was a senior engineer at NIST, where she conducted research on single-photon detectors and quantum entanglement. Her current research interests include quantum computers, lasers, fiber optics, and fiber optic sensors. and racial, gender, and disability equity in STEM education.

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Shellee Dyer

Department of Electrical and Computer Engineering

Weber State University

shelleedyer@weber.edu

Abstract: Quantum supremacy, the significant edge that quantum computers have compared to classical computers for some specialized problem sets, was recently demonstrated. Quantum computing has the potential to render our current standards of encryption obsolete, as well as the potential to revolutionize other computing problems. In this paper, I summarize my work on developing a quantum computer engineering course for senior- and master-level students. This was a challenging course for both the students and instructor, as we only had a single semester, and students had no prior background in quantum mechanics. We used the IBM Quantum Experience to give the students hands-on experience. This was essential to helping the student grasp the quantum concepts, which are often non-intuitive.

INTRODUCTION

This paper summarizes our efforts to develop a new quantum computer engineering course to serve as a technical elective for our senior-level and master's-level electrical and computer engineering students. The course was first offered in Spring semester 2022 and will be offered again in Spring semester 2024. We were able to offer our students hands-on programming experience using the IBM Quantum Experience, which offers access to multiple few-qubit quantum computers, as well as a quantum computer simulator [1].

The computing power of classical computers is rapidly approaching the long-anticipated end of Moore's law [2], a prediction of doubled microprocessor performance every two years. Historically, this increase in performance has been achieved by reducing transistor size, but as those dimensions rapidly approach the size of a few atoms, it is clear that future significant size reductions are unlikely.

One possible solution is quantum computing, particularly for niche applications, such as factoring large numbers and searching large databases. However, quantum computers are based on a new paradigm of computer architecture, and this necessitates a ground-up approach to teaching the material. Students are accustomed to thinking of classical bits that assume discrete on/off states and never a superposition state. However, in harnessing the power of the superposition state of qubits, quantum computers can solve some classes of computing problems significantly faster than classical computers. One important example is factorizing large numbers. Current encryption schemes are based on the products of large numbers, and the fact that factoring such large numbers with a classical computer is impractical. Shor's algorithm offers a quantum computing approach to the problem that offers the promise (and threat, depending on your point of view) of quickly unencrypting all private information, given a quantum computer with sufficient state space to tackle the problem.

BACKGROUND OF INSTRUCTOR

My own interest in quantum computing began while working at NIST. My quantum work there began with developing and characterizing entangled sources and high-efficiency superconducting nanowire single-photon photodiodes. I collaborated on a quantum teleportation experiment [3], as well as on a Bell state experiment that was free of all major loopholes [4]. That Bell experiment, combined with similar results from two other research groups who published at nearly the same time, was revolutionary because it finally settled the local realism versus quantum theory debate that began with many discussions about quantum theory between Einstein and Bohr. Einstein believed that some hidden variables were responsible for the measurement outcomes observed. By eliminating all major loopholes and showing that Bell's theorem correctly described the observed measurement outcomes, we concluded that, in this particular case, Einstein was not correct, and that quantum theory is a correct explanation of the observed quantum behavior.

STUDENT BACKGROUND

The students were senior- and master's-level electrical and computer engineering students. Their only prior exposure to quantum concepts, outside of popular culture, was in the Physics for

Scientists and Engineers series. That 2-semester course is a standard overview of physics concepts. Our students did have some knowledge of linear algebra from a required math course. Our students are also required to take a one-semester course in probability and statistics, so they had some prior knowledge of those topics. The other pre-requisite for this course is a sophomore-level digital course, and that enables comparisons to classical digital logic in the quantum course framework.

Approximately half the students were Master's level and the other half were seniors in either the electrical engineering or computer engineering program. Out of the 13 students that started the semester, we only had 70% who stayed in the class and finished with a passing grade. Quantum topics are notoriously difficult and counter-intuitive, as indicated by the following quote from John Wheeler: "If you are not completely confused by quantum mechanics, you do not understand it." This was a 3-credit hour course, and we met in-person twice per week on a Monday/Wednesday schedule.

COURSE COVERAGE

We started our semester with a review of linear algebra and probability theory. None of the students had any prior exposure to Dirac's bra-ket notation, so we introduced that topic during the linear algebra review. We then covered bases and the Bloch sphere, quantum key distribution, state spaces, entangled states, measurement of multi-qubit states, the EPR paradox, Bell's theorem, quantum state transformations, quantum gates, quantum teleportation, quantum circuits, decoherence, Shor's algorithm, Grover's algorithm, and the physical realization of a quantum computer. For discussions on the Bloch sphere, I relabeled some globes to demonstrate the effect of standard quantum gates on the quantum state.

My go-to reference for quantum computing topics is "Mike and Ike" [5], but I would not recommend that text as a first introduction to quantum topics. Instead, we used Robert Sutor's book [6], which is written at a level that is accessible to students who have no prior background in the topic. That book does not have many homework exercises, so I had to write many of my own homework problems, a time-consuming endeavor.

QUANTUM COMPUTING EXAMPLES

There are several books that provide quantum computing exercises for the IBM quantum computer; we used Loredo's book as our guide [7]. Our first exercise was to use the Hadamard gate to create an analogy to a coin-flip experiment. The quantum circuit and the measurement outcomes are shown in Fig. 1. The Hadamard gate (H) places the zeroth qubit into a superposition state of $|\psi\rangle = \frac{1}{\sqrt{2}}(|00\rangle + |01\rangle)$. After running this circuit on the quantum computer 1024 times, we see histogram plot of measurement outcomes shown on the right in Fig. 1. In each run, the zeroth qubit has 50% probability of measuring as zero and 50% of measuring as one. As is true of a large number of coin tosses, the results from a large number of measurements of a qubit in a superposition state will likely be close to 50/50, as shown in Fig. 1.

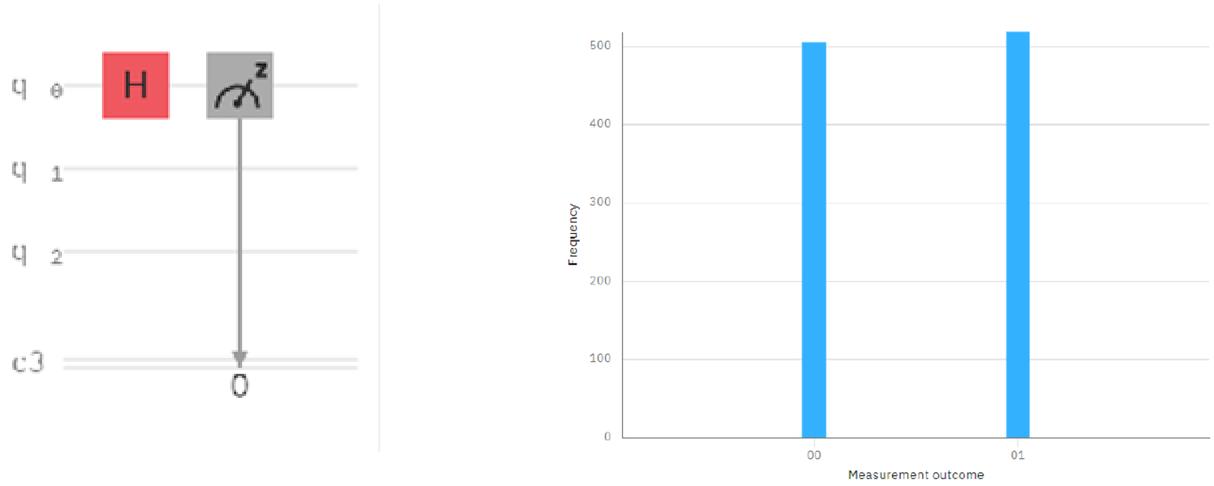

Figure 1. Creating a single-qubit superposition state. The Hadamard gate (H) places the zeroth qubit into a superposition state of zero and one. The histogram of the measurement outcomes after 1024 runs is shown on the right, where the observed histogram is consistent with the expected outcomes of a repeated experiment in which the two outcomes each have 50% probability.

In another experiment, the students used the CNOT gate to create a two-qubit entangled Bell state $|\psi\rangle = \frac{1}{\sqrt{2}}(|00\rangle + |11\rangle)$. The quantum circuit and the histogram of 1024 repeated measurements are shown in Fig. 2. In each measurement, we expect 50% probability of measuring the $|00\rangle$ state and 50% probability of measuring the $|11\rangle$ state, and 0% probability of measuring $|01\rangle$ or $|10\rangle$. However, a small number of measurement outcomes did result in a $|01\rangle$ or $|10\rangle$ state. This is likely a result of measurement noise, so an interesting future experiment would be to increase the number of measurements N and look for the expected $1/\sqrt{N}$ reduction in the noise.

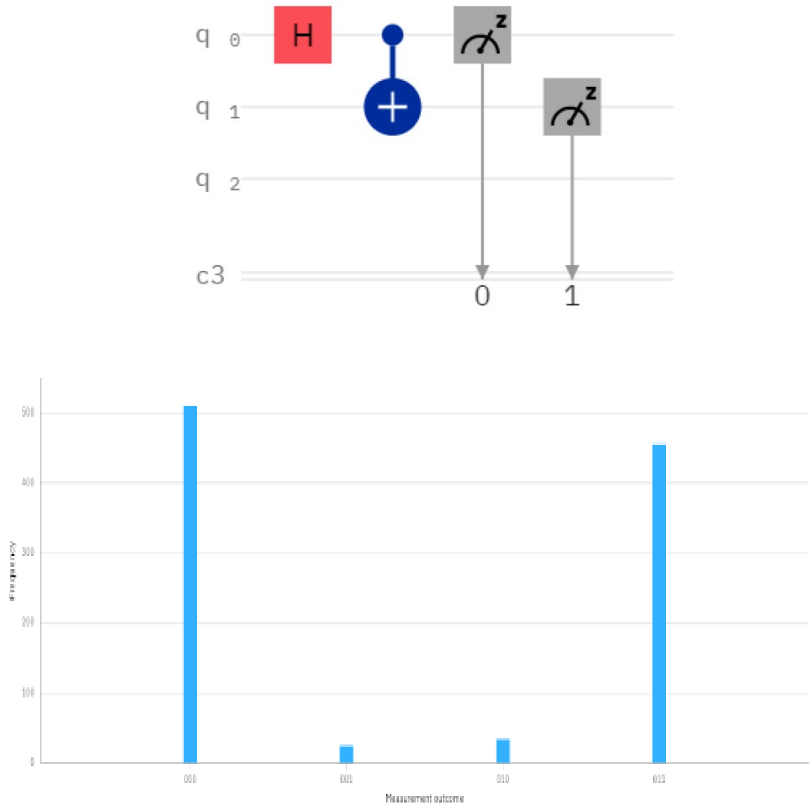

Figure 2. At the top is a quantum circuit consisting of a Hadamard gate and a CNOT gate, which generates a Bell state, and below is a histogram plot of measurement results after 1024 outcomes of the experiment on a quantum computer. We observe the expected Bell state measurement outcomes.

In a more ambitious experiment on the quantum computer, one of my students demonstrated Grover's search algorithm. This algorithm illustrates one of the significant advantages of a quantum computer: the ability to quickly search an unstructured database for a desired outcome. The circuit and histogram results are shown in Fig. 3.

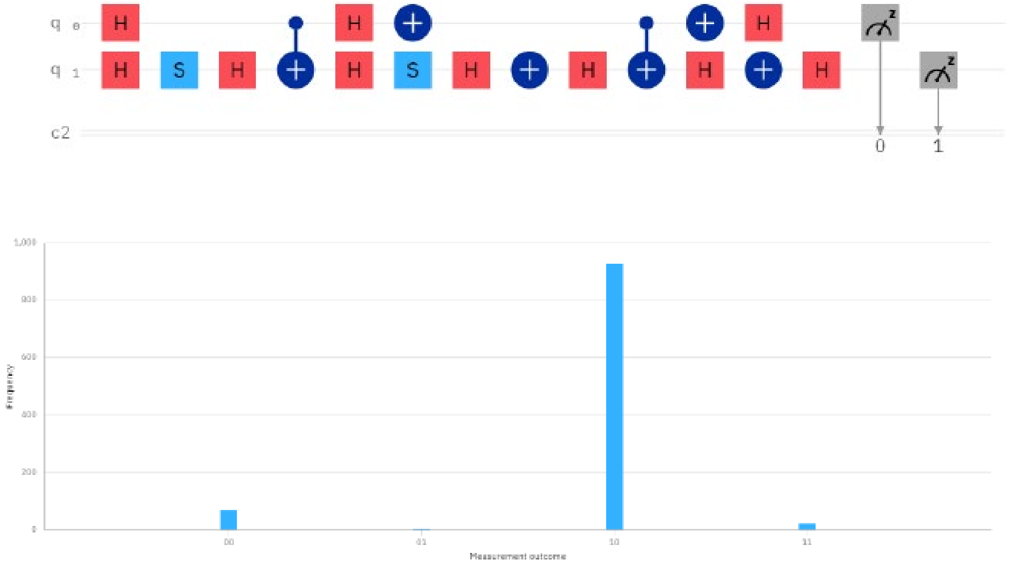

Figure 3. Grover's search algorithm to find the $|10\rangle$ state in a 2-qubit space. At the top is the quantum circuit, and below is the histogram of measurement outcomes for 1024 runs of this measurement.

CONCLUSIONS AND FUTURE WORK

This paper summarizes the creation of a new quantum computer engineering course using an open access quantum computer to facilitate learning. Based on the results from teaching the first semester of this course, I plan to refine and improve the overall course. One key goal is to incorporate more hands-on exercises with quantum computers. The graduate-level students were required to complete more computing exercises compared to the senior-level students, and the feedback from the graduate students was that they understood the concepts better after performing the exercises. My hope is that more hands-on practice with quantum topics will increase the rate of student persistence in the course. Other improvements planned include incorporating more clicker-style interactive questions. These interactive clicker questions are a hallmark of my classes, and one student recently described the questions and resulting discussions as, “the best part of my school day.” I hope that more interactive discussions will improve students’ understanding and persistence in the course.

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