An Introduction to Quantum Computing - Teaching the Basics

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Abstract. Quantum computing, a field that gained increased traction around 2016, utilises principles of quantum mechanics from the early 1900s to compute with quantum phenomena rather than the random simulations of classical computers. This interactive presentation introduces quantum computing to people without a background in computing or quantum mechanics. It compares classical logic gates and circuits to quantum ones to build understanding. The session covers set theory and probability as steps toward quantum states and Bloch spheres. It concludes with quantum circuits and simple algorithms, utilising hands-on examples to demystify quantum computing, enabling attendees to grasp its core principles and potential. This introductory course is drawn from the Full Stack Quantum Computing course offered at the School of Electrical and Information Engineering. For more information on the course, please contact us.

1 Introduction

Quantum computing is an emerging and rapidly advancing field at the intersection of physics, mathematics, and engineering [1, 2]. While current hardware has experienced significant growth over the last few decades, including an increase in the number of qubits, the development of cloud-based computing capabilities, and the proliferation of quantum computing (QC) approaches (e.g., ion-based, superconducting qubits, and photonics), most current systems remain noisy. Nonetheless, certain classes of computations can already be implemented through near-term intermediate-scale quantum (NISQ) computing [3]. Significant advancements are also being made to overcome the limitations caused by noise, aiming toward fault-tolerant (i.e., error-free) quantum computing architectures that fulfil all the necessary requirements [4].

As quantum computing begins to reshape both academic research and industry applications, especially in areas requiring high-performance computation, it becomes increasingly essential to integrate quantum computing into education and training pipelines to ensure a workforce that is prepared to make use of this technology [5]. This is crucial, as the technology is rapidly maturing, and many companies are already defining strategies to harness its potential once it reaches commercialisation and industry adoption [6]. Therefore, early integration of quantum computing across various domains not only accelerates learning and preparation but also helps cultivate future experts who will drive developments once the technology matures.

A common misconception is that quantum computing is reserved exclusively for physicists or domain experts in quantum science. However, many of its fundamental components, such as quantum circuits and gates used to control qubits, have clear parallels to classical logic gates widely taught in computer and electronic engineering. For example, operations like addition and multiplication can be taught using quantum circuits in a manner conceptually aligned with Boolean logic, making them highly accessible to electronics students [7]. (Note that the full adder is a common exercise in the early training of electronic engineers.) This overlap offers a powerful opportunity: by leveraging pre-existing knowledge in logic design, digital systems, and linear algebra, quantum computing can be taught more intuitively. Similar analogies can be drawn in other fields.

Furthermore, quantum phenomena such as superposition and state collapse, often viewed as abstract or esoteric, can be made more accessible through the lens of time-varying signals, probability theory, or stochastic analysis. These are concepts well established in engineering, statistical sciences, and financial modelling curricula [8, 9]. By drawing these connections, educators can present quantum computing in a relatable and structured manner, thereby demystifying the subject for non-physics students across various disciplines.

In this work, we outline a proven approach to teaching quantum computing in a relatable manner, utilising concepts already familiar to students from various disciplines. We describe how this method has been implemented with senior undergraduate students, detailing the strategies and tools used to bridge classical knowledge with quantum principles. We encourage course coordinators and presenters to draw from this work and adapt it to suit their environment and teaching style.

2 Literature review

2.1 Fundamentals of Quantum Computing

There are some new concepts in quantum computing that students are unfamiliar with. Each concept will need to be developed individually to create a foundation that enables students to learn quantum computing. The basic concepts featured in this paper are the block sphere, superposition, qubits, entanglement, quantum gates, circuits, measurement and quantum states.

2.2 Teaching Methodologies

The primary output of this paper is to describe a method for designing a curriculum for beginners in quantum computing. Your role as educators and researchers is crucial in this process. The outcome should be an introductory course that prepares students for more comprehensive quantum computing courses. The methodologies employed are chosen to build on students' current understanding and ease students into the new concepts [10]. Fundamental teaching concepts applicable include the use of visualisations and simulations, interactive tools [11], hands-on experiments [12], and reinforcement using existing knowledge [13].

Using established methodologies, the paper will introduce quantum computing concepts by employing simple electronic circuits and binary logic gates to draw parallels and describe the differences between quantum gates. Physical devices and student participation build the bridge between classical binary computer architecture and quantum computer architecture. Once these concepts are established, the discussion shifts to focus on quantum computing, mathematics, and quantum algorithms. The introductory course should conclude with access to materials, software programming platforms, and quantum computers, some of which are suggested below.

2.3 Educational Tools and Resources

Several disciplines are used to develop an understanding of quantum computing. In classical computing, these include electric circuits, logic gates, logic gate circuits and classical algorithms. In quantum computing, these are the block sphere, quantum gates, and quantum circuits (algorithms). Course development would need to delve further into quantum physics to explain theories behind entanglement, polynomial equations, noise and fault tolerance, and quantum algorithms. Fundamental mathematics, including different base number systems, probability, and linear algebra, will be beneficial.

To enhance the impact of the teaching methodologies, relevant aids such as access to the latest technologies, publications, textbooks, interactive online workshops, and artificial intelligence tools are necessary (Kumar, 2024). Quantum computing is a relatively new subject. Hence, access to material is predominantly online. However, several fundamental literatures introduce the subject. For instance, 'Introduction to Classical and Quantum Computing' provides a comprehensive overview of both classical and quantum computing, while 'IBM

Qiskit'[14] is a popular software platform for quantum computing. 'Learn Quantum Computation Using Qiskit' [6] is a practical guide to learning quantum computing, while 'Dancing with Qubits' [15] offers a more conceptual approach. 'Learn Quantum Computing with Python and IBM Quantum Experience' [16] is a resource for learning quantum computing through programming. These resources offer a comprehensive basis for teaching an introductory course in quantum computing.

Due to the nature of quantum computing, it can impact many industries and disciplines; therefore, discipline specific material should be sought. Quantum computing is presented as an alternative to classical computing, offering speedups and the ability to process multiple possibilities simultaneously [17]. Topically, current quantum algorithms offer data searching, number factorisation, optimisation, machine learning, and linear algebra operations [18]. Each of these has a basis in established classical computing environments and offers quantum solutions.

Fundamental to ensuring courses are current and informative is feedback. Several teaching techniques offer presenters valuable insights to enhance their presentations, including typical surveys, quick online quizzes (such as Kahoot), and assignments. Furthermore, there are many online resources, such as YouTube and Qiskit, that course developers can use to teach the principles.

In conclusion, the comprehensive bodies of knowledge discussed above collectively support the journey of introducing quantum computing. Course developers may not be experts in all these disciplines and may require colleagues to assist in teaching the different subjects. The following sections provide brief examples of how these disciplines can be applied to teach quantum computing to students across various disciplines. It has been successfully used in physics, engineering, applied mathematics, computer science, molecular chemistry, and general quantum computing outreach programs.

3 An introduction to quantum computing using established disciplines

This section focuses on presenting key concepts that guide students on their journey to understanding quantum computing. The course begins by introducing students to the physical structure of quantum computers, establishing the principles behind classical computing, and outlining the principles of quantum computing, while highlighting the comparisons and differences between the two computing sciences.

3.1 What do quantum computers look like

Course developers can draw on the multitude of web-based and literature-based pictures of classical computer chips, quantum chips, quantum computers (the pioneers), and quantum computer fridges. The key concepts include the types of superconductors and semiconductors used, refrigeration, and the physical mechanisms by which noise is reduced. Often, what helps is the analogy of old radio signals gathering more static as radio receivers are taken further from transmitters, or how video becomes pixelated if devices struggle to render the videos at high resolution. These analogies are useful in explaining the concept of noise and its impact on quantum computing systems, providing a foundation for discussing noise and fault tolerance later in the course.

3.2 Background mathematics and statistics

The basic Full adder is a convenient tool to introduce the similarities between classical and quantum algorithms. However, to understand the algorithms, the presenter must work through decimal (Base 10) and binary (Base 2) number systems—several resources that teach the subject, such as Number Systems and Binary Codes [19]. Presenters should work through conversions from decimal to binary, followed by simple addition examples to familiarise the students with binary number systems. This provides the background for the next section, where electronic circuits, gates, and binary decision-making are explained.

The following section introduces the working of quantum computing and relies on a fair understanding of Set theory and probability. Again, several easy web-based tools teach the subject.

3.3 Electronic circuits, gates and binary decision making.

The key concept of this section is establishing the binary concept in decision making. Sampled yes/no questions and decision trees generally establish the principle. The next step is to establish a similarity with a simple single off/on switch and light bulb circuit. This analogy leads to the concepts of electric power supply on and off, and how classical computers rely on voltage to represent ones and zeros in data.

The simple circuit is then developed in circuits with switches in series and parallel, which are analogous to AND and OR gates. Once these concepts are understood, students should be introduced to the full set of logic gates.

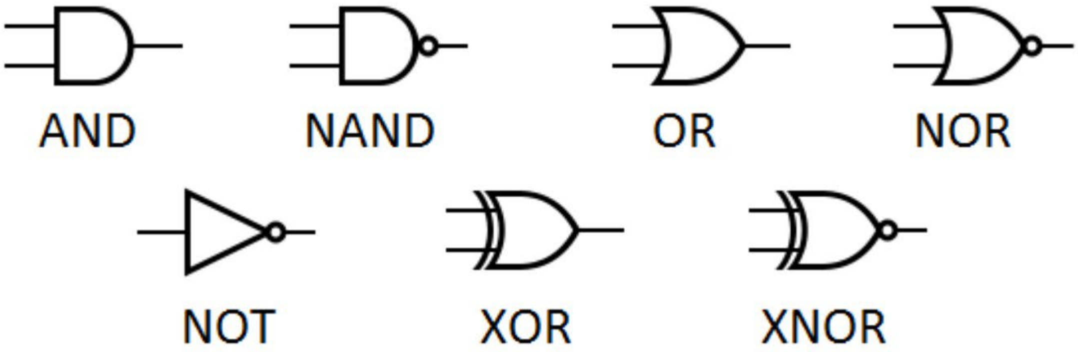

Figure 1: Classical gates [20]

A good example illustrating the concept of circuits as a combination of logic is the full adder and its quantum equivalent.

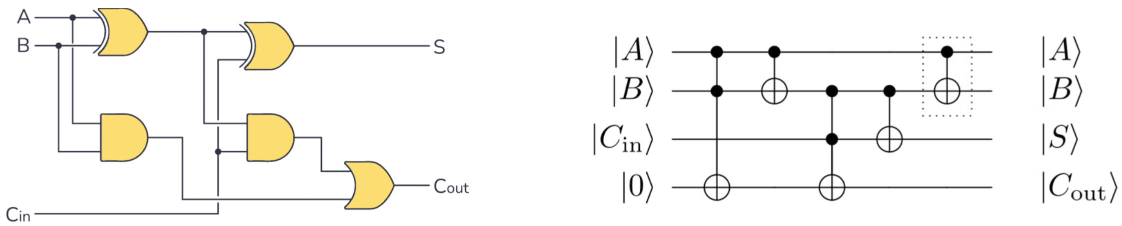

Figure 2: *(left)* Classical Full Adder [21]. *(right)* Quantum full adder [22].

A sample mathematical addition of two numbers can be worked out in front of the class. Depending on the progress, the presenter can show the sample with the quantum full adder circuit or opt to continue with the quantum gate section (below) before working through the quantum full adder circuit. Showing the circuit now (no need to explain the workings) shows students the similarities and differences between classical and quantum computing.

3.4 Block spheres, quantum gates, and quantum circuits

The section starts introducing students to the fundamentals of quantum computing. Superposition is generally explained with Schrodinger's cat example. Presenters can go through the example; however, a plasma ball provides a more engaging and interactive tool. Special attention should be placed on the Hadamard gate. Presenters can show multiple (all) possible solutions (superpositions) and, when describing how quantum gates work, point their finger around the ball to explain how the quantum gates work.

Students should be ready for their first quantum circuit. A simple five qubit circuit (figure 4) demonstrates a five sided dice. Five sides are chosen since there is access to 5 qubit quantum computers, and it is not easy to visualise a five sided dice. Presenters can choose five students to be "qubits" and have them randomly select either zero or one (by raising or lowering their finger), thereby adding up the qubit outputs.

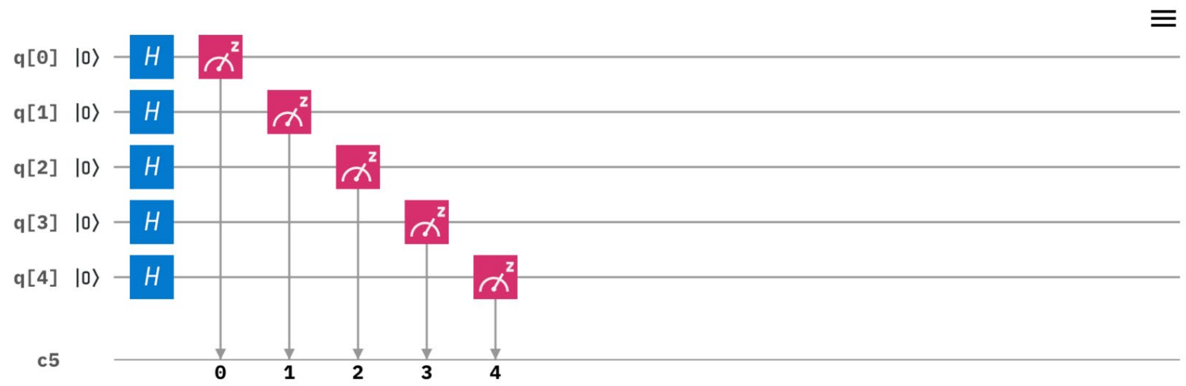

Figure 4: A simple five qubit circuit for a five sided dice

3.5 First complex Algorithm – Grovers

Grover's algorithm is a good first complex algorithm to teach students. The concept of the speed of finding data is easily explained using a book, which illustrates how classical algorithms examine each page and word until they find the solution. Grover's algorithm, on the other hand, will look at all the pages at once.

Grover's circuit provides a good standard for demonstrating oracles and how qubit flipping and phase changes (i.e., the quantum gates) manipulate data, even though the circuit and the gates do not resemble classical circuits.

4 Recommendations

This paper in the education track may differ from others in that section 3 describes a teaching method. Results are an ongoing process where presenters will learn from feedback and craft their presentations to suit their students. Several recommendations are available to enhance this introductory lesson. These include developing the interactive and descriptive tools. Videos showing the full adders, other circuits, block spheres, and the mathematics as the algorithms run will bring together various views of understanding circuits.

A second part of the instruction can delve into linear algebra to show how the gates manipulate data. Presenters can further the introduction with Qiskit [23], MATLAB [24], Python [25], and AI [26] to generate quantum circuits and algorithms.

These fundamentals lay the groundwork for introducing other quantum phenomena, such as entanglement, polynomial speedup, and a discussion of other key algorithms that offer a quantum advantage.

5 Challenges and Future Directions

Quantum computing has some difficult concepts to embed with nonphysicists. However, it is an emerging technology that has global impact. Many institutions cannot afford to house quantum computers; hence, fundamental teaching like this and cloud access are essential. Presenters should take on the challenge of using this article as a platform to design courses that suit their environments. AI offers tools that simplify video making to demonstrate further concepts, such as block spheres, bra-ket linear algebra, and gates in circuits. Presenters can adapt the teaching methodologies mentioned here with AI tools to design more in depth courses on quantum computing.

6 Conclusion

The introductory quantum computing course was developed to support the mainstream quantum Full Stack Quantum Computing course at the University of the Witwatersrand. The key takeaways of the course are to introduce the concepts of probability in the context of quantum thinking. Explain the difference between classical and quantum computing, and introduce students to quantum computing through visual aids, class participation and working through common quantum circuits. As a call to action for educators and researchers, it offers a starting point for presenters to develop a teaching program tailored to their teaching style.

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