Quantum Computing for the Faint of Heart

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***Abstract*—The quantum computing curriculum developed in the Freshman Research Initiative at The University of Texas at Austin caters to students who have not yet studied advanced math and science. We lower the barrier to entry by simplifying notation and teaching through application of the concepts, only covering math methods as they become necessary. Physical motivation and simulation connect with students, and embedded examples and practice problems help cement their understanding. Through learning to program in Python and completing creative technical projects, students gain valuable, transferable skills while exploring quantum information and computing.**

***Index Terms*—quantum computing, education, optics**

I. Introduction

In the quantum computing stream at the University of Texas at Austin, first and second year undergraduates learn to apply quantum information and computing concepts in a setting dedicated to experiential learning and research preparedness. The course is part of the Freshman Research Initiative (FRI) which is the nation's largest undergraduate research program at a single university and focuses on integrating teaching with research. The program is divided into "streams" which are class tracks grouped together based on shared aims, topics, and, often, shared teaching staff.

The quantum computing stream is divided into two main classes taking place in the spring and the following fall semesters, with an optional summer component. The spring semester focuses on introductory quantum topics, with an emphasis on states and transformations. The optional summer program is fully lab based, with students using real or virtual quantum optics experiments to build upon conceptual topics covered in the spring semester. The fall semester of the stream covers quantum computing and focuses on programming and quantum algorithms. No prior background in quantum physics, computer programming, or mathematics beyond college algebra is assumed. Although the stream is composed of three semesters, elements of it may be adapted for shorter courses, modules within an existing course, or focused summer programs. For example, we have adapted elements of the stream to form a full-year high school course on quantum computing [1].

The remainder of the paper is organized as follows: Section II gives an overview of the first semester of the course, which focuses on quantum states and their properties. Section III reviews the second semester of instruction, which strongly focuses on quantum computing and related tasks. Finally, section IV discusses the summer program, which falls chronologically between the other two semesters. The entire collection of course materials is available for use on Canvas Commons and at [2].

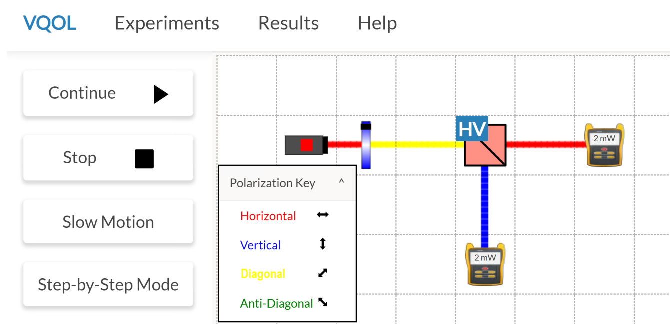

Fig. 1. (Color online) Experimentally verifying Malus's Law in the Virtual Quantum Optics Laboratory [3]

II. Spring - Quantum Information

The first semester of the quantum computing FRI stream revolves around familiarizing students with the properties and manipulations of quantum states. Students develop the ability to prepare arbitrary, single-qubit states using quantum gates, predict the outcomes of experiments on those states, and measure those states in an arbitrary basis. We also emphasize quantum communication protocols including programming and subsequently attacking the BB84 quantum key distribution (QKD) protocol using a model implemented in both Java and Python 3.

Approach

Our approach is built on physical motivation, in-class exercises (often exploratory), and just-in-time math instruction.

1) Physical Motivation: Heavy emphasis is given to exploring the polarization of light through physical implements such as sunglasses (i.e., polarizing filters), LCD screens, laser pointers, and birefringent crystals as well as through online simulation and visualization tools. Polarization makes a good connection point to students, as it builds on familiar topics while also accurately depicting quantum behaviors without employing extended metaphors or abstract analogies.

a) Example Polarization Activity: Students are tasked with exploring polarization and Malus's Law online with the Virtual Quantum Optics Laboratory [3]. The power dependence of polarization angle in Malus's Law (Figure 1) maps directly to the angle-dependent measurement probability of the Born rule.

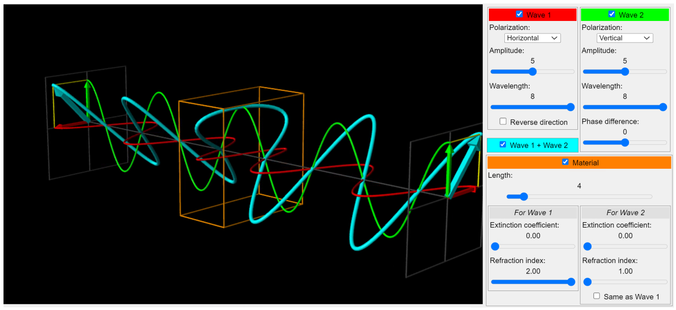

Fig. 2. (Color online) Using EMANIM to visualize a half-wavelength birefringent material acting as a NOT gate for diagonally polarized light. Copied, with permission, from Ref. [4].

b) Example Gate Activity: To build intuition with quantum gates, we again explore polarization with online simulations. Using the EMANIM wave animation tool [4], we visualize a laser's electric field (sinusoidal wave) as it moves through a wave plate in order to connect various transformations to physical processes that implement those transformations, as shown in Figure 2. Next, students use the Virtual Quantum Optics Laboratory [3] to find the characteristic wave plate angles associated with particular transformations. In completing these activities, students build a reference table which serves as an anchor point for future quantum gate problem solving.

2) Specific Approaches: In-Class Exercises and Just-In-Time Math: One needs certain mathematical tools to describe quantum states, and students need to be taught to use those tools. The prerequisite math experience for traditional quantum science courses may be intimidating and limit access. Widely adopted introductory texts often dedicate significant space to background math [5]. In order to cater to early undergraduate and high school students we avoid much of the foundational math in favor of introducing mathematical tools only when necessary and only as an integrated part of a larger lesson.

a) Dirac Notation: Rather than presenting quantum states in the context of partial differential equations, we represent states as vectors using bra-ket notation. Students are often familiar with the idea of vectors from their earlier science and math classes, and two-component vectors (representing a single, pure-state qubit) are sufficient to draw connections to the laser polarization states students have been using in class.

b) In-Class Exercises: Importantly, our lessons are not uninterrupted lectures but are instead a series of short explanations interspersed with practice and exploratory exercises. We aim to include an exercise within the first five minutes of class in order to engage the students with the subject and then to have at least two more exercises embedded in the lesson. These have the dual purpose of allowing individual assessment and feedback between the students and instructors and also giving the students a mental break to change pace and reengage with the material.

c) Just-in-Time Math: As much as we try to avoid requiring advanced math, some quantum information concepts can be understood much more clearly with the appropriate mathematical tools in place. However, we strive to teach math as it is needed rather than front-loading the instruction or requiring it as prerequisite.

Matrix multiplication, inner products, outer products and Kronecker tensor products are all used in qubit manipulation. Each of these is first introduced in the context of a physical representation from a previous lesson. For example, multiplying matrices is shown after students have already explored and understood transformations as optical gates. Inner and outer products are explained as both special cases of matrix multiplications and as interesting ways to work with bra and ket vectors, and students work out the properties of tensor products through a series of single-qubit operations before being shown the general formulas for working with multiple qubits. In every case, the math is relevant to the conceptual focus of the lesson.

III. Fall - Quantum Computing

The second semester of the quantum computing FRI stream focuses much more directly on computing. Students learn Python 3 programming while implementing popular and foundational quantum algorithms with Qiskit [6]. We discuss other aspects of practical quantum computing, such as theoretical complexity and metrics of performance, and we host a class hackathon and a final project to continue developing the students' creativity and research abilities.

Approach

The second semester reviews slightly some of the material from the spring semester but assumes basic knowledge of quantum states and gates. We use Python programming to teach students to actually implement the quantum algorithms and empower students to explore with visualizations. In-class exercises are included throughout our instructional Python notebooks, which also serve as the "lecture notes" for the class.

1) Interactive Python Notebooks: An important aspect of the class, most of the material is presented in interactive Python notebooks (.ipynb files), so we can seamlessly combine lesson notes, practice problems, demonstrative code and calculations, and graphics and visualizations into a single document. Notebooks are divided into cells, each of which either executes code or displays plain text. As seen in Figure 3, using cells of different types, practice problems are nested within the notes just beneath the relevant topics. Students are encouraged to add to or customize the notes as well as the code cells. We use Markdown and LaTeX for lesson notes and organization. Graphics are included either embedded or in the Markdown cells. Python 3 cells contain examples of calculations, algorithm implementations, and visualizations.

2) Hackathon and Final Projects: Alongside the implementation of quantum algorithms, students complete two major projects during the semester. One is a creative hackathon with some theme, and the other is a final research project. These projects encourage students to expand the limits of their quantum computing understanding through open exploration and creativity. Students must take the knowledge they have

Grover's Search Algorithm for M Solutions

1) Start with an n-qubit input and 1-qubit output register.

$$|0\dots0\rangle|0\rangle$$

2) Apply a NOT and then Hadamard to the output register.

3) Apply Hadamards to the input register.

4) Do the following R times, where $R = \lfloor \pi\sqrt{N/M}/4 \rfloor$

a) Apply the oracle $\mathbf{U}_f$

b) Apply $\mathbf{W} = -\prod_{i=1}^{n} \mathbf{H}_i\mathbf{X}_i \ \mathbf{C}^{\mathbf{Z}}_{n\dots21} \ \prod_{j=1}^{n} \mathbf{X}_j\mathbf{H}_j$ to the input register

5) Apply a Hadamard and then NOT gate to the output register.

6) Measure the input register; the result is most likely one of $a_1, \dots, a_M$.

Exercise 1

The oracle $\mathbf{U}_f = \mathbf{C}_{210}\mathbf{C}_{310}$ has $M = 2$ solutions.

Implement Grover's search algorithm on $\mathbf{U}_f$.

What values of a do you find?

Answer

```
[ ] U = QuantumCircuit(4)
    U.ccx(3,1,0)
    U.ccx(2,1,0)
    U.draw('mpl')
```

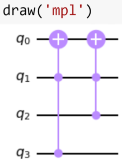

Fig. 3. An .ipynb notebook allows for exercises and coding practice embedded into lesson notes.

gathered from the two semesters to synthesize something entirely new.

The hackathon serves as the mid-semester project. It involves one class period dedicated to planning and programming, followed by some period of time (usually two to four weeks, depending on the university schedule) for students to work outside of class. Finally, the class dedicates another period to presenting and trading feedback on the projects. Hackathon themes in the past have included building quantum computer games [7] and speed-implementation of quantum algorithms with another quantum library such as Q# [8].

The final project assigns students to explore some topic of quantum computing more deeply. We suggest a series of topics, and the results often take the form of a creative programming project or a review and re-implementation of some recently published research. This provides structure for students who want a straightforward assignment while also broadening the scope of the project to encourage motivated students to flex their creativity.

IV. Summer - Optics Programs

The optional summer program occurs between the first and second semesters and offers students the opportunity to directly apply the quantum information concepts they have just learned in the spring to a real-world setting. The summer program is divided into two sections — an in-person optics lab and a virtual optics lab. In both sections, students perform

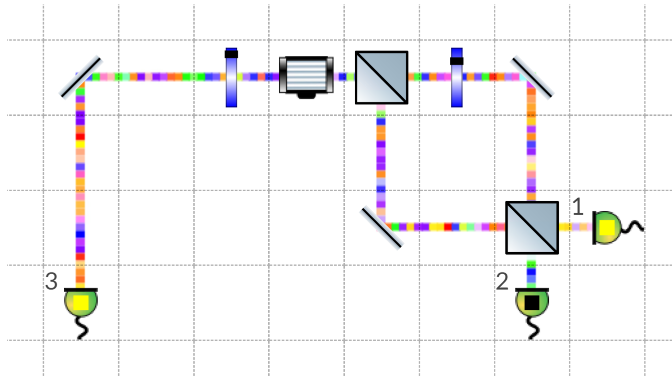

Fig. 4. (Color online) An entanglement source and Mach-Zehnder interferometer are modelled in order to study the delayed choice quantum eraser experiment in VQOL.

a series of classical and quantum optics experiments and learn to analyze the results of the measurements they make.

Approach

The teaching approach in the laboratories is anchored in giving just enough instruction for the students to start without providing step-by-step guidance on how to perform the experiments. The general theory and setup of the experiment is provided, but the particular measurements to make are left for the students to explore and decide for themselves.

The Virtual Quantum Optics Laboratory [3] is used by students in the lab programs to prototype and conduct experiments. The in-person lab students often build optical setups in VQOL to provide a prototype and diagram to which they can refer while constructing the apparatus on the optics table. The virtual students take this a step further by collecting data from a series of VQOL experiments and analyzing it to compare with theory. As in the spring semester, students begin with Malus's Law and the Born rule and progress toward more involved interferometry and entanglement experiments like the quantum eraser setup shown in Figure 4.

V. Conclusion

The quantum computing course developed as part of the Freshman Research Initiative at the University of Texas at Austin specifically targets early undergraduates by focusing on active learning and the incorporation of practice into exposition without an emphasis on mathematical prerequisites. We introduce topics and then challenge the students to explore through simulation and experimentation alongside traditional instruction. By focusing on experiential learning and giving students tools as they need them, we open the opportunity to offer the advanced topic of quantum computing to first and second year students.

VI. Acknowledgements

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