Quantum Computing for Undergraduate Engineering Students: Report of an Experience

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***Abstract*—This paper presents the experience of a Quantum Computer course addressed for the first time for undergraduate engineering students. Students' levels varied from year two to five of their careers and had previous knowledge on Calculus, Linear Algebra and Programming, but not on Quantum Mechanics or on Modern Physics. The main objective of the course was that students acquire programming skills in Quantum Computing, so it had a practical approach. Instead of beginning by introducing the physical phenomenology under the field, the course started directly with presenting the logic of quantum computing from an abstract point of view. The language used was Q#. The curricula was based on the one available for the Microsoft Quantum Network.**

Keywords—Quantum Computing, Education, Quantum Workforce, Undergraduate Engineering Education.

I. Introduction

It is well known that Quantum Computing (QC) will soon require skilled people and there is an active quest to create a quantum Smart workforce [1]. The discipline has garnered a lot of attention from academia, governments, industry, and individuals. Quantum computing will be part of people's lives in a few years from now.

The discipline was born from Physics and Mathematics. For this reason, the first experts came from the academy and from these specific branches. For a few years, QC moved towards the informatics area. There are online platforms through which professionals and students can work online. To name a few, IBM's Qiskit [2], D-Wave's Ocean [3], Microsoft's Q # [4] and AWS Braket [5]. IT professionals are increasingly related to the area and taking a leading role.

However, due to the great role that QC is expected to have, the need to create a much larger workforce than the current one is recognized [6]. The need for it to be more diverse has also been emphasized [1].

A. Previous Experiences

In recent years, the offer of QC courses to graduate students has been relatively common. Plunkett et al. [7] includes a list of master's degrees in the field, as well as courses in QC in the context of master's degrees in other fields. The programs included are located in developed countries such as USA, United Kingdom, Germany, Spain and Australia.

A list of universities with research groups in the field can be found at [8]. Noticeable, most of those universities are also in developed countries.

Westfall and Leider [6] recommend teaching QC in honors level high school (junior or senior). In the same direction, Angara et al. presented experiences of teaching QC to high school students [9], while Pashaei et al. reported teaching to even younger students from primary school [10].

Plunkett et al. [7] include a listing of resources available for professionals willing to increase their knowledge in the field.

Although [11] presents a methodology for teaching quantum computing to undergraduate level students, there are few reports of QC teaching for undergraduate students.

B. A classification of Quantum Workforce

In order to determine the knowledge and skills that a subject has in the field of QC, we find it is useful the classification introduced by Frantz [12]. Frantz classifies quantum workforce in five categories, as seen in Table I.

TABLE I. Clasification of Quantum Workforce by Knowledge

Category	Description
Quantum Curious	Individuals who are just asking the very basic about QC
Quantum Explorer	People who start exploring some concepts of QC
Quantum Climber	People who decides to get educated on the subject of QC
Quantum Enabled	Individuals familiar with the syntax of QC languages and platforms
Quantum Ready	People who understands and can write quantum circuits and understands complex algorithms
Quantum Professional	Individual with knowledge and skills to reach the market

C. About this paper

This paper presents an experience of a QC course carried out in the second semester of 2020 at Universidad de Montevideo, Uruguay, with undergraduate students. It has the novelty that it was carried out in a group of undergraduate students from different years. It also provides knowledge of geographic diversity, since for the best of our knowledge it is the first course in its kind to be taught at a Latin American university.

The course was based on the "Microsoft Quantum Curriculum" available for the curriculum partners of Microsoft Quantum Network [13], which the Universidad de Montevideo is a member.

We think our course has left students, close to the Quantum Ready category after tackling some additional topics, in the categorization depicted in Table I.

The rest of the paper is structured like this:

Section II presents the background of the course, including the characteristics of the group of students. Section III shows the curriculum, including the final projects proposed in the course. Section IV analyzes the experience and its implementation. Finally, Section V brings the conclusions.

II. General Data About the Course

The course was carried out by 25 students. Engineering degrees at the University of Montevideo have a duration of five years and have an important theoretical component in Mathematics delivered mostly in the first two years. Most of the students were juniors and seniors (at their third and fourth year). However, select sophomores (in their second year) were also admitted.

The second-year students had had two semesters of Calculus, two semesters of Linear Algebra, and they were taking Probability and Statistics. Depending on the orientation of each one, they had taken one more course in Calculus or one in Discrete Mathematics. Each of these courses typically has 90 class hours. As for Programming, they had completed an introductory C course, and two Programming courses using Python and Java languages; but never used Jupyter Notebooks before. Also, two courses in Database Design. It is noted that they had a background in Physics, but none of them in Quantum Mechanics or Modern Physics.

The professor responsible of the course was Laura Gatti, supervised by Rafael Sotelo.

The course was delivered in 15 weeks during the second semester of 2020, between Monday, August 10 and Friday, November 20, 2020. It was delivered with two weekly sessions of two hours each. These sessions were for theoretical exposition and practical work.

Due to the COVID-19 pandemic, the course was delivered online via MS Teams.

III. The Course

Universidad de Montevideo is a member of the Microsoft Quantum Network [13]. It is one of fourteen universities in the world teaching the Microsoft Quantum Curriculum [14]. It is a remarkable fact that it is the only one from a Latin American country and from a developing country. This contributes to the geographic diversity of the QC workforce.

Our course was based on the curriculum available to Microsoft Quantum Curriculum Partners developed by Mariia Mykhailova, Senior Software Engineer, Microsoft Quantum Systems [15]. This course was taught for the first time in 2019 and for the second time in the first quarter of 2020 where certain changes were made to the content. Our course is specifically based on that second edition.

However, this course was addressed for graduate students, in the context of a master program. It had a very different time duration structure than was possible in our case. Its concentration of hours and weekly dedication was greater than can be dedicated in a typical undergraduate semester in our university were students attend five to seven courses simultaneously.

Based on the above-mentioned restrictions, the curricula underwent some modifications. Considering that our students had diverse progresses in their careers, and the fact that they are undergraduates and their time availability for this course was limited, it was decided to leave for a later course the treatment of quantum noise, as well as error correction and fault tolerant computing.

We emphasize that the second edition of the original course had just been held in the months prior to the start of our course.

To carry out the course, the set of tools for quantum programming provided by Microsoft (QDK) [4] was used to simulate states and quantum gates. In particular, Q #, Microsoft's own language for quantum computing, was taught during the course.

A. Syllabus

The syllabus of the course was as follows:

Topic 1 - Introduction to quantum computing.

1.1 The qubit vs. the bit. Bloch sphere, overlap, measure.

1.2 Systems of several qubits, tensor product, entanglement, measure.

1.3 No-cloning theorem

1.4 Evolution of systems, quantum gates. Review of normal matrices and their spectral decomposition.

1.5 Introduction to Q#. Implementation of states and gates.

Topic 2 - Simple algorithms

2.1 Representation of quantum circuits

2.2 Teleportation

2.3 Deutsch algorithm

2.4 Extension to the Deutsch-Jozsa algorithm

Topic 3 - QFT, Simon, Phase and Shor algorithm

3.1 Implementation of the quantum Fourier transform for two qubits

3.2 Implementation of the general quantum Fourier transform

3.3 Simon's algorithm and phase estimation

3.4 Shor factorization algorithm, relationship with the RSA system of classical cryptography

Topic 4 - Grover's algorithm.

4.1 Introduction to algorithms by oracles

4.2 Rotation in the solution spaces of a search in unstructured data

4.3 Implementation of the algorithm

4.4 Optimality of search steps

Topic 5 - The reality of quantum computers

5.1 Physical implementations of the qubit

5.2 Limitations

5.3 Industry and associated business areas

The objective of the course was that students acquire programming skills in QC. We wanted them to be confident by the completion of the course on their ability to program, instead of seeing QC just as a theoretical subject. Therefore, we had focus on practice. That is one reason that supported the introduction of the project at the end of the course.

We highlight that these students had no prior knowledge of quantum mechanics, but they had very good training in mathematics and programming. It is very common for courses on quantum computing to begin by explaining the physical phenomenology that explains the logic behind QC. However, we decided not to take this approach, but to start directly with presenting the logic of quantum computing from an abstract point of view.

B. *Assessment*

The evaluation of the course has had two components: (i) deliveries every three classes (that weighted 40% of final qualification) and (ii) a final project (that weighted 60% of final qualification).

Every three classes, the professor proposed a list of exercises that the students had to carry out. These exercises were both programming tasks and theoretical exercises. Every third class was taken as a set-up of the previous ones and discussion of the list of exercises. As the course was held through videoconference, the progress of the students was permanently monitored through quizzes, which were based on the exercise lists. Both theoretical concepts and their implementation in the Q # language were evaluated. Some of these controls made up the final grade, while others were indicators of the individual performance in the subject, just as a feedback for students and the professor. The modality of the exercises varied from individual to group depending on the type of exercise.

The exercises sometimes were different for each student (or group) in such a way as to promote the originality of the solution. Sometimes, some of these exercises were to be solved in class.

After two thirds of the course, the final project to be carried out in groups was proposed to the students. From that moment on, each third class were also dedicated to monitoring the progress of these projects. The final project was evaluated in three ways: (i) through the project progress that the students had to report week by week (30%), (ii) through a speech of the student addressed to the rest of the class in the last week of the course (30%), and (iii) through an individual defense of each student for the group task (40%).

All the course material, the schedule of activities and their monitoring, was available to students on the Moodle platform.

IV. Experience and Results

The course went smoothly.

The theoretical approach that was utilized was to introduce the aspects of quantum mechanics as postulates used a priori. We prioritized an abstract approach to the subject and its mathematical formulation. This was especially convenient for students whose background in linear algebra was strong, recent and fresh. As the concepts were consolidated during the progress of the course, the questions about the physical implementations aroused alone. The last weeks of the course were dedicated to investigate a little more about the physical support that allows the implementation of quantum computing. We emphasize that it was a great success to do it this way for our students, since concepts such as quantum measurement seemed to their eyes much more natural due to the familiarity with its probabilistic formulation of its mathematical representation. The students were able to conceptualize the logical abstraction without the support of physical explanation, and were able to implement programs and algorithms.

A very important tool of the course was the Quantum Katas, a collection of tutorials and programming exercises on quantum computing, provided by Microsoft implemented in Jupyter Notebook. This allowed the students, after addressing the topics theoretically, to practice, either on their own or supervised, on how such concepts could be translated into code; as already said, that was the main objective of the course. The self-corrected exercises were of great help to the students. The brief theoretical description that accompanied each topic helped as summary of what was presented in class.

As said, during the last third of the course, students worked on a project. The project topics were distributed among the students by the professor. The methodology used was continuous correction. The first task consisted of an exploration of the topic, selection of a tentative bibliography, together with the elaboration of a schedule and distribution of tasks among the members of the group. The professor controlled and adjusted the schedule each week according to the progress of each group. This guided the weekly deliveries that were supervised and corrected by the professor. When the task time ended, each group of students had made five exchanges with the professor. The compliance with the agreed schedule was part of the final evaluation.

The objective of the project was the discussion of some aspects of computing that seem counterintuitive with respect to the classical world. We decided to simplify the projects so that the students were able to create the necessary code to run simulations in Q# that would reinforce the theoretical concepts. In this sense, arousing the curiosity of the students was prioritized over the theoretical complexity of the topics.

Some of the topics addressed in the final projects were the following:

- Graph coloring: Use of the Grover algorithm to optimize the assignment of colors to the vertices of a graph.
- Mermin-Peres magic square: A typical example of quantum pseudo telepathy in a Bayesian game in which the players have imperfect information. It is a first approximation to states of maximum entanglement.
- GHZ game (Greenberger, Horne, Zellinger): This is another example of a non-local game, in which players, based on a previously agreed strategy, can obtain a quantum strategy that allows them to beat a referee with 100% probability. Part of the work is to prove the non-existence of such a classically strategy.
- 3-SAT Problem: Given a Boolean expression, it is a question of knowing if there is any assignment of values that makes the expression true. It is the first problem that was proven to be NP-complete. Grover's algorithm offers a quadratic speed-up compared to its best classical implementation.
- Protocol B884: It is the simplest quantum key distribution scheme. It gives a first complete vision of how the physical laws of quantum mechanics allow a secure distribution of private keys over classical channels.

- Superdense code: It discusses how the use of entanglement calls into question the principles of Shannon's information theory, apparently violating the capacity of a classical channel. Like the rest of the projects, it requires the conceptual use of entanglement and brings students closer to the subject of quantum information theory.

The course had some more peculiarities. There were visits from professors and professionals who made an important contribution, each one from the beginning.

The first class received Dr. Salvador Venegas-Andraca from the Instituto Tecnológico de Monterrey, Mexico. Dr. Venegas-Andraca is an outstanding researcher in the field from the Latin American quantum community. He greeted the students live by videoconference; he encouraged them to study in this wonderful and promising field of QC; and encouraged them to create a vibrant QC community in Latin America.

By the end of the course, there was a visit from a physics professor who explained the phenomenology of quantum mechanics that supports QC. Another professor from the university, who also is co-founder of the startup Quantum-South [17], presented the business ecosystem of QC and industrial applications to the students.

Finally, the class received greetings and a special message from Mariia Mykhailova, the original designer and instructor of the course.

Fig 1. Screenshot of the last day class

Second and third-year students, who have had Math courses recently, easily caught the convenience of the Dirac notation and the mathematical formulation of Quantum Computing. On the other hand, students who were close to graduating, many of them with an industry-oriented profile, in general terms better faced the development of the practical projects, while having more difficulties with the formal formulation of the field.

Some significant results of the final survey made to the students showed that:

- 84% considered that their previous knowledge allowed them to properly attend the course.
- The global satisfaction of the students with the course was 4.8 out of 5.

Three of the students are working with our research group after completing the course.

Fig. 1 shows a screenshot of the last class of the course. As said, MS Teams was in use due to COVID-19 pandemia. Students had to follow the course from home. Note happy faces of students and professors.

V. Conclusions

The fact that the University of Montevideo is the only Microsoft Quantum Network university curriculum partner in Latin America is an important component in the search for diversity, particularly geographic and developing country diversity.

The fact that the course was offered during the pandemia of COVID-19 posed additional challenges to the novelty of the course. We believe that the strength of the course was in the chosen methodology of classes and of evaluation, in which a permanent monitoring of the remote activity of the students was held. The criterion of every two theoretical classes having a discussion and problem-solving class greatly encouraged the participation (even in a virtual environment) of the students, involving them with the subject. In future editions of the course, we would increase the practical activities with projects, at the expense of the exposition of the theory, so that the latter does not carry the central role that it had on this occasion.

Engineering students from year 2 to 5 of their careers were able to properly approve the course, acquiring practical skills in programming Quantum Computers. The students had previous knowledge on Calculus, Linear Algebra and Programming, but not on Quantum Mechanics or on Modern Physics.

In our opinion, students in the initial stage of their careers after pursuing Algebra and Calculus can take more profit of an introductory course on Quantum Computing, even awaking research vocations, than those in more advanced stages, which are more oriented to technologies currently in use in the industry.

We found that students approach this field moved by curiosity and a certain halo of mysticism that surrounds the subject. This imaginary of a quasi-magical functioning collapses when faced to the mathematical formulation, strongly discouraging many of the naive curious. The main challenge was to show, even in the most basic formulations, the advantages offered by this theory over classical computing. Elements such as the 3D representation of the Bloch sphere helped to understand the concept of gates acting in the Hilbert space. We found that in this kind of courses it is essential to explain in depth simple algorithms such as Deutsch Jozsa or Grover's, since this allows the students to understand the power of Quantum Computing.

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