Quantum Computing for High-School Students An Experience Report

Prashanti Priya Angara
Department of Computer Science
University of Victoria
Victoria, Canada
pangara@uvic.ca

Ulrike Stege
Department of Computer Science
University of Victoria
Victoria, Canada
ustege@uvic.ca

Andrew MacLean
Department of Computer Science
University of Victoria
Victoria, Canada
andrewdm@uvic.ca

***Abstract*—Quantum computing is an emerging field that can revolutionize our ability to solve problems and enable breakthroughs in many areas including optimization, machine learning, chemistry, and drug design. With the increasing computational power of quantum computers and the proliferation of quantum development kits, the demand for a skilled workforce in quantum computing increases significantly. The theory of quantum computing lies at the crossroads of quantum physics, mathematics, and computer science. The field of quantum computing has matured and can now be explored by all students. While today, quantum computers and simulators are readily accessible and programmable over the internet, quantum computing education is just ramping up. This paper describes our experiences in organizing and delivering quantum computing workshops for high-school students with little or no experience in the above-mentioned fields. We introduce students to the world of quantum computing in innovative ways, such as newly designed "unplugged" activities for teaching basic quantum computing concepts. Overall, we take a programmatic approach and introduce students to the IBM Q Experience using Qiskit and Jupyter notebooks. Our experiences and findings suggest that basic quantum computing concepts are palatable for high-school students, and—due to significant differences between classical and quantum computing—early exposure to quantum computing is a valuable addition to the set of problem-solving and computing skills that high-schoolers obtain before entering university.**

***Index Terms*—Quantum computing, education, training, high schoolers, teachers, workforce development, CS-unplugged, qubit systems, quantum gates, measurement, superposition, entanglement, quantum teleportation, Qiskit, quantum computing games**

I. Introduction

Researchers in education have long advocated teaching computational thinking in all schools [1] and describe it as key skill not just for our 21st-century workforce but for all humans [2]. So far, these skill developments focus on classical computing and do not yet include quantum computing concepts. With recent advances in quantum technology, quantum computing has gained significantly in importance. Governments, funding agencies, and companies are heavily investing in the development of quantum computing today—for both hardware and software [3]–[7]. Many scientists and engineers consider quantum computing as one of the most interesting, exciting, and challenging topics in the fields of computer science and engineering, with enormous potential in a number of application areas [8]. Amin et al. argue convincingly that quantum computing workforce development plans must involve the entire spectrum of an educational system: high-school, undergraduate, graduate, and continuing training programs. This paper presents our experiences in training high-school students in quantum computing as part of the University of Victoria's HighTechU program [9].

The field of quantum computing is not new. In 1981, Feynman encouraged the physics community to build a quantum computer with his famous quote: "Nature isn't classical, and if you want to make a simulation of nature, you'd better make it quantum mechanical, and by golly, it's a wonderful problem, because it doesn't look so easy." After delivering his seminal lectures on 'Simulating Physics with Computers', the field began in earnest with quantum information theory, computing models, and algorithms. Over the next decade, several important quantum algorithms emerged [10]–[17], including Shor's factoring algorithm [18], and Grover's search algorithm [19]. Over the last 15 years, companies (e.g. [20]–[25]) engineered the first real quantum computers and developed quantum development kits (QDK) such as IBM Qiskit, D-Wave Leap, Microsoft QDK, Google Cirq, Rigetti Forest, or Strawberry Fields [26]–[28]. We are now in the noisy intermediate-scale quantum (NISQ) era [29]. NISQ computers have 50–200 qubits; their noise places serious limitations on their capabilities. Recently, software engineers have developed effective hybrid quantum-classical algorithms and platforms to take advantage of the NISQ quantum processing unit (QPU) [30], [31]. The combination of these efforts has created significant opportunities for the current and future workforce.

The field of quantum computing has matured and can be entered by students from a variety of backgrounds. In his book "Quantum Computing since Democritus" [32], Aaronson points out that quantum mechanics, the foundation of quantum computing, "is a beautiful generalization of the laws of probability" and "while quantum mechanics was invented a century ago to solve technical problems in physics, today it can be fruitfully explained from an extremely different perspective: as part of the history of ideas in math, logic, computation, and philosophy, about the limits of knowable."

This paper presents our experience in introducing high-

978-1-7281-8969-7/20/$31.00 ©2020 IEEE
DOI 10.1109/QCE49297.2020.00047

school-aged youth to quantum computing through a one-day hands-on workshop. For participation in our workshops for high-school students, we have no expectations regarding the students' prior knowledge—the workshop does not require a background in quantum computing, quantum physics, quantum mechanics, computer science (including programming and algorithms), mathematical topics (such as complex numbers and linear algebra), or software development environments. We also discuss the design of a two-day workshop[1] that—in contrast to our one-day offering—dives into the linear algebra of quantum circuits, including vector and matrix operations.

The next section overviews relevant literature we consulted while designing our workshop, including quantum computing education and training with a focus on the delivery of quantum computing to youth, computer science unplugged activities (*CS unplugged*), and quantum computing games. Section III discusses the design of our workshops through activities—choosing from best practices, and lays out the developed activities, including activities for a potential new chapter of CS unplugged: *Quantum CS Unplugged*. Section IV describes our experience in delivering our one-day workshop. Section V introduces our proposed two-day workshop and Section VII concludes the paper with lessons learned and an outlook.

II. Related Work

Quantum Computing Education. The Qiskit *Textbook* embodies literate programming [33] and is an evolving online resource with complete Qiskit documentation [34]. It is an introduction to programming using Qiskit on the IBM Q Experience while explaining quantum computing concepts and algorithms. *Coding with Qiskit* is an online series of videos introducing beginners to programming using Qiskit with Python and Jupyter Notebooks [35]. Tappert et al. [36] overview their experience of teaching quantum computing as a graduate course as well as a one-week high-school workshop. For high-school students, the focus was on short lectures followed by hands-on programming utilizing the Composer interface on the IBM Q Experience, to then run their programs on the quantum simulator as well as an actual quantum computer. "Quantum Computing as a High School Module" [37] is a textbook with exercises for teaching quantum computing and serves as bridge between popular articles and undergraduate texts. This work is intended as a one-week course for high-school students. Many exercises are given in the form of practice sheets that can be completed without computers. Billig's textbook on "Quantum Computing for High School Students" [38] introduces mathematical foundations of quantum computing, assuming high-school level mathematics. It intentionally leaves out complex numbers. "Quantum Computing the easy way" [39] is a Udemy course that teaches quantum computing in the form of online lectures. This course introduces the basics of quantum computing and quantum algorithms and is open for students from any background. The material is delivered in terms of PowerPoint slides only and does not involve programming. Barabasi et al. [40] discuss student experiences using IBM's platform in developing games based on quantum randomness. By developing small games, students learn about the differences between classical and quantum computing and understand concepts in an engaging way.

Computer Science Unplugged. CS Unplugged has its origin in the early 1990s and was first publicized via a 1998 manuscript entitled "Computer Science Unplugged . . . off-line activities and games for all ages" by Bell, Fellows, and Witten [41].[2] Today, CS Unplugged is considered an educational method for introducing K–12 non-specialists to computing concepts through hands-on activities that do not require the use of a computer [42]. The success of CS unplugged activities has been demonstrated for learning computing concepts at a primary, secondary, and high-school level. Nishida et al. introduced CS unplugged at the high-school level and concluded that students found the topics enjoyable and understandable [43]. Taub et al. evaluated CS Unplugged activities by conducting interviews with middle schoolers [44]. While they found that not all set-out objectives were met by teaching computer science concepts using only unplugged activities, they did confirm that students comprehend the computing concepts taught. Carruthers describes the impact of unplugged instruction with Grade 6 students when teaching graph theory [45], [46]. The results indicate that students are capable of learning graph theory, and applying these skills when working on mathematical word problems. Rodriguez [47], [48] created assessment strategies that use in-class assignments and a final project and evaluated computational thinking principles with a well-defined rubric and notes from classroom observations. The results show that CS Unplugged activities can yield an increase in computational thinking. To the best of our knowledge, no quantum computing unplugged activities have been made available as of yet.

Quantum Computing Games. Game-Based Learning (GBL) is a learning strategy focused on achieving the particular objectives of given educational content through game play [49]. Games facilitate collaborative learning and positive interdependence and help us teach complex concepts engagingly [50].

The first quantum game played on an actual quantum computer, called *Cat/Box/Scissors* [51], was presented by Wootton in 2017, and is a quantum version of the popular hand game Rock/Paper/Scissors.[3] Since then quantum enthusiasts have invented many different games around core quantum concepts such as qubits, superposition, entanglement, and measurement (e.g., Quantum Battleships [52] and Entanglion [53]). Several quantum games exploit quantum randomness. The state-space of a quantum system increases exponentially with an increasing number of qubits thereby increasing the number of outcomes exponentially. For example, in *Quantum Battleships*, each qubit on a ship is a potential position, and bombs are implemented through 1-qubit rotations. *qCraft* is a quantum

[1] This workshop was set to be offered in March of 2020 but was postponed due to the COVID-19 pandemic. It is being converted to a virtual workshop.

[2] See revised edition at classic.csunplugged.org.

[3] en.wikipedia.org/wiki/Rock_paper_scissors

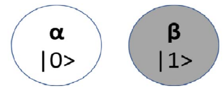
take on Minecraft [54]. It is a single-player game where players discover materials and build structures in a procedurally-generated 3D-world. Using *qCraft*, players learn superposition and entanglement by solving a series of puzzles. *Quantum Chess* is a re-imagination of chess [54] and involves pieces that can be in a superposition of different squares on the board where measurements occur when a piece is attacked. *Quantum Cats* [55] is a single-player game developed by the Institute for Quantum Computing (IQC) and teaches the differences between classical and quantum computing with the help of cats. *Entanglion* [53] is a two-person co-operative board game designed at IBM Research. It exposes players to the fundamental concepts of quantum computing. The goal is to build a quantum computer by visiting Galaxies to pick up components that can build a quantum computer.

III. Effective teaching methodology

The British Columbia Teaching Federation (BCTF) [56] outlines effective teaching strategies and classroom complexity for high-school students. The principles of learning are described as follows: (1) Learning requires the active participation of the student. (2) People learn in a variety of ways and at different rates. (3) Learning is both an individual and a group process. BCTF's teaching strategies include direct instruction, experiential learning, independent study, indirect instruction, and interactive instruction. The design of our quantum computing workshop incorporates a mix of strategies, combining direct instruction with participant activities. Our activities are categorized into Unplugged Activities, Practice Sheets, Quantum Games, and Programming. The following subsections explain the particular activities in detail. Table I describes a mapping of BCTF's teaching strategies to each of the activities, while Table II shows a mapping of the quantum computing concepts covered in the corresponding activities.

A. Unplugged activities. We describe unplugged activities designed to support the teaching of quantum computing concepts: *1) Qubit doughnuts:* A qubit or a quantum bit is the basic unit of quantum information. We use images of a doughnut and a doughnut-shaped pillow to demonstrate a qubit. The idea of representing qubits using doughnuts was inspired in a quantum computing talk by Jessica Pointing[4]. Qubits can be in state $|0\rangle$ or $|1\rangle$, or a linear combination of both. The sprinkled side of the doughnut represents $|0\rangle$ and the plain side represents $|1\rangle$. While no classical analogy is perfect to explain quantum mechanical phenomena, we believe that qubits represented as doughnuts provided a memorable visualization for the students. We also use doughnuts to demonstrate the concept of entanglement. Two assistants hold up and spin the two doughnuts at opposite ends of the classroom (i.e., entangled qubits can be separated by a large distance). When measuring the state of one of the doughnuts, the two assistants stop the spinning and display opposite sides of the doughnuts (i.e., plain and sprinkled) facing the class—simultaneously.

[4]Jessica Pointing: Quantum Computing (explained with doughnuts)—www.youtube.com/watch?v=YIDdPbnnqsA



$$|\psi >= \alpha|0> + \beta|1>$$
$$\alpha^2 + \beta^2 = 1$$

Fig. 1: Find your quantum partner setup

Participants are asked to reconstruct a quantum state given a set of measurement outcomes. In other words, the students have to decide whether the doughnut's displayed side (i.e., the qubit state) is measured as plain or sprinkled (i.e., $|0\rangle$ or $|1\rangle$).

2) Find Your Quantum Partner: The "Find Your Quantum Partner" activity demonstrates quantum states and their properties. The activity involves uni-colored balls of two different colors with numbers written on them (Figure 1). The numbers correspond to amplitudes of quantum states in a qubit. Each student is given one ball—they have to find a person with a ball that is of a different color, and marked with an amplitude such that the sum of the squares of both amplitudes equals 1. This activity also doubles up as an ice-breaker activity for the participants as there is an element of interaction involved.

3) Bloch Sphere—Drawing on a balloon: The Bloch Sphere is a geometrical representation of the pure state space of a qubit. For this unplugged activity we show the Bloch sphere as a balloon, demonstrating different states a qubit can be in. Alternatively, participants are given balloons and are instructed marking different statesConcepts related to states, gates, and rotations can be demonstrated using this activity.

4) Measurement and Probability: The outcome of measuring a quantum system is probabilistic. In Province of British Columbia, probability theory is absent from the K-11 mathematics curriculum; concepts are introduced in a statistics course in grade 12.[5] Thus, participating students typically only have an intuitive idea about the notion of probability. The intuition behind probability, uncertainty, and randomness is illustrated with the use of a black box (a black colored box) containing uni-colored balls of two different colors. The activity is described as follows: (1) Setup: Box with seven black and three white balls. (2) Goal: Determine the more likely color of a randomly picked ball from the box. (3) Process: Blindfolded (or without looking into the box) pick a ball and write down its color. Place the ball back into the black box. Repeat. (4) After enough draws, about 70% of the time black is obtained, and black is observed as the more likely color. In addition, we vary the experiment by switching up the ratio of black and white balls in the black box.

B. Practice Sheets. Between sessions, participants are given practice sheets to reinforce the learning of concepts. Concepts included for practice sheet activities are quantum states, entanglement, 2-qubit systems, and quantum gates. The quantum states' practice sheet includes a list of valid and invalid quantum states represented using dirac notation. Students have to work out which states are valid and which ones are invalid. This exercise extends to 2-qubit systems, where students are presented with four amplitudes instead of two. Not only do

[5]curriculum.gov.bc.ca/curriculum/mathematics

TABLE I: Effective Teaching Strategies mapped to activities

	Experiential Learning	Independent Study	Indirect Instruction	Interactive Instruction
Quantum doughnuts	✓			✓
Find Your Quantum Partner	✓			✓
Bloch Sphere	✓			
Measurement/Probability	✓			✓
Practice Sheets		✓	✓	
Entanglion/Games	✓			✓
Programming			✓	✓

TABLE II: Quantum computing concepts mapped to activities

	Quantum State	2-qubit System	Gates	Superposition	Measurement
Quantum doughnuts	✓	✓		✓	✓
Find your Quantum Partner	✓				
Bloch Sphere	✓		✓	✓	✓
Measurement/Probability	✓			✓	✓
Practice Sheets	✓	✓	✓	✓	✓
Entanglion/Games	✓	✓	✓	✓	✓
Programming	✓	✓	✓	✓	✓

the students learn the concept of normalization through these practice sheets, these also help them getting comfortable with dirac notation. Practice sheets for gates involve calculating the different outcomes when 1- and 2-qubit gates are applied to specific qubit states. This sheet also includes a subsection on measurement where students are to write down the most likely outcome when measuring specific quantum states.

C. Programming. While the unplugged approach takes students away from computers, programming plugs them right back in. Concepts in quantum computing are introduced using Jupyter Notebooks and Qiskit. We chose the IBM Q Experience platform for the following reasons: (1) IBM provides quantum computers and simulators free to use. (2) The circuit composer is a user-friendly graphical tool that allows to design and run quantum circuits without any prior programming knowledge. (3) Qiskit and Jupyter notebooks are integrated into their cloud platform, making it easy to use and setup. (4) Students can continue working at home using their IBM Q Experience account set up during the course and demonstrate their quantum computer programs to family members.

Students are given skeleton Jupyter notebooks to import into the IBM Quantum Experience. A handy cheat sheet is provided, consisting of a list of some basic quantum operations such as creating, drawing, measuring a circuit, and performing gate operations. The first notebook introduces the students to Jupyter notebooks. Here they learn how to differentiate between code cells and markdown cells, create cells, write markdown, and execute cells. In the initial notebook, we ask students to write down their expectations for the workshop and read it out to other participants. In addition to making the students familiar with the Jupyter notebook environment, these activities also remove some students' initial hesitation to interact with other participants and help to make the workshop more interactive and fun for students and instructors alike.

D. Quantum Games. During the last hour of the one-day workshop, the students play the *Entanglion* open-source quantum board game developed by IBM [53]. *Entanglion* is a two-person co-operative board game that introduces, or enforces, fundamental concepts of quantum computing such as quantum states, gates, and entanglement. Its goal is to build a hypothetical quantum (space) ship by going into entangled planets (states) and collecting features to build the ship. For ships to land on an entangled planet, it is essential to put them in superposition. This is achieved using gate cards.

IV. Experience Report: One-Day Workshop

This section describes our experience in delivering the one-day workshop[6] on quantum computing in January 2020 to 25 high-school students (we had received 40 registrations). We carefully tailored the course materials to the high-school level. While the participants' demographics were diverse, the majority of our workshop participants were high-school-aged youth. All participants responded to an Eventbrite announcement. To gain an understanding of quantum computing basics, this workshop introduced basic principles by providing hands-on experience on quantum computers and simulators, using Jupyter Notebooks and Qiskit. We will let the experience gained through this workshop, as well as other—shorter—offerings of introductory quantum computing sessions for youth, guide us in planning future workshops. A brief rundown of our one-day workshop is depicted in Table III.

A. Introduction and Motivation. We began the session with a brief introductory presentation, motivating participants regarding quantum computing. Most of our participants had only heard of the term "quantum computing" but did not know anything beyond the fact that it is a cool technology. The presentation highlighted some promising applications (such as the simulation of molecules) and helped students understand why such problems are classically intractable.One of our main goals of this part was to educate students regarding

[6] All materials related to our one-day workshop can be accessed on GitHub: github.com/pangara/high-school-quantum

the existence of this technology and demonstrate how readily accessible it is to everyone.

B. Introduction to Jupyter Notebooks, Python and Qiskit. Participants were introduced to the IBM Q Experience early on so that they could start experimenting with quantum programs. We helped students create IBM Q accounts and provided them with skeleton notebooks containing boilerplate code that they were asked to fill in based on the topic discussed. Participants were introduced to the basics of Jupyter notebooks as described in Section III and then to Jupyter notebook code cells where they could enter some entry-level Qiskit quantum code, such as creating and drawing a quantum circuit.

C. Qubits, Gates, Superposition, Measurement. This crucial workshop part introduced participants to fundamental concepts of quantum computing. This session alternated between direct instruction and unplugged activities, to foster participant engagement. This part integrated the qubit doughnuts, and the unplugged activities "Find Your Quantum Partner" and "Measurement and Probability". Moreover, participants were given practice sheets to reinforce the understanding of the notions of quantum state and measurement.

D. Hands-on Programming. After a lunch break, participants focused on programming in a session that made use of the topics related to the fundamentals of quantum computing introduced before using three Jupyter notebooks. With the help of a handy cheat sheet, the notebooks were easy to follow.

E. 2-qubit Systems and Entanglement. After the hands-on programming session, participants were introduced to 2-qubit systems. Students were given practice sheets to understand the concepts of 2-qubit systems and entanglement. Similar to the practice sheets for 1-qubit systems, students had to check the validity of a 2-qubit quantum state. They were asked to predict the outcomes of measurements for different quantum states. Finally, students were given the practice sheet to create different kinds of entangled states. The doughnuts were used as a prop to explain these concepts.

F. Entanglion. We concluded the workshop by pairing up the students and providing each group with a copy of the board game *Entanglion*. While playing *Entanglion* does not require the players to have a background in quantum computing, the game provided additional learning reinforcements for the basic quantum computing concepts acquired earlier in the day.

TABLE III: One-day Workshop Schedule

9:00 AM	Introduction and Motivation
9:30 AM	Account Setup on IBM Q Experience
10:00 AM	Break
10:15 AM	Introduction to Jupyter Notebooks, Python, and Qiskit
11:00 AM	Qubits, Gates, Superpostion, and Measurement
12:30 PM	Lunch
1:00 PM	Hands-on Programming
2:30 PM	2-qubit Systems and Entanglement
3:30 PM	Break
3:45 PM	Entanglion
4:45 PM	Closing Remarks, Feedback, and Outlook

V. Design of a Two-Day Workshop

In addition to a one-day workshop, we designed a two-day workshop to allow participants to gain a deeper understanding of the basic quantum computing concepts than the one-day workshop will allow. In the one-day workshop, the quantum computing concepts introduced were qubits, one- and two-qubit quantum systems, superposition, gates, and entanglement. Here, quantum arithmetic rules were introduced for the bra-ket notation. The two-day workshop is designed to introduce the mathematical foundations of quantum computing as well as to verify the correctness of the quantum arithmetic by means of vectors and matrices. Additionally, the workshop introduces students to some notable quantum algorithms that demonstrate advantages of quantum mechanical phenomena such as superposition and entanglement.

On the first day of the two-day workshop, after an introduction to quantum computing and before learning anything else, students are introduced to basic linear algebra, including complex numbers. In his book, Billig introduces mathematical foundations of quantum computing without touching complex numbers [38]. Similarly, we designed the workshop to only mention the concept of complex numbers but not delve deeply into them—as most basic properties can be explained using real numbers only. Mathematical foundations are primarily required for describing the bra-ket notation for qubits and gate operations. We designed practice sheets for the same: (1) Understanding vectors and matrices: unitary matrices, transpose, addition, multiplication (Day 1) (2) Converting vectors to and from bra-ket notation (Days 1 & 2) (3) Tensor products (Day 2) (4) Mathematical operations when applying gates to qubits (Days 1 & 2).

Items above with both Days 1 and 2, signify that practice sheets are planned for both 1- and 2-qubit systems. Tensor products come into play for multi-qubit systems, covered on Day 2. On the second half of Day 2, we will work through the details of significant algorithms such as Superdense Coding, Quantum Teleportation or the Deutsch-Josza algorithm. These are introduced as Qiskit notebooks, where a skeleton of the program is given to them to complete and run. In their textbook, Perry et al. [37] outline teaching quantum computing to high-school students over one week. The textbook involves several exercises, some of which we think are useful additions when delivering our two-day workshop (e.g., linear algebra, entanglement, gate operations, or teleportation). Table IV provides an outline of our two-day workshop.

VI. Lessons Learned

The quantum computing workshops discussed in this paper grew out of HighTechU [9], an innovative learning community and skills incubator for high-school-aged youths at the University of Victoria in Canada. In addition to the high-school workshops, we delivered half-day events for middle-schoolers as well as the general public during UVic's 2020 IdeaFest. While this paper mainly reports on the lessons learned from the high-school events, all of these events contributed to our understanding of how to engage people in quantum computing.

TABLE IV: Two-Day Workshop Schedule

Day 1	Day 2
Introduction and Motivation	Review of Day 1
Account setup on IBM Q Experience	1-qubit systems/entanglement
Introduction to Jupyter Notebooks, Python and Qiskit	Math: 2-qubit systems and entanglement
Linear algebra, vectors, matrices, complex numbers	Qiskit: programming/Jupyter with 2-qubit systems
Qubits, gates, measurements (math)	Introduction to quantum algorithms
Qubits, gates, measurements (programming)	Superdense Coding/Teleportation/Deutsch-Josza
Entanglion	Implementation
Closing and Feedback	Closing and Feedback

While background and age of workshop participants varied, by and large the students were highly motivated and eager to engage in quantum computing. The list below includes specific lessons learned during the design, development, and delivery of our quantum engagements with youths. *Teaching strategies.* We incorporated a mix of teaching strategies, including direct instruction, group activities, individual practice activities, and games. Mixing up these strategies helped considerably in keeping the students engaged and creating a lively day.

Engagement and active participation. Activities that foster interaction among the participants was critical for student satisfaction and overall experience. The first few activities — "Jupyter notebook where students could express their Workshop Expectations" and "Find Your Quantum Partner" served as effective icebreakers and nicely stimulated interaction.

Diversity. While this workshop was intended for high-school-aged youths, there was considerable interest by other age groups—older (e.g., graduate students) and younger siblings signed up. Initially, we thought that this diversity of age groups might be an impediment but it actually generated synergy and fostered collaboration.

Props and handouts. Students clearly enjoyed props, especially the qubit doughnuts we used to explain entanglement. In their feedback, students mentioned that the usage of doughnuts helped them understand the concept of entanglement better. Reinforcement learning through practice sheets was quite popular and effective. Most of the students took these printed sheets home with the intention to engage their family.

Jupyter notebooks. Most students had little or no programming experience. Jupyter notebooks are effective to communicate concepts in a step-by-step manner. Separating the introduction of 'text'- and 'programming code'-cells was critical to get started. Providing code fragments, templates, and complete solutions is important for a seamless and satisfying experience.

Quantum programming on IBM Q Experience. The IBM Q Experience is an excellent platform for onboarding students. The Qiskit software development kit with its Composer and Python interfaces is easy to learn. The "Gates glossary" and "Qiskit cheat sheet" answered many questions along the way.

Reinforcement learning through games. Entanglion with its instructions and rules is an interesting game but challenging to learn after a long day when the students have already reached information overload. While the participants enjoyed playing *Entanglion*, they had difficulties identifying the quantum concepts they learned during the day in the *Entanglion* game.

Feedback. The students enjoyed the workshop and provided extensive feedback which was mostly positive.

VII. Conclusions

The contributions of this paper include a literature review of papers dealing with teaching quantum computing to high school students including "unplugged activities," a presentation of the design, development, and delivery of our quantum workshops for high-school-aged youths, and lessons learned during this journey. While the in-person delivery has slowed down due to the pandemic, we are pursuing several quantum computing education avenues. We are in the process of converting the above described two-day workshop for high-school students into a virtual or online workshop.

Computer Science Unplugged has been highly successful in teaching algorithms to youths. Some of these ideas can be leveraged to teach the basics of quantum algorithms. For example, Lamagna et al. investigated how to use puzzles to introduce students to algorithmic thinking, which they define as the "ability to understand, execute, evaluate, and create computational procedures" [57]. Since the structure of quantum algorithmic procedures differs significantly from classical algorithms, we need to develop innovative ways to teach quantum algorithmic and probabilistic thinking.

At the *IEEE International Conference on Quantum Computing and Engineering (QCE20)* [58], we will run a one-day workshop for high-school students in partnership with Honeywell Quantum Solutions. We also designed a two-day hands-on event for graduate and undergraduate students as a part of a summer school to be held at ICESI University in Cali, Colombia. This summer school has now been moved to 2021 due to the pandemic. We are also set up to conduct a research study that includes data collection at the end of workshops to gauge the understanding of quantum computing of high-school-aged youths. With this study, we will hopefully verify our hypothesis that basic quantum computing can be readily taught at the high-school level achieving the same level of understanding as to when classical computing is taught.

VIII. Acknowledgement

This work is funded in part by the National Sciences and Engineering Research Council (NSERC) of Canada, IBM Canada Ltd. and the IBM Center for Advanced Studies, and the University of Victoria. The proposed research study has been approved by the University of Victoria Human Research

Ethics Board under Protocol Number 20-0057. The authors thank Callysto Canada and HighTechU for supporting the development and delivery of our quantum computing workshops. Copies of the board game *Entanglion* were donated by IBM Research Yorktown Heights.

REFERENCES

[1] A. Lamprou and A. Repenning, "Teaching how to teach computational thinking," in *Proc. 23rd Ann. ACM Conf. Innov. and Techn in Comp. Sci. Education (ITiCSE)*, 2018, pp. 69–74.

[2] J. M. Wing, "Computational thinking," *Communications of the ACM*, vol. 49, no. 3, pp. 33–35, 2006.

[3] E. Grumbling and M. Horowitz, *Quantum Computing: Progress and Prospects*. National Academies of Sciences, Engineering, and Medicine, 2019. [Online]. Available: www.nap.edu/catalog/25196

[4] S. Aaronson and D. Bacon, "Quantum computing and the ultimate limits of computation: The case for a national investment," 2008. [Online]. Available: bit.ly/2EV3LoG

[5] M. G. Raymer and C. Monroe, "The US National Quantum Initiative," *Quantum Science and Technology*, vol. 4, no. 2, p. 020504, 2019.

[6] B. Sussman, P. Corkum, A. Blais, D. Cory, and A. Damascelli, "Quantum Canada," *Quantum Science and Technology*, vol. 4, no. 2, 2019.

[7] "Germany invests $717 million in IBM quantum computing."

[8] M. N. Amin, R. P. Uhlig, P. P. Dey, B. Sinha, and J. Shatha, "The needs and challenges of workforce development in quantum computing," *American Society for Engineering Education*, 2019.

[9] U. Stege and A. MacLean, "HighTechU, University of Victoria." [Online]. Available: hightechu.ca

[10] D. Deutsch, "Quantum theory as a universal physical theory," *Intl. Journal of Theoretical Physics*, vol. 24, no. 1, pp. 1–41, 1985.

[11] D. Deutsch and R. Jozsa, "Rapid solution of problems by quantum computation," *Proc. Royal Society London*, vol. 439, pp. 553–558, 1992.

[12] C. H. Bennett and S. J. Wiesner, "Communication via one- and two-particle operators on Einstein-Podolsky-Rosen states," *Phys. Rev. Lett.*, vol. 69, no. 2881, 1992.

[13] C. H. Bennett, G. Brassard, C. Crépeau, R. Jozsa, A. Peres, and W. K. Wootters, "Teleporting an unknown quantum state via dual classical and Einstein-Podolsky-Rosen channels," *Phys. Rev. Lett.*, vol. 70, 1993.

[14] D. R. Simon, "On the power of quantum computation," in *Proc. 35th Symp. on Foundations of Computer Science (FOCS)*, 1994, pp. 116–123.

[15] E. Bernstein and U. Vazirani, "Quantum complexity theory," in *Proc. 25th Ann. ACM Symp. Theory of Computing (STOC)*, 1993, pp. 11–20.

[16] D. Coppersmith, "An approximate Fourier transform useful in quantum factoring," *RC, IBM Research Division*, vol. 19642, 1994.

[17] E. Bernstein and U. Vazirani, "Quantum complexity theory," *SIAM Journal on Computing*, vol. 26, no. 5, pp. 1411–1473, 1997.

[18] P. W. Shor, "Algorithms for quantum computation: discrete logarithms and factoring," in *Proc. 35th Ann. Symp. on Foundations of Computer Science (FOCS)*, 1994, pp. 124–134.

[19] L. K. Grover, "A fast quantum mechanical algorithm for database search," in *Proc. 28th Ann. ACM Symp. on Theory of Computing (STOC)*, 1996, pp. 212–219.

[20] "Google Quantum." [Online]. Available: research.google/teams/applied-science/quantum

[21] "Rigetti Forest SDK." [Online]. Available: docs.rigetti.com/en/stable

[22] "Microsoft Azure Quantum." [Online]. Available: azure.microsoft.com/en-ca/services/quantum

[23] "IBM Quantum Experience." [Online]. Available: www.ibm.com/quantum-computing

[24] Xanadu, "Strawberry Fields and PennyLane." [Online]. Available: www.xanadu.ai/software

[25] "D-Wave Leap^2." [Online]. Available: www.dwavesys.com/take-leap

[26] "Qiskit." [Online]. Available: qiskit.org

[27] "Microsoft Quantum Development Kit." [Online]. Available: www.microsoft.com/en-us/quantum/development-kit

[28] "Google Cirq." [Online]. Available: cirq.readthedocs.io/en/stable

[29] J. Preskill, "Quantum computing in the NISQ era and beyond," *Quantum*, vol. 2, p. 79, 2018.

[30] P. J. Karalekas, N. A. Tezak, E. C. Peterson, C. A. Ryan, M. P. da Silva, and R. S. Smith, "A quantum-classical cloud platform optimized for variational hybrid algorithms," *Quantum Science Technology*, vol. 5, no. 2, p. 024003, 2020. [Online]. Available: arxiv.org/abs/2001.04449

[31] A. J. McCaskey, D. I. Lyakh, E. F. Dumitrescu, S. S. Powers, and T. S. Humble, "Xacc: A system-level software infrastructure for heterogeneous quantum-classical computing," *Quantum Science and Technology*, vol. 5, no. 2, 2019.

[32] S. Aaronson, *Quantum computing since Democritus*. CUP, 2013.

[33] D. E. Knuth, "Literate Programming," *The Computer Journal*, vol. 27, no. 2, pp. 97–111, 1984.

[34] A. Asfaw, L. Bello, Y. Ben-Haim, S. Bravyi, L. Capelluto, A. C. Vazquez, J. Ceroni, R. Chen, A. Frisch, J. Gambetta, S. Garion, L. Gil, S. De La Puente Gonzalez, F. Harkins, T. Imamichi, D. McKay, A. Mezzacapo, Z. Minev, R. Movassagh, G. Nannicni, P. Nation, A. Phan, M. Pistoia, A. Rattew, J. Schaefer, J. Shabani, J. Smolin, K. Temme, M. Tod, S. Wood, and J. Wootton, *Learn Quantum Computation Using Qiskit*. IBM, 2020. [Online]. Available: community.qiskit.org/textbook

[35] A. Asfaw, "Coding with Qiskit," 2019. [Online]. Available: bit.ly/33KYKJs

[36] C. C. Tappert, R. I. Frank, I. Barabasi, A. M. Leider, D. Evans, and L. Westfall, "Experience teaching quantum computing," in *52nd Ann. Meeting Assoc. Supporting Computer Users in Education*, 2019.

[37] A. Perry, R. Sun, C. Hughes, J. Isaacson, and J. Turner, *Quantum Computing as a High School Module*. FERMILAB, 2019. [Online]. Available: arxiv.org/abs/1905.00282

[38] Y. Billig, *Quantum Comp. for High School Students*. Amazon, 2018.

[39] D. Sabol, A. Leider, and J. Glinka, "Quantum Computing the Easy Way." [Online]. Available: bit.ly/3ipqCXX

[40] S. Barabasi, J. Barrera, P. Bhalani, P. Dalvi, R. Dimiecik, A. Leider, J. Mondrosch, K. Peterson, N. Sawant, and C. C. Tappert, "Student user experience with the IBM Qiskit quantum computing interface," in *Adv. in Information and Communication*, vol. 70, 2020, pp. 547–563.

[41] T. Bell, I. Witten, and M. Fellows, "Computer Science Unplugged: Off-line activities and games for all ages (original book)," 1998. [Online]. Available: bit.ly/3gzXAUS

[42] T. Bell and J. Vahrenhold, *CS Unplugged—How Is It Used, and Does It Work?* Springer, 2018, pp. 497–521.

[43] T. Nishida, Y. Idosaka, Y. Hofuku, S. Kanemune, and Y. Kuno, "New methodology of information education with CS Unplugged," in *Proc. Third Intl. Conference on Informatics in Secondary Schools—Evolution and Perspectives*, vol. 5090 LNCS, 2008, pp. 241–252.

[44] R. Taub, M. Armoni, and M. Ben-Ari, "CS unplugged and middle-school students' views, attitudes, and intentions regarding CS," *ACM Transactions on Computing Education*, vol. 12, no. 2, 2012.

[45] S. Carruthers, *Grasping Graphs*. MSc Thesis, Univ. of Victoria, 2010.

[46] S. Carruthers, Y. Coady, C. Gibbs, K. Gunion, U. Stege, and T. M. Milford, *Teaching Problem Solving and Computer Science in the Schools*. SensePublishers, 2011, pp. 99–112.

[47] B. R. Rodriguez, *Assessing Computational Thinking in CS Unplugged Activities*. MSc Thesis, Colorado School of Mines, Golden, 2015.

[48] B. Rodriguez, S. Kennicutt, C. Rader, and T. Camp, "Assessing computational thinking in CS unplugged activities," in *Proc. ACM Technical Symp. on Computer Science Education (SIGCSE)*, 2017, pp. 501–506.

[49] B. Kim, H. Park, and Y. Baek, "Not just fun, but serious strategies: Using meta-cognitive strategies in game-based learning," *Computers & Education*, vol. 52, no. 4, pp. 800–810, 2009.

[50] M. Romero, M. Usart, M. Ott, J. Earp, S. De Freitas, and S. Arnab, "Learning through playing for or against each other? Promoting collaborative learning in digital game based learning," *Proc. 20th European Conference on Information Systems (ECIS)*, 2012.

[51] J. Wootton, "Introducing the world's first game for a quantum computer," 2017. [Online]. Available: link.medium.com/QXFwsW85H6

[52] ——, "Quantum Battleships." [Online]. Available: bit.ly/3ijFC9v

[53] J. D. Weisz, M. Ashoori, and Z. Ashktorab, "Entanglion: A board game for teaching the principles of quantum computing," *Proc. Ann. Symp. on Computer-Human Interaction in Play (CHI PLAY)*, pp. 535–548, 2018.

[54] "Quantum Games." [Online]. Available: bit.ly/3kqZ4TB

[55] "Quantum Cats." [Online]. Available: quantumcats.ca

[56] "Teaching strategies and classroom complexity." [Online]. Available: bctf.ca/NewTeachers.aspx?id=31830

[57] E. A. Lamagna, "Algorithmic thinking unplugged," *Journal of Computing Sciences in Colleges*, vol. 30, no. 6, pp. 45–52, 2015.

[58] P. Angara, U. Stege, A. MacLean, R. Considine, and S. Genco, "From Qubits to Quantum Teleportation: A Hands-On Experience for High Schoolers," in *IEEE International Conference on Quantum Computing and Engineering (QCE20)*, 2020.