Teaching Quantum Computing to High-School-Aged Youth: A Hands-On Approach

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ABSTRACT Quantum computing is an interdisciplinary field that lies at the intersection of mathematics, quantum physics, and computer science, and finds applications in areas including optimization, machine learning, and simulation of chemical, physical, and biological systems. It has the potential to help solve problems that so far have no satisfying method solving them, and to provide significant speedup to solutions when compared with their best classical approaches. In turn, quantum computing may allow us to solve problems for inputs that so far are deemed practically intractable. With the computational power of quantum computers and the proliferation of quantum development kits, quantum computing is anticipated to become mainstream, and the demand for a skilled workforce in quantum computing is expected to increase significantly. Therefore, quantum computing education is ramping up. This article describes our experiences in designing and delivering quantum computing workshops for youth (Grades 9–12). We introduce students to the world of quantum computing in innovative ways, such as newly designed unplugged activities for teaching basic quantum computing concepts. We also take a programmatic approach and introduce students to the IBM Quantum Experience using Qiskit and Jupyter notebooks. Our contributions are as follows. First, we present creative ways to teach quantum computing to youth with little or no experience in science, technology, engineering, and mathematics areas; second, we discuss diversity and highlight various pathways into quantum computing from quantum software to quantum hardware; and third, we discuss the design and delivery of online and in-person motivational, introductory, and advanced workshops for youth.

INDEX TERMS Computer science (CS) unplugged (CS Unplugged), education, entanglement, high-school-aged youth, measurement, qiskit, quantum computing, quantum computing games, quantum gates, quantum teleportation, qubit systems, superposition, teachers, training, workforce development.

I. INTRODUCTION

Many scientists and engineers consider quantum computing as one of the most interesting, exciting, and challenging topics in science and engineering, with enormous potential in numerous application areas [1]. In 2017, Marr wrote in *Forbes Magazine*: "Quantum computers will disrupt every industry. They will change [...] how we fight disease and invent new materials, and solve health and climate problems" [2]. With recent rapid advances in quantum technology, quantum computing has gained significant importance and has become one of the fastest-growing fields in the science, technology, engineering, and mathematics (STEM) areas [3]. Governments, funding agencies, and companies have been heavily investing in the development of quantum computing with the mission to realize hardware and software innovations that allow the full potential of quantum computing [4]–[9].

The accelerating progress in the area has now paved a way to educate a workforce for a diverse industry. Universities have begun to offer courses and degree programs at the graduate and undergraduate levels. Furthermore, quantum computing is now an active research area not just in physics but in disciplines such as chemistry, electrical and computer engineering, and computer science (CS). The quantum *computing*

journey was initiated by Feynman in the early 1980s [10]. Since then, several important results in quantum algorithms have emerged [11]–[18], including Shor's factoring algorithm [19] and Grover's search algorithm [20]. Over the last 15 years, companies (e.g., [21]–[27]) have engineered the first real quantum computers and developed quantum development kits (QDK), such as IBM Qiskit [28], D-Wave Leap [29], Microsoft QDK [30], Google Cirq [31], Rigetti Forest [32], and Xanadu Strawberry Fields [33]. Today, we are in the noisy intermediate-scale quantum (NISQ) era [34] chasing quantum advantage with shallow circuits and hybrid quantum-classical algorithms. The need for continued research and development in quantum computing at all levels remains stark, and quantum skills are (still) rare to find [35]. The labor pool in quantum computing is anticipated to be interdisciplinary. From quantum software to quantum hardware, knowledge from physicists, engineers, computer scientists, software engineers, and mathematicians among others is essential for quantum computing [3]. Fortunately, there are many pathways into quantum computing from a variety of disciplines.

In addition to diverse skill sets, we require workforce diversity. It is predicted that "25% of the Fortune Global 500 will gain a competitive edge from quantum computing by 2023."[1] As such, the area of quantum computing presents a (likely short) window of opportunity to create a truly diverse pool of quantum computing talent. In this spirit, Asfaw, IBM's Global Education Lead, calls for quantum education programs to reach a diverse student body: "IBM realizes that quantum computing's success both in the laboratory and the enterprise relies heavily on our ability to expand educational opportunities to a broader diversity of students" [36]. According to Johnson [3], Brower-Thomas, Education Director, and Howard University Executive Director of the Center for Integrated Quantum Materials, posits: "So the question is are we preparing our K–12 to go to the schools that have a requisite curriculum that will prepare them to be in the [quantum] industry? I think, unfortunately, the answer is 'no'." Also, preparation in classical computing and computational thinking skills is still lacking for K–12, although education researchers have long advocated teaching (classical) computational thinking in all schools [37] and describe them as key skills not just for our 21st Century workforce but for all humans [38]. At the same time, the lack of gender diversity in the tech industry continues to be problematic [39], despite mounting evidence that more diverse teams are not just required for a healthy tech sector [40] but are also more successful financially. Research published by McKinsey in 2015 found that companies in the top 25% for racial and ethnic diversity are 35% more likely to have better financial returns than the corresponding national median, and companies in the top 25% concerning gender diversity are 15% more likely to have financial returns above their national

median in the corresponding industry [41]. In 2020, the United States National Center for Women and Information Technology (NCWIT) published statistics[2] on the proportion of women in computing in the student body in universities as well as the workforce in industry: While 57% of professional occupations in the U.S. workforce were held by women, only 26% held computing occupations, and women only held 18% of CIO positions in the Top 1000 Companies. This may not come as surprise when looking at the recipients of bachelor degrees: While 57% of bachelor degree recipients were women, only 21% women were recipients of bachelor degrees in computing in 2020, in 1985, 37% were recipients of bachelor degrees in computing. Results from a Microsoft study in the U.K. published in 2017 identified that the critical window to motivate girls for careers is between the ages of 11 and 15: they start gaining interest in STEM areas typically at the age of 12 or 13 and start losing interest shortly after they turn 15 [42]. One of the reasons for their choice to turn away from a tech career is apparently the lack of (perceived) equal opportunity in the workplace.

Since the field of quantum computing education is still in its early stages, it presents many opportunities to include diversity and gender balance in the field of quantum computing. We advocate that teaching quantum computing to youth should begin no later than in Grade 9 (i.e., students are about 14 years old). Through teaching quantum computing at this level, we hope to add information for career choice and strategies of entry into technology, specifically quantum computing. In addition to supporting career choice decision making, since quantum computing is quite different from classical computing, introducing a different way of thinking early might make the area of quantum computing more approachable. In his book *Quantum Computing Since Democritus* [43], 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." We follow this ideology for our workshops and posit that a background in quantum mechanics or quantum physics is not required to understand fundamental concepts in quantum computing. We submit that understanding quantum computing can open doors to understanding quantum mechanical concepts [44]–[46]. For participation in our quantum computing workshops for high school students, we have no expectations regarding the students' prior knowledge—workshop attendance does not require a background in quantum computing, quantum physics, quantum mechanics, CS (including programming and algorithms), mathematical topics (such as linear algebra and complex

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[1]https://www.analyticsinsight.net/when-will-quantum-computing-come-to-mainstream/

[2]https://www.ncwit.org/sites/default/files/resources/ncwit_btn_07232020.pdf

numbers), or software development environments. Nevertheless, we do assume that the common K–8 syllabi have been covered by all the participants. This article presents our experiences in training high-school students with the goal to show different pathways into quantum computing as part of 1) the University of Victoria's HighTechU program [47] and 2) the IEEE International Conference on Quantum Computing and Engineering 2020 (QCE20) in collaboration with Honeywell Quantum Solutions. We will refer to QCE20 also as Quantum Week.

The rest of this article is organized as follows. Section II overviews relevant literature on quantum computing education and training with a focus on the delivery of quantum computing to youth, computer science unplugged (CS Unplugged) activities—hands-on activities teaching computing concepts without the use of a computer, and quantum computing games. We also took into account the K–12 curricula in Canada and the U.S., with a focus on British Columbia, Canada. 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 [48]: *Quantum Computing Science Unplugged*. Section IV describes the goals and the overarching theme of our workshops. Section V introduces three workshop formats, and their respective design and delivery methods. Section VI discusses lessons learned from delivering workshops and student feedback. Finally, Section VII concludes this article and presents some of the materials used in delivering the workshops given in Section VII-A.

II. RELATED WORK

This section begins by summarizing ongoing work in quantum computing education efforts, including introductory textbooks and courses suitable for high-school students, CS Unplugged resources, and quantum computing games. Quantum computing education is developing fast around the globe. Notable developments include the White House Office of Science and Technology Policy and the National Science Foundation spearheading a partnership between the Federal government, industry, professional societies, and the education community called the *Q2Work* Program [49]. This program enables a range of training opportunities to increase the capabilities, diversity, and number of students who are ready to engage in the quantum workforce. It caters to K–12 education in quantum computing with outreach for middle and high-school students. We next discuss selected recent educational efforts in quantum computing primarily aimed at the K–12 demographic. The year-long course of the *Qubit by Qubit* initiative[3] is offered with the goal to "increase diversity in the field of quantum" as well as "ensure that students [participating in the program] are prepared for the quantum workforce" and "to educate and inspire students to learn more about quantum computing." Qubit by Qubit is

offered collaboratively by IBM and MIT and makes quantum computing accessible to everyone, and specifically to high-school students. This course is an initiative by The Coding School[4] and sponsored by IBM Quantum and Google Quantum AI [24], [50]. The book *Dancing With Qubits* [51] begins by providing a gentle introduction for those who are new to quantum computing, but soon delves deeper into the foundations and algorithms. It offers programming examples using Python and IBM Qiskit. The goal of this book is to make quantum computing approachable to people without a quantum physics background. University of British Columbia's K–12 Quantum Education Program[5] offers educational resources and unique games (such as *Qubit Jump!* and *Quantum Adventures!* to learn quantum computing). In their article, Economou *et al.* [52] offer an educational outreach program for high-school students that provides hands-on knowledge of quantum circuits and algorithms and is based on the book *Q is for Quantum* by Terry Rudolph.[6] This book allows students to learn some basic quantum computing concepts without the use of any linear algebra. The authors use marbles to represent qubits (with the color representing a state) and superposition represented by misty marbles. They also introduce Deutsch's algorithm through a game called *Money or Tiger*. Shoshany [53] presents an introduction to quantum theory for exceptional high-school students through a series of lectures that span four days at the Perimeter Institute at the University of Waterloo in Ontario, Canada. The lectures focus on building a mathematical foundation for quantum computing and ramp-up to advanced mathematical foundations related to infinite-dimensional Hilbert spaces. Mykhailova and Svore [54] provide an experience report teaching quantum computing as an undergraduate course through a practical software-driven approach. They rely on self-paced programming exercises called the *Quantum Katas* and observe that programming assignments help internalize theoretical concepts much better than relying on just lectures. The *Qiskit Textbook* embodies literate programming [55] and is an evolving online resource with complete Qiskit documentation [56]. It is an introduction to programming using Qiskit on the IBM Quantum Experience [57] while explaining quantum computing concepts and algorithms. *Coding with Qiskit* is a famous online series of videos introducing beginners to programming using Qiskit with Python and Jupyter Notebooks [58], [59]. Tappert *et al.* [60] overview their experience of teaching quantum computing as a graduate course as well as a one-week high-school workshop. They describe that for high-school students, the focus was on short lectures followed by hands-on programming utilizing the composer interface on the IBM Quantum Experience, to then run their programs on the quantum simulator as well as an actual quantum computer. *Quantum Computing*

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[3]https://www.qubitbyqubit.org/

[4]https://www.codeconnects.org
[5]https://quantumcomputing.ubc.ca/education/k-12-education
[6]https://qisforquantum.org/

as a High School Module by Perry *et al.* [61] is a textbook with exercises for teaching quantum computing and serves as a 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* [62] introduces mathematical foundations of quantum computing, assuming high-school-level mathematics. They include selected linear algebra elements but intentionally leave out complex numbers. Billig argues that this simplification helps in conveying and visualizing quantum concepts. *Quantum Computing the Easy Way* [63] is a Udemy course that teaches quantum computing and introduces the basics of quantum computing and quantum algorithms. It is open to students from any background. The material is delivered using PowerPoint slides only and does not involve programming. Barabasi *et al.* [64] discuss student experiences using IBM's Quantum Experience platform in developing games based on quantum randomness. Salehi *et al.* [65] conduct an extensive study teaching introductory quantum computing using a CS oriented approach where quantum computing is viewed as a generalization of probablistic computing. They conduct two- or three-day workshops for students coming from diverse backgrounds. However, very few students were from a high-school demographic (only 19 students out of 317). *CS Unplugged* [48] emerged in the early 1990s[7] and was first publicized via a 1998 manuscript entitled *Computer Science Unplugged . . . off-line activities and games for all ages* by Bell *et al.* [66].[8] Today, CS Unplugged is considered an educational method for introducing K–12 nonspecialists to computing concepts through hands-on activities that do not require the use of a computer [67]. The success of CS Unplugged activities has been demonstrated for learning computing concepts at the K-12 level. Nishida *et al.* [68] introduced CS Unplugged at the high-school level and concluded that students found the topics enjoyable and understandable. Taub *et al.* [69] evaluated CS Unplugged activities by conducting interviews with middle schoolers. While they found that not all set-out objectives were met by teaching CS concepts using only unplugged activities, they did confirm that students comprehend the computing concepts taught. Carruthers *et al.* [70], [71] describe the impact of unplugged instruction with Grade 6 students when teaching graph theory. Her findings indicate that students are capable of learning graph theory, and applying these skills when working on mathematical word problems. Rodriguez [72], [73] 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.

A number of *quantum computing games*, based on quantum computing concepts, have been developed for educational purposes. Game-based learning is a learning strategy focused on achieving the particular objectives of given educational content through game play [74]. Games facilitate collaborative learning and positive interdependence and help us teach complex concepts engagingly [75]. The first quantum game played on an actual quantum computer, called *Cat/Box/Scissors* [76], was presented by Wootton in 2017 and is a quantum version of the popular hand game Rock/Paper/Scissors.[9] Since then quantum enthusiasts have invented many different games around core quantum concepts, such as qubits, superposition, entanglement, interference, and measurement (e.g., Quantum Battleships [77] and Entanglion [78]). 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 take on Minecraft [79]. It is a single-player game where players discover materials and build structures in a procedurally generated 3-D world. Using qCraft, players learn superposition and entanglement by solving a series of puzzles. *Quantum Chess* is a reimagination of chess [79] 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* [80] is a single-player game developed by the Institute for Quantum Computing and teaches the differences between classical and quantum computing with the help of cats. Decodoku [81] is a puzzle available for example as iOS and Google Play app, which focuses on quantum benchmarking through quantum error correction: through the solving of puzzles, the quantum computer must be kept free of errors to keep running. *Entanglion* [78] is a two-person co-operative board game designed at IBM Research. It exposes players to the fundamental concepts of quantum computing such as superposition, entanglement, and gates. The goal is to build a quantum computer by visiting Galaxies to pick up components that can build a quantum computer.

III. EFFECTIVE TEACHING METHODS

This section discusses selected effective methods that we use to teach quantum computing to high-school students. The British Columbia Teaching Federation (BCTF) [82] outlines effective teaching strategies and classroom complexity for high-school students and describes the principles of learning as follows.

1) Learning requires the active participation of the student.
2) Students learn in a variety of ways and at different rates.

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[7] https://csunplugged.org/en/
[8] For a revised edition see classic.csunplugged.org.

[9] https://en.wikipedia.org/wiki/Rock_paper_scissors

TABLE 1 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 2 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	✓	✓	✓	✓	✓

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 subset of these strategies as participant activities. Our activities are categorized into unplugged activities, practice sheets, quantum games, and programming. The following sections explain the particular activities in detail. Table 1 describes a mapping of BCTF's teaching strategies to each of the activities, while Table 2 presents a mapping of the quantum computing concepts covered in the corresponding activities.

A. UNPLUGGED ACTIVITIES
We describe our 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.[10] 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 $|1\rangle$. Superposition is shown to be a spinning qubit that stops at the sprinkled side or the plain side upon measurement.

   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
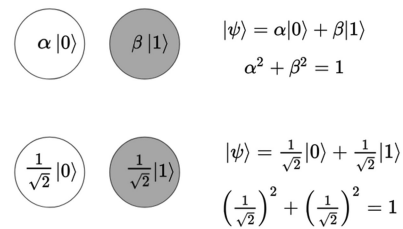

$$|\psi\rangle = \alpha|0\rangle + \beta|1\rangle$$
$$\alpha^2 + \beta^2 = 1$$

$$|\psi\rangle = \frac{1}{\sqrt{2}}|0\rangle + \frac{1}{\sqrt{2}}|1\rangle$$
$$\left(\frac{1}{\sqrt{2}}\right)^2 + \left(\frac{1}{\sqrt{2}}\right)^2 = 1$$

FIGURE 1. Find your quantum partner activity.

the class—simultaneously. 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. 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 unicolored balls of two different colors with numbers written on them (cf. Fig. 1). The numbers correspond to the 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. The north pole is labeled $|0\rangle$

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[10]The idea of representing qubits using doughnuts was inspired in a quantum computing talk by Jessica Pointing. See http://www.youtube.com/watch?v=YIDdPbnnqsA

and the south pole is labeled $|1\rangle$. If, for example, a Pauli-X gate is applied, using a marker a line is drawn from the north pole to the south pole indicating a state change from $|0\rangle$ to $|1\rangle$. Alternatively, participants are given balloons and are instructed to mark different states. Concepts 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 British Columbia, probability theory is absent from the K–11 mathematics curriculum; concepts are introduced in a statistics course in Grade 12.[11] Thus, participating students typically only have an intuitive idea about the notion of probability. In our youth workshops, we illustrate the intuition behind probability, uncertainty, and randomness with the use of a black box (a black colored box) containing unicolored balls of two different colors. The activity is described as follows.

   1) Setup: Box with seven $|0\rangle$ and three $|1\rangle$ balls.
   2) Goal: Determine the more likely state of a randomly picked ball from the box.
   3) Process: Blindfolded (or without looking into the box) pick a ball and write down whether it is a $|0\rangle$ or a $|1\rangle$ ball. Place the ball back into the black box. Repeat.
   4) After enough draws, about 70% of the time $|0\rangle$ is obtained, and 0 is observed as the more likely state. 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 two-qubit systems, where students are presented with four amplitudes instead of two. Not only do the students learn the concept of normalization through these practice sheets but also get comfortable with the Dirac notation. Practice sheets for gates involve calculating the different outcomes when one- and two-qubit gates are applied to specific qubit states. This sheet also includes a section on measurement where students are asked 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 Quantum Experience platform for the following reasons: First, IBM provides quantum computers and simulators free to use. Second, the circuit composer is a user-friendly graphical tool that allows us to design and run quantum circuits without any prior programming knowledge. Third, Qiskit and Jupyter notebooks are integrated into their web-based cloud platform, making it easy to use and set up. Fourth, students can continue working at home using their IBM Quantum Experience account setup 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, comprising a list of some basic quantum operations such as creating, drawing, and 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 familiarizing the students with the Jupyter notebook environment, these activities also remove 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

Entanglion is a two-person co-operative open-source quantum board game developed by IBM [78] 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. We normally schedule Entanglion at the end of the workshop, when it becomes too overwhelming to learn more new topics. This allows students to think about quantum computing concepts in a different, fun, and engaging way.

E. ONLINE TOOLS

The delivery of online workshops involves additional tools that are useful for fostering collaboration and interaction.

1) *Online lectures via Zoom:*[12] Every session is hosted as a Zoom meeting so that participants can access the workshop virtually. To promote interactivity and collaboration, students are divided into groups of four or five students. Zoom's feature of breakout rooms is used for team and group activities. A team of moderators cycle through the breakout rooms to answer any questions that the students might have. Zoom's feature of

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[11]http://curriculum.gov.bc.ca/curriculum/mathematics

[12]https://zoom.us/

polling allows the organizers to ask multiple-choice questions to attendees. Therefore, it is used intermittently in lectures to make sure that students follow the material. The anonymity of polls also helps students be more comfortable answering the questions.

2) *Quirklogic Workbooks:*[13] Quirklogic provides remote education learning solutions where digital handwriting is used on their e-ink devices (such as Papyr and Quilla) and can be accessed using an application on iOS/Android platforms[14] as well as a web-based application.[15] Documents are stored as Quirklogic workbook files that can be downloaded as PDFs. Files can be uploaded as PDFs, which get translated into Quirklogic workbook files. Since the notation and mathematics in quantum computing cannot be typed easily (such as the Dirac notation or matrices), digital tools that use handwriting are helpful. If available to them, students are recommended to use the application on iOS/Android devices (e.g., the iPad) because of their touch capabilities and the fact that many students or their parents own such a device. The first Quirklogic notebook is used as an icebreaker activity where students can write in their name and their expectations of the workshop. This allows them to get familiar with the platform and encourages collaboration. The remaining notebooks contain practice sheets (which in an in-person setting are printed and handed out to students). For the breakout-room activities, each group of students is assigned to one shared Quirklogic workbook on which they can collaborate and figure out the solutions to the questions asked.

This section introduced the effective teaching methods, activities, and tools used in in-person and online settings. The following section describes pathways into quantum computing by discussing some quantum computing challenges and recommended classical skills to delve into quantum computing.

IV. PATHWAYS INTO QUANTUM COMPUTING

This section introduces the overarching theme used in our workshops (workshop design and delivery are described in detail in Section V). We introduce quantum computing to a high-school-aged audience with the following goals in mind.

1) Students learn hands-on how quantum computing works.
2) Gain understanding about the larger context of quantum computing and the breadth of fields that are crucial for the future of quantum computing.

Students are provided with an overview of the workflow of a quantum computing program to highlight different parts of
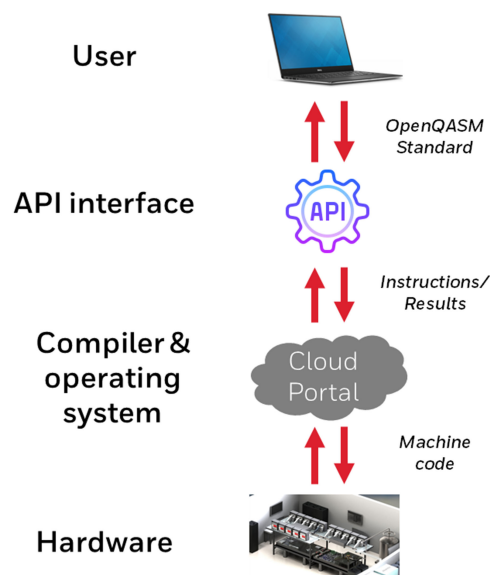

FIGURE 2. Software stack linking users to quantum hardware.

the quantum software stack linking users to quantum hardware. In the following, we provide an overview of quantum computing systems with an emphasis on hardware. The goal is to introduce some of the science and technologies required on the other side of the programming interface. Introducing students to the breadth of engineering disciplines necessary to build a quantum computer is intended to stimulate their interest in STEM-related classes. Areas that provide a pathway to quantum education include electrical and computer engineering, CS, chemistry, and physics. A summary of the quantum stack consisting of the user interface, Application Programming Interface, Compiler and operating system, and Quantum Hardware is given below.

Quantum computers, such as their classical counterparts, are built in layers. The software stack model depicted in Fig. 2 introduces a high-level generic model used by various quantum systems today.

User: The user writes the quantum program in a high-level language such as the Open Quantum Assembly Language (openQASM) standard. Alternatively, users can also take advantage of libraries (such as Qiskit, Microsoft QDK, Rigetti Forest SDK, or Pennylane) to convert their programs to the openQASM standard. This allows the user to describe the particular quantum circuits constituting the quantum algorithm. OpenQASM also supports linking quantum and classical computations in a hybrid quantum-classical model. In our workshops, students are introduced to the IBM Quantum Experience where they can implement quantum programs using the circuit composer or a Python program using the Qiskit library (as a Jupyter notebook). The IBM Quantum Experience supports Jupyter notebooks natively, that is, students can access these from the Quantum Experience cloud platform in a web browser.

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[13]https://www.quirklogic.com/
[14]iOS/Android application: https://www.quirklogic.com/products/quirklogic-connect
[15][Online]. Available: https://portal.quirklogic.com/
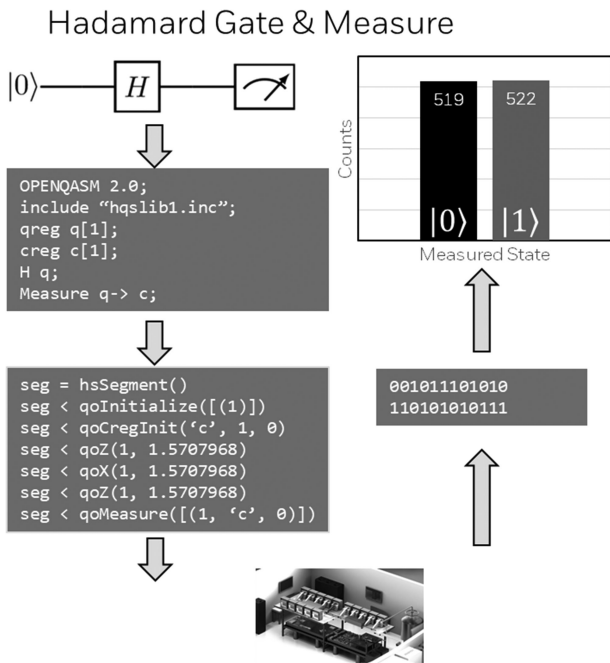
Hadamard Gate & Measure

FIGURE 3. Processing of a quantum circuit as it moves through the quantum stack.

Application programming interface: Quantum computers are large, expensive, and complex hardware systems. Thus, users require a method to submit the programs created in openQASM to the quantum computer. The application programming interface (API), often implemented as an internet-accessible resource, provides the path. The API handles account creation, user login, job submission, job status, and delivery of the job results. In the workshops, students submit jobs to a quantum simulator or IBM quantum computer using the IBM quantum experience.

Compiler and operating system: The quantum computer cannot directly run the openQASM circuit. First, the open-QASM code must be translated or compiled into machine code which the quantum hardware can execute. The "operating system" function schedules resources, performs calibration when necessary, controls running the quantum job then validates the results and sends the result back to the user via the API.

Quantum Hardware: The hardware layer consists of the quantum processor (e.g., ion trap manipulating ytterbium ions) and the controls that turn ON/OFF lasers, turn ON/OFF microwave signals, control magnetic fields, regulate radio frequency (RF) energy and maintain temperatures and vacuum around the quantum gates. Fig. 3 provides an example of how a quantum circuit is processed as it moves through the layers shown in Fig. 2. Within the world of classical computing, the hardware technology is mature and most classical processors as those used in laptops or cell phones use a chip built using complementary metal–oxide–semiconductor field effect transistors, CMOS for short. In contrast, quantum computing technology is new, and with several competing technologies. Experienced engineers and computer scientists often find the probabilistic model of quantum computing requires new approaches. We introduce two approaches to quantum computing hardware to provide students with an appreciation for science and engineering, which underlies the machine that runs their openQASM circuit. The science of quantum computing involves quantum mechanics and an understanding of electron behavior. Engineering in the context of quantum computers is about taking science and making it reproducible, reliable and cost-effective.

Superconducting qubits: D-Wave Systems are a Canadian company that produces quantum computers focusing on the quantum annealing process. D-Wave uses the Superconducting QUantum Interference Device (SQUID) as the building block. The magnetic spin states of SQUID can be placed into quantum superposition. These building blocks are then connected via "couplers" to represent the circuits submitted by users.

IBM uses superconducting qubits built upon Josephson junctions. Both D-Wave and IBM perform quantum computations then use classical electronics to read out the state of the qubits in order to return 1 s and 0 s to the user.

Trapped ions: Honeywell Quantum Solutions, IonQ, the Universities of Sussex and Waterloo work on building qubits by trapping a small number of ions and then manipulating those ions using lasers, magnetic fields and microwave energy. Quantum charge-coupled device traps hold ions within an RF field and use potential wells generated by electrodes to move the ions to different locations on the trap. Trapped ions have longer coherence times and lower error rates than superconducting qubits.

The challenges for both hardware approaches include scaling the number of qubits, reducing the errors introduced into the system, and providing longer coherence times. Some specific challenges and courses students may take to prepare themselves to support research overcoming the challenges are listed in Table 3. The table also depicts which part of the quantum stack the challenges belong to.

V. WORKSHOP FORMATS

Our workshops are classified into three categories based on the content delivered: motivational, introductory, and advanced. They can be delivered in-person or online. Topics are grouped together as modules, and a collection of modules forms a workshop.[16]

A. MOTIVATIONAL WORKSHOPS

The motivational workshops primarily aim to generate interest and provide pathways to a career in quantum

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[16]All materials related to our workshops can be accessed on GitHub: https://github.com/pangara/TQE-HighTechQ.

TABLE 3 Engineering Challenges and Recommended Education

Quantum stack	Quantum computing challenge	Recommended classical skills
User and API Interface	Developing quantum algorithms and interpreting their results	Linear algebra, probability theory and classical algorithms
	Creation and execution of hybrid programs combining classical and quantum computing	Computer Science, programming, software engineering, algorithms
Compiler and Operating System	Compiling complex quantum circuits to execute efficiently on quantum processor	Computer science: Algorithm development, compilers, sorting and routing
	Scaling up digital control systems to handle 10,000 to a million qubits	Digital system design, control systems and computer architecture
Quantum Hardware	Providing extremely low noise analog designs for control and measurement	Analog design, calculus and radio frequency (RF) design
	Design of scalable, stable laser systems and optics	Optics, photonics, materials science and physics
	Designing components and operating them at cryogenic temperatures near absolute zero	Physics, mechanical engineering and materials science

computing. Such a workshop can be used as part of other, longer, workshops—described in the following—as a motivation module. Motivational workshops are designed to be delivered in less than two hours.

We begin such a workshop interactively by asking the audience what they know about quantum computing. Then the field of quantum computing is introduced by relating it to quantum physics and CS. This is followed by describing computational problems that current classical computers cannot solve, but potentially could be solved by quantum computers. This provides a segue into careers and pathways to get started in quantum computing. We then introduce superposition, entanglement and measurement using qubit doughnuts (cf. Section III). Finally, we demonstrate running quantum circuits on the IBM Quantum platform using the circuit composer and available quantum computers to show the accessibility of quantum computers today.

B. INTRODUCTORY WORKSHOPS

This section describes our experience in delivering an introductory workshop on quantum computing, delivered in 6–8 h. All course materials are carefully tailored to the high-school level. This workshop introduces basic principles of quantum computing by providing a hands-on experience on quantum computers and simulators, using Jupyter Notebooks and Qiskit. A secondary aim of this workshop is to feature our unplugged quantum computing activities, thereby contributing to CS Unplugged in general and a "Quantum Computing Unplugged" chapter in particular. A brief rundown of our introductory workshop is depicted in Table 4 and described in detail in the following paragraphs.

1) MOTIVATION MODULE

This module provides a brief introductory presentation, motivating participants regarding quantum computing. This is similar to our motivational workshop, but we leave the basic

TABLE 4 Sample of an Introductory In-Person Workshop Schedule (8 H)

09:00	Introduction and Motivation
09:30	Account Setup on IBM Quantum Experience
10:00	Break
1015	Introduction to Jupyter Notebooks, Python, and Qiskit
11:00	Qubits, Gates, Superposition, and Measurement
12:30	Lunch
13:00	Hands-on Programming
14:30	multi-qubit Systems and Entanglement
15:30	Break
15:45	Entanglion
16:45	Closing Remarks, Feedback, and Outlook

concepts such as superposition and entanglement for later. We assume that most participants would have only heard of the term "quantum computing" but not know anything beyond the fact that it is a cool technology. This presentation highlights some promising applications (such as molecule simulation) and helps students understand why some problems are classically intractable. The main goal is to educate students regarding the existence of quantum computing technology and to demonstrate how readily accessible the technology is to everyone.

2) QUANTUM BASICS MODULE

This crucial workshop part introduces participants to fundamental concepts of quantum computing. This session alternates between direct instruction and unplugged activities, to foster participant engagement. This part integrates the qubit doughnuts and the unplugged activities "Find Your Quantum Partner" and "Measurement and Probability." Moreover, participants are given practice sheets to reinforce the understanding of the notions of quantum state and measurement.

3) BASIC PROGRAMMING MODULE

Participants are introduced to the IBM Quantum Experience [57] early on so that they can start experimenting with

TABLE 5 Schedule of a Virtual Workshop (Quantum Week)

Session	Module
Motivation	What is Quantum Computing? A quick introduction Main concepts: Qubits, Superposition, Entanglement, Measurement, Quantum Gates Hands On: Circuit Composer
Different kinds of quantum computers	Ion-Trap Quantum Computing Dive into D-Wave Setup for Session 3
Programming Quantum Computers	Multi-qubit systems IBM-Quantum Experience and Qiskit Teleportation

quantum programs. We help students create accounts to access both Quantum Composer and Quantum Lab on the IBM Quantum Experience. Participants are then introduced to the basics of Jupyter Notebooks including markdown and code cells where they can enter some entry-level Qiskit quantum code, such as creating and drawing a quantum circuit.

4) INTERMEDIATE QUANTUM COMPUTING MODULE

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

5) HANDS-ON PROGRAMMING MODULE

In this module, participants are provided with skeleton Jupyter Notebooks containing boilerplate code that they are asked to fill in, based on the topic discussed. With the help of a handy cheat sheet, the notebooks are easy to follow. This module builds upon the quantum basics module, and topics such as Entanglement, Teleportation, and Superdense coding are programmed by participants.

6) GAMING MODULE

Workshops can be concluded by playing a quantum game that reinforces some of the concepts learned earlier in the workshop. An example is the board game Entanglion. Students are paired up and provided each 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 provides additional learning reinforcements for the basic quantum computing concepts acquired earlier in the day.

Our Online workshop: This part is based on our experiences delivering an online introductory workshop titled "From Qubits to Quantum Teleportation" held at the IEEE International Conference on Quantum Computing on October 12, 2020. Participating students were Grade 8–12 students in Victoria, BC, Canada, and Broomfield, Colorado.

The main aim of this particular workshop was to stimulate the interest and awareness of high-school-aged youth and introduce high-school teachers to quantum computing as a possible field to teach. Since there are limited materials available that are targeted toward high-schoolers in the realm of practical quantum computing [83], this workshop aims to demonstrate how quantum computing can be a part of teachable component in high school.

We deliver the workshop in three modules, with each module lasting 1.5 h. An outline of the topics taught through the day is given in Table 5. Since this is an online workshop, it is easier to involve guest speakers who might not be from the same city where the workshop is hosted, which helps in diversifying the kind of content that can be delivered.

As usual, the first module introduces students to quantum computing. In this specific workshop, we started the session with a talk by a high-school student from The Knowledge Society[17] (an organization that exposes youth to emerging STEM fields) with the aim to inspire high-school students and show them that (1) it is indeed possible to learn quantum computing in high-school (2) it is an exciting topic that they might find interesting to study further at university.

The content in the first module is similar to the content delivered in the motivation and quantum basics module of the in-person introductory workshop (i.e., students are introduced to single-qubit systems, superposition, measurement, and gates). In the second module, students learn about the different kinds of quantum computers that are available today with talks on superconductivity and ion-trap quantum computer technologies. In the third module, students encounter multiqubit systems, entanglement, and programming with Qiskit using the circuit composer (mapped to the Intermediate Quantum Computing Module).

C. ADVANCED WORKSHOPS

An advanced workshop allows participants to gain a deeper understanding of the basic quantum computing concepts than an introductory workshop allows. In the introductory workshop, the basic quantum computing concepts include qubits, one-, and two-qubit quantum systems, superposition, gates, entanglement, quantum arithmetic rules, and the bra–ket notation. The advanced workshop is designed to develop the mathematical foundations of quantum computing as well as to verify the correctness of quantum arithmetic by means

[17]https://tks.world/

TABLE 6 Advanced Workshop Schedule (Sample)

Part 1	Part 2
Introduction and Motivation	Review of Part 1
Account setup on IBM Quantum Experience	1-qubit systems/entanglement
Introduction to Jupyter Notebooks, Python and Qiskit	Math: multi-qubit systems and entanglement
Linear algebra, vectors, matrices, complex numbers	Qiskit: programming/Jupyter with multi-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

of vectors and matrices. Additionally, the workshop introduces students to some notable quantum algorithms that demonstrate quantum advantage. Delivery of an advanced workshop takes about 16 h and can be delivered in two or more days.

In the first part of the advanced workshop, students are introduced to basic linear algebra, including complex numbers. As discussed earlier (cf. Section II) in his book, Billig introduces mathematical foundations of quantum computing without touching on complex numbers [62]. Similarly, we designed our advanced workshops to only mention the concept of complex numbers but avoid delving 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 (Part 1).
2) Converting vectors to and from bra–ket notation (Parts 1 and 2).
3) Tensor products (Day 2).
4) Mathematical operations when applying gates to qubits (Parts 1 and 2).

Items above with both Parts 1 and 2, signify that practice sheets are planned for both single and multiqubit systems. Tensor products come into play for multiqubit systems, covered in Part 2. In the second half of Part 2, we work through the details of significant algorithms such as Superdense Coding, Quantum Teleportation, or the Deutsch-Josza algorithm. These are taught using Jupyter Notebooks and Qiskit, where a skeleton of the program is given to them to complete and run. In their textbook, Perry *et al.* [61] 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 advanced workshop (e.g., linear algebra, entanglement, gate operations, or teleportation). Table 6 provides an outline of our advanced workshop.

VI. DISCUSSION/LESSONS LEARNED

This section describes the observations, feedback, and lessons learned from our introductory online workshop (held in 2020 at Quantum Week in collaboration with Honeywell

Quantum Solutions) and our introductory in-person workshop (delivered by HighTechU at the University of Victoria).

A. FEEDBACK

Six students completed the Quantum Week Workshop Survey, with an average respondent age of 16. While 80% of respondents had no prior knowledge about quantum computing prior to the workshop, all had studied either linear algebra or complex numbers before entering the workshop. None had studied both. Using doughnuts for teaching the concept of quantum entanglement was reported as the most effective activity to aid in student understanding of quantum computing concepts, with 80% of respondents indicating that the activity had been helpful in their understanding of concepts. As a result of the workshop, students rated their understanding highest in how gates operate (Hadamard, Pauli-X, and CNOT gates) and lowest in entanglement and the teleportation algorithm discussed at the end of the workshop, with similarly low levels of comfort reported with the tools introduced in the workshop such as Qiskit and Jupyter Notebooks. Overall, respondents rated the workshop with a high overall average score of 4.2 out of 5, with 60% of respondents indicating they were likely to recommend the workshop to a friend. These results correlated with those from the introductory in-person quantum computing workshop delivered by HighTechU in January 2020 at the University of Victoria, where an average score of 4.2 out of 5 and a 80% recommendation rate was recorded for a group of 18 respondents and where students reported that "the next revolution in the world of computer systems will require yet another set of completely new skills" and that "Quantum computing is at the forefront, and my generation will be able to achieve major breakthroughs."

Online versus offline teaching: The online teaching environment did not allow for instructors to see the faces of some of the students who decided not to turn on their cameras for most of the time. For privacy reasons, we made it optional for students to turn on their cameras. Without the ability to read the students' body language, it was difficult to determine how well students were grasping the materials. This suggests that the structure should be modified to stimulate more interaction with the students and obtain more feedback. For example, rather than a long lecture, the materials could be broken into short segments. Following each segment, the instructor could ask the students a few questions to gauge their understanding. Simply asking the students if anyone has questions may not

produce adequate feedback if students are not comfortable speaking up.

B. LESSONS LEARNED

The quantum computing workshops discussed in this article grew out of HighTechU [47], 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.[18] While this article mainly reports on the lessons learned from the high-school events, the other events contributed to our understanding of how to engage people in quantum computing.

While the 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: As described earlier, 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 were critical for student satisfaction and overall experience. The first few activities —*Hello Jupyter*, where students could express their Workshop Expectations and *Find Your Quantum Partner*— served as effective icebreakers and nicely stimulated interaction.

Age 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 the IBM Quantum Experience: The IBM Quantum Experience is an excellent platform for

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[18]https://www.uvic.ca/ideafest2020/

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the onboarding of students. The Qiskit software development kit with its Composer and Python programming interfaces is easy to learn. Our "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. We think that this may be because there are many rules for the game and students had less time to play it. Given more time, they might appreciate it more.

VII. CONCLUSION

The evolution of both the quantum computer and the area of quantum computing is often compared with the evolution of the classical computer—more than 200 years passed since the invention of the first (mechanically programmable) computer by Babbage in 1800, and Alan Turing's conceptual model of the Turing machine, as well as the arrival of the first digital computer in the 1930s, to today's readily available access to computation power, via devices, such as smartphones and access to powerful computing machines via cloud access. The development of quantum computers and their uses is—in comparison—much faster, also since quantum computing research benefits on many levels from the developments in classical computing. The quantum computing journey itself started in 1981. In 1998, the first physical model of a quantum computer was presented [84]. As described, over the last 15 years, companies did not just engineer a variety of quantum computers but also designed QDK. These as well as cloud access to quantum computers and simulators is what accelerates quantum computing today. IBM's recently published quantum computing roadmap envisions moving speedily from the current era of NISQ devices to the era of universal fault-tolerant quantum computers by 2023 [85]. Next to qubit-technology development, the focus will be on seamless integration of classical and quantum computing devices, as well as the evolving development of the quantum-classical software stack. This will ensure that quantum computing is seamlessly accessible as a service for application-level users. For this vision to come to fruition, a diverse workforce in quantum computing is needed.

This article discussed our design of different kinds of quantum computing workshops for high-school students. Today, different pathways into quantum computing are possible. Exposing high-school students to quantum computing concepts and possibilities early will enrich their decision-making when choosing a career path, which begins with selecting courses in the years before finishing high school. The implications for early exposure to quantum computing will likely positively impact the diversity of the large workforce needed in this area. As laid out above, diversity is needed in all dimensions, including background and specialization, as well as gender diversity.

All areas that interplay with the development of quantum computing, be it on the software or hardware side and the engineering or science side, have in common that these areas are under-represented by women. The rapid advancements in and the promise of quantum computing and its impactful applications are an opportunity to build a truly diverse quantum computing research and development workforce. Thus, the area in its current development stage presents an unprecedented opportunity to advertise science and technology areas to a diverse population. We believe that, since the diverse education of quantum computing experts allows a rather seamless transition into many other areas in tech, a more diverse quantum computing workforce can also positively impact the diversity of the tech workforce in general. We submit that, to reach women, quantum computing should be introduced early, ideally no later than Grade 9, the earliest high-school grade.

Our own intense efforts educating youth in quantum computing in the form of workshops with high-school-aged youth (grades 9–12) are short-term in nature. At the same time, our participants in our HighTechU community have the opportunity to engage in the longer term with a broad variety of themes in technology as well as mentors from the industry. We conducted preliminary formal evaluations for both the online and in-person workshops with 6 and 18 participants, respectively. Since these workshops were conducted over the course of a day, feedback was gathered from the students in the form of an exit survey where they were asked to evaluate themselves by rating their understanding of the different topics discussed in the workshop. To gain a more thorough formal evaluation, an updated survey should include short answer and multiple choice questions to test the students' understanding. This research is a part of an ongoing study where we continually improve our material based on the feedback of students and our own observations. The size of a cohort has been limited to 30 students so that there can be more effective attention given to each student. While the limited number of participants is not representative of the demographic, it provides a good starting point. One way to move forward is to conduct multiple iterations of the workshops and, subsequently, present this material as a course at the high-school level, which will increase the size of our case study. Given more time in the workshops, evaluations can be conducted for as group activities in the same cohort which probe their understanding of the material. Surveys can also be conducted over a period of time to test the students knowledge retention.

While there exist other longer-term efforts engaging youth in quantum computing in Canada (see Section II), we believe that an even broader effort directed through schools should not only be encouraged for a wider reach but is also feasible and practical.

Successful efforts in teaching quantum computing to youth around the world, such as our workshops, demonstrate that they can help inform young students when having to choose electives in high school as they can show a path for a future career. Early exposure to career possibilities and paths toward that need are critical to be presented sufficiently early. Both classical and quantum computing concepts and computational thinking skills are a way to train and deepen problem-solving skills that are beneficial for everyone.

So far, exposure to any form of quantum computing in school can be limited to chemistry or physics courses that some students in high school choose to take, and which content can strongly depend on schools and teachers. As discussed, despite the recognized need and benefits for all humans [38], classical computing and computational thinking skills are still lacking in our schools, as access to such materials is still not guaranteed for every student in K–12.

So far, to the best of authors' knowledge, the Computer Science Teachers Association (CSTA), the preeminent American Computer Science education association behind initiatives like the K–12 CS Standards,[19] has demonstrated limited engagement in the area of Quantum Computing Education preuniversity, despite launching the AI4K12 working group in 2018 to explore how a similarly leading-edge technology—Artificial Intelligence—could be introduced into the elementary and secondary curriculum [86].

We advocate to refresh and widen the efforts of the integration of computational thinking skills into our K–12 curricula and include basic concepts from quantum computing in addition to concepts from classical computing. Quantum computing concepts are not only an asset to the problem-solving skill set of each individual, quantum computing can also serve as motivation to teach other foundational skills, including when working with probabilities, the manipulation of matrices, and complex numbers.

Exposing students to quantum computing through project work is another possibility. Accessible and always improving online resources, and free access to quantum computers support such endeavors just as much as the possibilities enabled by quantum computing in the near future, including faster, safer, and cheaper ways to design drugs and vaccines.

Quantum computing, through its diverse pathways, is also accessible to people beyond high school. So far, most university quantum computing programs are found at the graduate level, although individual courses in the area are offered in more and more undergraduate programs. In addition, larger companies in the area have their own training programs for new employees, as few highly qualified quantum computing personnel are available on the job market.

We anticipate that in the near future quantum computing will enter undergraduate education at a broad level, be it as stand-alone programs or options that can be chosen when pursuing a degree in science or engineering.

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[19]https://k12cs.org/

A. TEACHING MATERIALS

All materials related to our workshops can be accessed on GitHub: https://github.com/pangara/TQE-HighTechQ.

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