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The Needs and Challenges of Workforce Development in Quantum Computing

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THE NEEDS AND CHALLENGES OF WORKFORCE DEVELOPMENT IN QUANTUM COMPUTING

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ABSTRACT

Quantum computing is one of the most interesting and demanding topics in the field of computer science and engineering. The potential of quantum computing in many areas such as computer security, big data, finance, health science, and many other fields are now clear because of its incredible capacity and high processing speed. In a traditional computing system, all data and information are represented with 0 and 1 bits. But quantum computers operate in a different way, using Quantum Bits, or qubits. These qubits are created and manipulated using quantum principles of superposition and entanglement and can perform certain types of complex and large calculations on vast amounts of data very rapidly. A few examples of potential applications of quantum computing include much more secure quantum encryption, tremendous speed up of database searches using Grover's database search algorithm, protein folding, and modeling of electrons in materials and molecules. Many scientists including Christopher Monroe at the University of Maryland and IonQ believe, within the next five years, a quantum computer will be capable of calculations that could never be run on traditional computing machines.

In order to foster and expedite quantum computing research and development, the United States House of Representatives recently passed "The National Quantum Initiative Act (H.R. 6227)" which includes an emphasis on workforce development. In the USA, a number of startups and big tech companies are now involved in building quantum computing machines using different mechanisms of quantum physics, including ions trapped in electrical fields, superconducting circuits, quantum cloud service, spins of a single electron, etc. The computer industries are working hard to use their existing semiconductor resources and technologies combined with quantum principles to build the desired computing systems. In parallel, there is an urgent need for a new generation of engineers, scientists, and programmers who can use quantum computers to solve real-world problems. This paper discusses some opportunities and challenges in quantum computing and preparing college students to fulfill the workforce demand. It further discusses how complex quantum computing courses can be integrated into the curricula of computer science, engineering, and related programs to address future workforce development issues. A multifaceted strategy for boosting enrollment, retention and successful graduation in quantum computing is proposed in order to address workforce development issues because we need to succeed in the tough competition we are facing from other countries.

INTRODUCTION

A well-designed workforce development plan supports all aspects of an educational system and propels the economy forward by providing learners with skills that are in increasing demand [1]. New technology based economies with emerging engineering and computing tasks need a diversified work force with innovative problem solving skills. The workforce development in emerging computing fields such as quantum computing is enormously challenging because these fields are not yet fully understood. Students are not adequately prepared because quantum physics and math are perceived to be difficult by most students. Courses are not offered in most colleges because adequate resources and supports are missing. The United States House of Representatives has recently passed "The National Quantum Initiative Act (H.R. 6227)" which includes emphasis on workforce development; however, actual allocation of funds has not been made yet[2]. Developing a workforce in quantum computing is strategically important, but little or no progress has been made so far due to lack of adequate planning, support and actions. An initial step towards developing a top quality workforce is to understand the emerging field for the purpose of building the teaching-learning environment. It needs to be emphasized here that a reasonable broad understanding of the field will provide a strong foundation to the plan of study and workforce development proposed in this paper [2-3].

The scientific theories, principles, laws, and postulates of quantum mechanics were developed through the hard work of Max Planck, Albert Einstein, Louis de Broglie, Arthur Compton, Niels Bohr and many other scientists [3,4]. Quantum mechanics is applicable to all nano-particles (of the order of 10^{-9} m) or smaller including all the elementary particles and some compounds [5,6]. Recently, the concept of quantum computation has become viable and it is gaining in popularity. Worldwide many organizations are working aggressively towards building quantum computing machines [7-46]; scope and limitations of these machines should be carefully examined before adopting them for any teaching-learning environment. For example, D-wave quantum computers are annealing systems that cannot run many well-known algorithm and their theoretical and practical viability in educational purposes needs to be carefully examined [72].

The next generation computer may look like an upside down cake of several layers wrapped with many metallic cylinders and at bottom there will be a black chip [7]. It is expected that this computer will change entire computing methods and solve some undiscovered mysteries of human dreams and future life styles [8]. This computer is known as a Quantum Computer and it uses the principles of quantum physics at both hardware and software levels.

We are living in a time where computers are used in all aspects of our lives. Computers are integral and inseparable devices of our lives. Classical computers (present computers) are very good at algebra and calculus, but the quantum computer is even better at sorting large data, finding prime numbers, molecular modeling simulation, and system optimization [8, 47-54]. Therefore, quantum computing could open the door to a new computing era. According to the current news, quantum computing is no longer science fiction, but an engineering product whose development is underway and will be used for real practical applications [13-46]. Quantum computers will never be a replacement of current computers, but it offers a new innovative method of computation to solve many large and complex problems in the areas of science, medicine, communications, business, socioeconomics, and much more [8]. This will lead to a revolutionary expansion in technology and will have significant impacts worldwide. Quantum computers are able to solve complex problems that are beyond the capabilities of classical computers. In July 10, 2017 Forbes Magazine published an article which stated *"Quantum computers will disrupt every industry. They will change the way we do business and the security we have in place to safeguard data, how we fight disease and invent new materials, and solve health and climate problems [8]."*

The following is a summary of a few expected changes [8]: 1) Online security **-** current data encryption tactics will be at risk and vulnerable, but new quantum encryption methods will be more safe and secure, 2) Artificial intelligence – machine learning will be improved from the analysis of large quantities (fast processing and accurate information) to improve performance, 3) Drug development **-** effective drugs will be developed from the interactive evaluations among multiple molecules, proteins and chemicals, 4) Improved weather forecasting and climate change predictions – meteorologists will have much faster and more accurate information about weather and climate models to alert people which will ultimately save lives, anguish and money, 5**)** Traffic control **-** streamlined traffic control for both air and ground will be able to quickly calculate the optimal routes for efficient scheduling and reduced traffic congestion to facilitate maximum supply chains, safe air traffic control, fleet operations and deliveries, 6) Tackling the whole problem - tackle the entire large problem at once instead of considering it bit by bit at a time, and 7) Teleportation for fast and secured data transfer.

RACE OF QUANTUM COMPUTER DEVELOPMENT

At the present time, there is an aggressive race going on worldwide. Everyone is trying to be the first to create a commercially viable quantum computer. Many giants are involved in the quantum computer development race. Major players in the USA include: Google, Microsoft, IBM and Intel. Some other companies in the quantum computing race include, but are not limited to: Alibaba, Nokia, Intel, Airbus, HP, Toshiba, Mitsubishi, SK Telecom, NEC, Lockheed Martin, Rigetti, Biogen, Volkswagen, Amgen, D-Wave, 1QBit, Accenture, Alpine Quantum Technologies, AT&T, Cambridge Quantum Computing Limited, Elyah, Everettian Technologies, Fujitsu, Hitachi, Honeywell, HRL Laboratories, Huawei, ionQ, InfiniQuant, Northrop Grumman, NTT Laboratories, Q-Ctrl, Qbitlogic International, Quantum Circuits, Siemens Healthineers, Delft Circuits, RIKEN, Strangeworks, Xanadu, Zapata Computing, and many universities worldwide [9,55]. A large number of universities worldwide are engaged in research and development in quantum computing both at the hardware and software levels [40].

Recently, IBM predicted, within five years quantum computers will be used in the mainstream. In November 2017, IBM announced its first working 50 qubit processor and started serving 12 big clients through the IBM Q Network to solve their previously "unsolvable" problems [7]. In 2013, Google**,** NASA and the Universities Space Research Association (USRA) set up a collaborative lab called the Quantum Artificial Intelligence Lab (QuAIL) [9]. The aim of this collaborative effort was to improve NASA's ability to solve difficult optimization problems in aeronautics, earth and space sciences, and space exploration. They used the D-Wave Two quantum computer developed by the world's first quantum computing company, D-Wave Systems. In 2017, the D-Wave 2000Q system was installed at QuAIL [9]. In March 2018, Google developed its new quantum processor, Bristlecone which is capable of building larger scale quantum computers [56]. In 2005, Microsoft built Station Q for testing of topological quantum computing performance [57]. Microsoft was successful in building a quantum computer based on a type of qubit – or unit of quantum information – called a topological qubit. In December 2017, Microsoft first released a free version of its Quantum Development Kit (QDK) for review and an updated version in February 2018 [9,58].

The United States has recently taken an initial step for winning the quantum-computing race. The National Quantum Initiative Act (H.R. 6227) has addressed the quantum computer development issue and proposed devoting $1.275 billion over five years to support a coordinated research and development effort led by the Department of Energy, National Science Foundation, and National Institute of Standards and Technology [2,10]. In China, Alibaba and Huawei are actively involved in this race. In September 2018, the Chinese government granted $10 billion to build the world's largest quantum research facility (4-million-square-foot) in Hefei province by March 2020 [59]. The national laboratory will be engaged in making major advances in quantum technology, including computers, sensors, and cryptography. China launched its Micius quantum satellite in 2016 [10]. This is able to anchor a secure ground-to-space quantum communications network using the quantum entanglement principle. They also established an unhackable 2,000-kilometer quantum communications network from Shanghai to Beijing [10]. The U.S. also needs to develop a strong quantum strategic plan to protect the country and its citizens. Worldwide, almost all powerful and developed countries are engaged in developing a viable quantum computer. The Telegraph claimed, the United Kingdom invested 270 million pounds in 2013, but only 80 million pounds in 2018 [12]. The quantum computer race is serious and everybody is trying to win and get the jackpot. It is now clear from the news and research reports that quantum computing is no longer a science project, but it has become a most challenging and competitive engineering project [7-61]. Hence, the authors of this paper strongly believe there is an urgent need to introduce the quantum computing related topics to regular students of computer science and engineering.

DIFFERENCE BETWEEN CLASSICAL COMPUTER AND QUANTUM COMPUTER

The difference between a classical computer and a quantum computer is not like the difference between an old car and a new car. Rather, it is like the difference between a car and an airplane (one can move; the other can fly). Classical computers use classical digital computing principles and theories. But Quantum computers use the *quantum* principles more specifically the properties of *superposition* and *entanglement* [14, 60].

Quantum phenomena have the potential to enable computing capability using Quantum Physics. This is a fundamentally new approach to solving large and complex problems. In a traditional computing system, all data and information are represented with 0 and 1 bits. These bits can exist in either a 1 or 0 state which can be created using specific voltage or current levels in a digital electric circuit. In this method, there is a limit as to how quickly transistors in classical computers can manipulate these bits to carry out calculations. As a result, many complex and large computations cannot be completed on classical computers.

But quantum computing operates in a different way. It uses Quantum Bits, or qubits. These qubits are created and manipulated using two quantum principles: superposition and entanglement. This new computing method can perform certain types of complex and large calculations on vast amounts of data very rapidly. Qubits can be created in many ways where the values of two distinct quantum states are measurable and can be represented with 0 and 1 like a classical computer bit. The lifetime of qubits in a quantum computer is very short (of the order of several milliseconds) [11].

A simple quantum computer can be built with a single *qubit* using an electron's spin values: +1/2 (anticlockwise) or -1/2 (clockwise) and these values can be set up as 0 and 1 (if these values can be measured) to create the quantum *logic gates* like logic gates in digital computers. Figure 1 describes the spin directions and corresponding qubits.

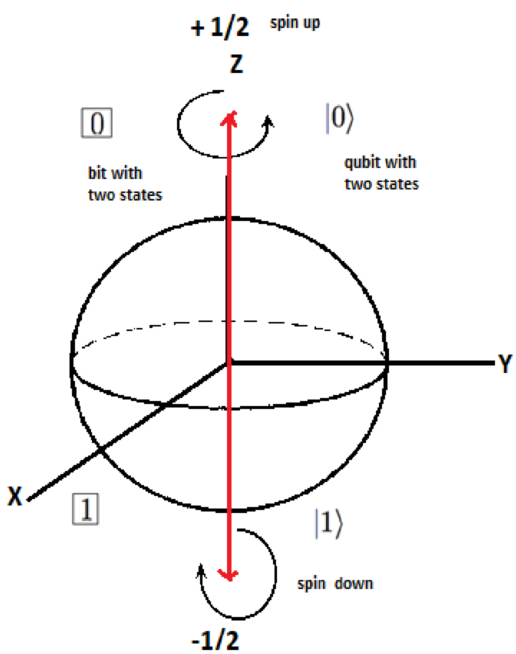

Figure 1: Directions of Electron Spin + ½ and - ½ and corresponding qubits

One of the fundamental principles in quantum physics is wave–particle duality [5,6]. According to this principle, every quantum entity (nanometer or smaller object size) has both particle and wave natures. Examples of quantum entities are electron, proton, neutron, atom, molecule, electromagnetic wave, etc. Schrodinger equation is a second order non-homogeneous differential equation which is shown in Equation (1). This can be used to find the allowed energy levels (states) of any quantum mechanical system (such as electron in atom, energy gap of a diode, electromagnetic radiation energy). The solution of this equation is called a wave function which describes the probability of finding the particle at a certain position and time [5,6].

$$i\hbar\frac{\partial\psi}{\partial t} + \frac{\hbar^2}{2m}\nabla^2\psi - V\psi = 0 \quad (1)$$

ψ is a complex probability wave function also known as wave vector. The product of this function with it complex conjugate, $\psi\,\psi^*$ is known as probability density which helps to measure some quantum values associated with quantum variables or parameters of nano systems. Details of this technique can be found in the literature or any quantum mechanics book [5,6,54,62].

QUANTUM SUPERPOSITION THEORY

Superposition theory is applicable to any linear system described by a vector quantity, wave function, complex algebra, matrix algebra, etc. [54,62]. Let us consider an electron that exists in a system which has two possible *quantum* states and can be represented by Equation (2).

$$\psi_1 = |0\rangle = \begin{bmatrix} 1 \\ 0 \end{bmatrix} \; and \; \psi_2 = |1\rangle = \begin{bmatrix} 0 \\ 1 \end{bmatrix} \quad (2)$$

(Angle-bracket is known as Dirac-ket)

These two orthonormal basis vectors represent a linear two dimensional vector space which is also known as Hilbert space [54, 62].

According to classical mechanics, this electron can either exist in state-one (ψ_1) or state-two (ψ_2) at a certain time and it cannot exist in both states at the same time. This strategy can be represented by a single bit with a value of either 0 or 1 in a classical computing system. But in quantum mechanics it can be described by the probability of the same electron existing at a certain time by the following wave vector described in Equation (3).

$$|\psi\rangle = \alpha|0\rangle + \beta|1\rangle \quad (3)$$

Here α and β are the probability amplitudes and they must satisfy the orthonormal condition described by Equation (4).

$$|\alpha|^2 + |\beta|^2 = 1 \quad (4)$$

Similarly, a two-electron system can be described with two classical bits one of the following values: 00, 11, 01 and 10 shown in Equation (5). But quantum mechanically, the same system can be described with two-qubits as following:

$$|\psi\rangle = \alpha|00\rangle + \beta|01\rangle + \gamma|10\rangle + \delta|11\rangle \quad (5)$$

In a four dimensional Hilbert space with the following four orthonormal basis vectors described in Equation (6) and their orthonormal condition in Equation (7).

$$|00\rangle = \begin{bmatrix} 1 \\ 0 \\ 0 \\ 0 \end{bmatrix}, \; |01\rangle = \begin{bmatrix} 0 \\ 1 \\ 0 \\ 0 \end{bmatrix}, \; |10\rangle = \begin{bmatrix} 0 \\ 0 \\ 1 \\ 0 \end{bmatrix} \text{ and } |11\rangle = \begin{bmatrix} 0 \\ 0 \\ 0 \\ 1 \end{bmatrix} \quad (6)$$

$$|\alpha|^2 + |\beta|^2 + |\gamma|^2 + |\delta|^2 = 1 \quad (7)$$

In general, n bits in a classical computing system can be represented by n qubits in a 2^n dimensional Hilbert space [54,61,62]. The quantum value or state is described by the linear sum of all 2^n orthonormal components. This linear sum is known as quantum superposition. The sum of all square probability amplitudes must be equal to one in order to satisfy the orthonormal condition. More details are available in the literature [54,61,62].

QUANTUM ENTANGLEMENT THEORY

Quantum entanglement is a quantum mechanical phenomenon (characteristic) which is able to describe the quantum states of two separate objects (or particles) with reference to each other, even though they are separated by an infinitely large distance [54,62]. For example, a pair of entangled electrons system where one is located at the north pole with spin up (+1/2) and other is at the south pole with spin down (-1/2). If the electron's spin at the North Pole is changed to spin down then the electron at South Pole would have spin up instantaneously. This instantaneous action at a distance was not recognized by Einstein. He referred this phenomenon as *"Spooky action at a distance"*. This entanglement provides a unique correlation between two measurable quantities. As a result, measurements performed on one object instantaneously influence the other object when they are entangled. The entangled state can be described quantum mechanically as shown in Equation (8).

$$|\psi\rangle = \frac{1}{\sqrt{2}}(|00\rangle + |11\rangle) \quad (8)$$

The quantum entanglement is real and it can leverage the quantum computing process. Many reports have been published with experimental data about quantum entanglement. Entanglement is also possible for more than two objects when they are separated by far distances. Entanglement of a two-particle system is important because, two-state classical logic gates are being used in quantum computing to build qubit logic gates. More detailed information can be found in the literature [54,60,62]. Recently, China has established a secured 2,000-kilometer quantum communications network from Shanghai to Beijing using the entanglement property of quantum cryptography [14]. Entanglement may be used in future teleportation for transferring data faster than the speed of light [63].

RESULTS OF INTRODUCING QUANTUM COMPUTING TO COMPUTER SCIENCE STUDENTS

When children do not know what to do with something new, they usually play with it, and come up with interesting things to do with it. The popularity of computer games is an example of this phenomenon. The National Association for Education of Young Children (NAEYC) has observed that "Play and learning go hand-in-hand. They are not separate activities. They are intertwined. Think about them as a science lecture with a lab" [66].

We have introduced quantum computing to master's level Computer Science and Electrical Engineering student groups in a cybersecurity course. The project builds on what they have learned about Public Key Cryptography. Public Key Cryptography protects vital information transmitted through the Internet. A pair of keys is employed for encrypting and decrypting information. Either key may be used for encryption. The other key in the pair will then reverse the process or decrypt. One key is known as a "public key", while the other key termed a "private key". The strength of the encryption depends on the difficulty of factoring a large number which is the product of two large prime numbers (often 1000 digits or more). Using conventional computers to factor the product of two large prime numbers requires exponential time. As a result, Public Key Cryptography is generally considered reliable. However, Shor's algorithm [67,68] makes it possible for quantum computers to do the factorization in polynomial time. This drastically reduces the time, and threatens the reliability of current approaches to secure transmission of information.

Uhlig et al have shown the effectiveness of small group projects in both online and onsite courses for teaching [69,70,71]. A small group project designed to allow students to "play with" some concepts of quantum computing was introduced three years ago into a cybersecurity course required for all students in our university's MSCS and MSEE programs. The first goal is to show students that quantum computing will undermine what is currently the heart of public key cryptography, but that quantum phenomena should provide an even more powerful approach to encrypting information for transmission over the internet. An important second goal is to alert students that quantum computing is a rapidly developing new aspect of CS, and they need to keep abreast of developments in the field at least during the next few years.

The following is the description of the assigned project provided to the students:

"Quantum computing has the potential for a huge disruption in the computer industry. In particular, it has the potential to make all existing encryption algorithms, including AES and RSA obsolete. Several companies are making a lot of progress on research in Quantum Computing. One of them is Google. You can read a Wall Street Journal Oct 17, 2017 article about Google's research at https://www.wsj.com/articles/how-googles-quantum-computer-could-change-the-world-1508158847. If that link doesn't work for you, ask your instructor for a copy of the article. If you choose this project, your instructor will also provide you with an article entitled, "How quantum computing could unpick encryption to reveal decades of online secrets" to get you started. On the other hand, in June 2016, MIT Technology Review reported on the first experimental demonstration of a "Quantum Enigma Machine." Your instructor will also provide you with a copy of the article. Put together a presentation on the issues, including 1) some essentials of quantum computing, 2) your forecast of how far in the future the disruption might be, and 3) your estimate of whether the "quantum enigma machine" will be the solution. You can also check out http://computer.howstuffworks.com/quantum-computer3.htm , http://www.bloomberg.com/news/articles/2015-12-09/quantum-supercompers-entice-wall-street-vowing-higher-returns and Canadian company D-Wave Systems Inc."

Six different small groups of two to four persons have completed the project during the past three years. Results have demonstrated that the project is an effective way to generate student interest in quantum computing. Each group developed a 10 to 15 minute presentation using voice-over narration of PowerPoint charts. Three groups were in onsite classes and three other groups were in online classes. Students conducted research and commented. They were expected to go beyond the references that were suggested in the project description as starting points – in other words, they were encouraged to "play with" the concept of quantum computing.

Our findings show that: (1) Students did not have any background in quantum physics. (2) Despite all having the same project definition, each group approached the problem slightly differently. Each group tended to focus on different aspects of quantum computing as being the "most important". (3) Some groups were more thorough. Presentations differed a lot, but they all had excellent quality. (4) Each group showed that they understood the basic concepts of qubits and superposition, and they demonstrated a general understanding of how qubits could be used to compute much faster than traditional computers. (5) All discussed the Quantum Enigma machine, (6) Student estimates of when quantum computing would become a threat to existing encryption varied from a few years to two decades. (7) One group provided a very complete explanation of how the encryption key is derived in the Quantum Enigma machine. (8) Grades on the quantum computing project were above the class average for all projects. (9) All six groups were graded either Outstanding or Very Commendable in the rubric for Quality of Research, Original Thinking, and Understanding of the Subject.

TWO PROPOSED QUANTUM COMPUTING COURSES FOR THE MS IN ELECTRICAL ENGINEERING (MSEE) AND MS IN COMPUTER SCIENCE (MSCS) PROGRAMS

The hardest part of teaching quantum computing is getting started with some courses at the current stage of understanding of the field when it is still emerging, and getting tools, administrative supports, and other essential resources. We propose to get started with two graduate level courses initially and then based on the experience, design and develop undergraduate level tools and learning environments for undergraduate courses. The cybersecurity course project that is described above will be used to generate student's interest in the proposed quantum computing courses that will be offered immediately after the cybersecurity course. We initially propose the following two courses (QCS661 and QCS671) at the graduate level, which can be integrated into our existing MS in Electrical Engineering (MSEE) and MS in Computer Science (MSCS) programs. Usually, the graduate students in these programs have some background and understanding of physics and math. Those who do not have a reasonable background, will be provided with developmental support at every levels. If they try, they will succeed – this is the central socio-psychological inspirational goal close to our heart.

QCS661 Introduction of Quantum Computing Concepts (pre-requisite: a cybersecurity course)
This course introduces a brief history of modern physics and quantum mechanical properties of nano objects with some practical examples. It also describes the limitation of classical computing systems and the potential of quantum computing in different areas. Vulnerability of cryptographic protocols based on integer factorization is examined. Students also learn the concepts of qubits and will be able to relate these with the classical bits 0 and 1 in computing.

QCS671 Quantum Computing Methods (pre-requisite: QCS661)
This course introduces the concepts and theories of quantum algorithms. Students will review some popular quantum computing algorithms including Shor's algorithm, Grover's algorithm, Quantum algorithm for systems of linear equations, etc. Students will study quantum logic gates and learn about quantum computing tools (open source) to write some simple programs for quantum computers.

The above description of the courses will be updated as the quantum-computing field changes. The proposed textbook for the courses is "Quantum Computing: A Gentle Introduction" by Rieffel and Polak [74]; chapters 1-6 are proposed for QCS661, and chapters 7-13 for QCS671. Lecture notes prepared by the authors of this paper will supplement the textbook. Several other books including Nielsen and Chuang (2000) [54] will be used as references. Students will develop strong theoretical knowledge in quantum computing and learn about the class of problems known as BQP (bounded-error quantum polynomial time) [54, 72, 73]. We also plan to provide practical experience using programming kits, simulators and the quantum computer of IBM [19].

CHALLENGES AND OPPORTUNITIES FOR WORKFORCE DEVELOPMENT

It is widely recognized by the U.S. Congress [64] and other governmental, industrial, and scientific organizations [65] that creating a "quantum-smart" workforce is extremely important to the nation. However, most of the initiatives are slow and struggling with challenges. Quantum computing concepts are difficult for students and faculty. One of the challenges is that it is hard for students to understand quantum computing without a strong background in quantum mechanics and math. Usually, only a small number of students are adequately prepared for studying quantum computing. However, properly designed collaborations among students in small groups improve student-student interaction in additions to student-teacher interaction and enhance learning opportunities for weaker students [70]. We plan to use a wide variety of interactions in the computer systems security course and the two quantum computing courses proposed in the preceding sections. To offer an introductory course such as QCS661 may require some special care and adjustments in most environments in order to retain students. Many students may need special help, which will be provided in a flexible manner. QCS661 should mainly provide some basic concepts in quantum computing. *Vulnerability of cryptographic protocols based on integer factorization* mentioned in QCS661 is closely related to the projects completed by the students in the security course which precedes QCS661. It is necessary to integrate QCS661 and QCS671 initially in complete graduate programs such as MS in Electrical Engineering (MSEE) and MS in Computer Science (MSCS) programs after generating appropriate interests and motivations from the security course projects described above. In these two courses, students will learn the current trends in quantum computers and computational algorithms developed by famous scientists including Shor and Grover [48-53]. Hopefully, students will develop adequate knowledge for the class of problems knows as BQP (bounded-error quantum polynomial time) [54, 72, 73]. Students will also be provided a free Quantum Development Kit [QDK] to write some quantum computing programs in order to gain some hands on experience before graduation. Reflections on our experience will be disseminated widely to North American universities (using emails, flyers etc.) so that others can learn from our experience. Will Knight reported [16] that Isaac Chuang suspects ". . .that the revolution will not really begin until a new generation of students and hackers get to play with practical machines. Quantum computers require not just different programming languages but a fundamentally different way of thinking about what programming is" [16]].

DISCUSSIONS

Quantum Computing needs multidisciplinary knowledge to fully understand quantum computer hardware and software. This includes quantum physics, computer science, mathematics, electrical engineering and much more depending upon the field where it would be applied. Some quantum computer applications are expected to be in the areas of computational biology, molecular modelling, Big Data analysis, drug development, meteorology (accurate weather forecasting), environmental changes, traffic control systems, artificial intelligence, automated manufacturing, world economics, cybersecurity, etc. The authors of this research paper have backgrounds in Quantum Physics, Computational Science, Biology, and Electrical and Computer Engineering. They have conducted research to identify the current status of quantum computing and the needs of related workforce development. No single place was found where all current and future job openings are listed. Nevertheless, the literature cited in this paper validates the worldwide need for a large number of professionals in the quantum computing field. This discipline is new and it needs work to make our dream come true. National University deals with adult learners who are employed and busy in their family life. These learners need special mentorship and guidance to learn these challenging topics in quantum computing. Most National University students come with work experience and they are already motivated to learn. National University is not highly selective in its admission process. The authors are fulltime faculty members who are fully committed to participate in every aspect of the workforce development process in the proposed quantum computing courses implementation. Our primary job as faculty is to explain a complex subject in a simple way to the learners. The authors of this paper are filled with enthusiasm to develop relevant course materials in quantum computing and teach these in the classroom. We have a flexible agile approach to achieve the primary goals outlined above. All constructive ideas, criticisms, fruitful discussions, collaborations and contributions are welcome by these authors. A clear understanding of the theoretical and practical implications of the quantum computing fields is needed to develop adequate teaching plans for success. We therefore emphasized the knowledge base of the area with sufficient clarity so that the scope and limitations are understood in the current context. For example, D-wave quantum computers are annealing systems that cannot run many well-known algorithms including Shor's algorithm or Grover's algorithm although D-wave computers are useful for many other problems [67, 72].

CONCLUSIONS

Quantum Computing is knocking at our doors. Soon it will be used in different areas for fast, accurate and secured data processing and transmission. Computer Scientists and related professionals must update their knowledge to meet the 21st Century's computational challenges. Academia should offer sufficient quantum computational courses in order to prepare graduates to be ready to work in the field. This is the right time to recognize this urgent and critical need and get ready to contribute appropriately. Many universities worldwide are deeply engaged in Quantum Computing related research [40]. A few universities including UC Berkeley, UC Santa Barbara, MIT, Caltech, Stanford, USC, UW Madison, UT Austin, Oxford, University of Maryland, University of Montreal, University of Sydney, University of Science & Technology of China and University of Waterloo have already started offering quantum computing related courses. However, a crucial challenge of workforce development is to offer courses with quantum computing skills that are in demand on adequate theoretical foundations to diverse student groups in universities and colleges that are not highly selective. We are fully committed to work with all stakeholders in order to succeed in our primary goals of workforce development in quantum computing.

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