Training Needs in Quantum Computing

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Abstract. Quantum computing as a new computing paradigm is carrying a lot of changes in many industries, economy, legal, and other concerns. In addition to this, new training needs are raising to provide the future, demanding professional profiles and even new jobs. This paper analyzes the existing international curriculums as well as some training programs around the world to point out the quantum computing education needs. Thus, this paper defines a quantum computing specialization that can be included within the existing international curriculums.

Keywords: Quantum computing, Education, Training.

1 Quantum Computing

We can identify several different industrial "revolutions" in recent and relatively recent history: the first one took place at the end of the 18th century, thanks to the creation of the steam engine and the telegraph. The second -in the first decade of the 19th century- came about with the advent of the combustion engine fuelled by petrol, alongside electricity, the telephone and the radio. These first two revolutions were followed by a third, provoked by computer science/engineering and the dissemination of Internet.

In the last two decades we have been witnessing another confluence of technologies: social networks, mobile, big data and data analytics, cloud computing, artificial intelligence, 3D printing, virtual and augmented reality, robotics, blockchain, IoT (Internet of Things) and the Internet of Everything, etc., which are bringing about a real "digital revolution/transformation" in companies and organizations.

The next revolution has appeared in our own times; this revolution is the result of the combination of nanotechnology, biotechnology, genomics, and quantum computing. In fact, we can already use quantum computers and take advantage of their huge computational capacity to solve problems that are considered very difficult for "classic" computers.

This new situation has been made possible by the fact that, at the beginning of the last century, many exceptional scientists happened to meet: Planck, Einstein, Bohr, Schrödinger, Born, Dirac, De Broglie, Heisenberg, Pauli, etc. (several of whom won the Nobel prize). Together, they settled the basis for a new Physics theory: quantum mechanics. Quantum mechanics is the field of Physics which describes the behaviour of nature at subatomic levels (photons, electrons, etc.), behaviour for which classical mechanics did not have a satisfactory explanation. Quantum mechanics became increasingly necessary due to the advances achieved by the miniaturization of integrated circuits.

In 1982, Nobel laureate Richard Feynman asked: What kind of computer are we going to use to simulate physics? (Feynman, 1982). He thus inaugurated the “second quantum revolution”; in fact, this was when the idea for a quantum computer was born, and so quantum computer science came into being. Over the last three decades, our understanding of “quantum computers” has expanded drastically, as the efforts to realize such an exotic computer have made steady yet remarkable progress (Maslow, 2019). Using various “counterintuitive” principles, such as superposition and entanglement, quantum computers will provide faster computing speed, providing high value in different important applications.

There are in fact thousands of extremely interesting applications for this new paradigm, in several areas (IDB, 2019):

- Economics and finance services: Portfolio risk optimization and fraud detection, actual randomness for financial models, simulations and scenario analysis, prediction of financial crashes, etc.
- Chemistry: simulations of complex molecules, discovery of new materials, advanced molecular design, etc.
- Medicine and health: Protein folding and drug discovery, disease detection, non-invasive and high-precision surgeries, targeted drug design, tailored medicine, prediction of therapeutic prescriptions, etc.
- Supply chain and logistics: optimization problems in procurement, production and distribution, vehicle routing optimization, etc.
- Energy and agriculture: production of ammonia, better distribution of resources, asset degradation modelling, etc.

As Humble and DeBenedictis (2019) highlight, the prospects of quantum computing are exciting, and extraordinary expectations are now fuelling a global effort that aims to perfect quantum computing. Many countries (China, U.S., Japan, Russia, U.K., etc.) are investing huge quantities in quantum technology. The involvement of governments is highly important, as was evidenced by the introduction of the National Quantum Initiative Act in the United States, the funding of the Institute for Quantum Computing by the Canadian government, or the European “Quantum Manifesto and Quantum Technologies Flagship?”. The long-term vision of the Flagship (EU, 2016) is to develop a so-called quantum web in Europe, where quantum computers, simulators and sensors are interconnected via quantum communication networks.

It should also be observed that the most important companies (Google, IBM, Microsoft, Intel, Atos, Alibaba, etc.) are investigating how to make the most of this new technology for their businesses. There are many tools available for programming quantum systems, both in simulation and with actual hardware: IBM’s Composer (part of the IBM Q Experience), Google’s Quantum Computing Playground, Microsoft’s LIQUi, etc. There are also several open-source quantum platforms available (Fingerhuth et al., 2018).

In conclusion, if the 19th century was the machine age, and the 20th the information age, several experts agree that the 21st will be the quantum age. In fact, “The thing driving the hype is the realization that quantum computing is actually real … It is no longer a physicist’s dream—it is an engineer’s nightmare.” (Knight, 2018). However, for quantum computing to become a more effective reality and an “waking up from the nightmare”, we need quantum computing training and education.

In fact, the EU´s Quantum Flagship Coordination and Support Action (CSA) "QFlag", includes a WP4 for Education, Training and Outreach to “Promote European curricula in Q-engineering and coordinate education activities”. Also the Quantum Software Manifesto , emphasises that “quantum computing education is crucial” and that “the pool of people who have enough knowledge to program a quantum computer is small, so education programs need to be set up and developed, both at university level and in industry”.

2 New jobs in quantum computing

Until a few years ago, most of the new jobs related to quantum computing were research posts. These kinds of jobs have increased dramatically; see for example, www.quantiki.org/, covering post-doc. and professor positions in quantum information theory, quantum sensors, quantum computing theory, quantum information, machine learning in quantum information technologies, etc.

In Chen (2018), several companies point out that “Quantum computer scientists are in high demand right now” and that “There’s definitely a shortage of people coming”. But companies are seeking not only quantum researchers, as Gambetta (2018) observes: “quantum computing has evolved from exploring the fundamental science of quantum information to, more recently, showing that it’s possible to build a quantum computer and make it available for free via the cloud. We refer to this as the transition from quantum science to quantum ready”. For example, IBM request not only Superconducting Qubit Researchers, Quantum Control Researchers, Quantum Error Correction Researchers, Quantum Algorithms Researchers; but also Quantum Computer Architects, Quantum Complexity Theorists, Quantum Cryogenic Engineers, Quantum Microwave Engineers, Quantum FPGA Engineers, Quantum Software Developers, Quantum Community Builders, and Quantum User Experience Designers.

3 Quantum computing in the computing curricula

3.1 ACM/IEEE/AIS/IFIP Curricula

The most prestigious computing curricula disregard quantum computing. In fact, not even once is quantum mentioned either in the Software Engineering 2014 Curriculum Guidelines for Undergraduate Degree Programs in Software Engineering (CC, 2015) or in the MSIS 2016 Global Competency Model for Graduate Degree Programs in Information Systems (CC, 2017a) or Information Technology Curricula (CC, 2017b)..

Only in the Computer Engineering Curricula CE2016 (CC, 2016), in the “4.2 Strategies for Emerging Technologies”, more specifically in the “4.2.1 Applied Emerging Technologies” part, is it commented that “Computer engineers should be aware of applied emerging technologies……Computer engineers are already or will soon be interacting with optical, biological, or quantum computers or they will be designing a new-age robotic system for manufacturing. These newly emergent and modern technologies present challenges to computer engineering students and practitioners that could involve financial and ethical tradeoffs affecting professional practice in a changing world”. But no specific topic is proposed in relation to quantum computing.

In the Computer Science Curricula (CC, 2013), in Information Assurance and Security (IAS) KA (Knowledge Area), Quantum Cryptography is proposed as a topic, and this curricula includes as a learning outcome: “Describe quantum cryptography and the impact of quantum computing on cryptographic algorithms”. In addition, in the Cybersecurity Curricula (CC, 2017c), in the Knowledge Area: Data Security, within the Knowledge Unit of “Cryptography” the subject is mentioned as “Advanced concepts”: “Advanced recent developments: fully homomorphic encryption, obfuscation, quantum cryptography, and KLJN scheme”.

In summary, only quantum cryptography is considered to some extent as a topic for inclusion in computing curricula.

3.2 Online learning platforms

Several online learning platforms offer different courses related to quantum computing.

UDEMY includes the courses: QC151 Quantum Physics for Quantum Computing” and QC051: Math Prerequisites for Quantum Computing, a “C101 Quantum Computing & Quantum Physics for Beginners”, and also a “Master Quantum Computing, Quantum Cryptography, and Quantum Physics with Microsoft Q# (Q Sharp) & IBM Quantum Experience”.

edX offers the quantum courses of Delft University of Technology, and its “Professional Certificate in Quantum 101: Quantum Computing & Quantum Internet”, which includes “The hardware of a Quantum Computer” and “Architecture, Algorithms, and Protocols of a Quantum Computer and Quantum Internet”. On this platform we can also find a “Quantum Machine Learning” course from the University of Toronto; and a set of courses from the Massachusetts Institute of Technology: Quantum Information Science I Part 1, Quantum Information Science I, Part 2, Quantum Information Science I, Part 3, Quantum Information Science II: Efficient Quantum Computing - fault tolerance and complexity, y Quantum Information Science II: Advanced quantum algorithms and information theory.

In Coursera, there is “The Introduction to Quantum Computing” from the Saint Petersburg State University.

Brilliant, with the collaboration of Microsoft and Alphabet X, offers the most comprehensive catalog of courses to “Learn to build quantum algorithms from the ground up with a quantum computer simulated in your browser”. It covers: Introduction, Information, Circuits, Foundational Algorithms, Near-Term Algorithms, Advanced Algorithms, Physical Qubits, etc.

3.3 Other proposals

There are several universities and research centers which offer degrees, masters and PhD courses related to quantum computing. In this section we summarize some of the most relevant.

The University of Waterloo, in collaboration with the Institute for Quantum Computing (IQC), offers a new interdisciplinary graduate program in Quantum Information that leads to MMath, MSc, MASc, and PhD degrees. Through the following courses: QIC 750 - Quantum Information Processing Devices, QIC 885 - Quantum Electronics and Photonics, QIC 890 - Applied Quantum Cryptography, QIC 890 - Applications of Operator Algebras in QIT, QIC 890 - Advanced Topics in Quantum Optics, QIC 890 - Quantum Error Correction and Fault Tolerance, QIC 895 - Programming Quantum Computers, QIC 710 - Quantum Information Processing, QIC 820 - Theory of Quantum Information, QIC 880 - Nanoelectronics for Quantum Information Processing, QIC 890 - Modern Quantum Optics and Nanophotonics, QIC 890 - Spin-Based Quantum Information Processing, QIC 890 - Approximate Representation Theory of Groups and Non-Local Games, QIC 890 - Introduction to Noise Processes, y QIC 890 - Matter Wave Optics and Interferometry.

EHT Zurich proposes a Master of Science in Quantum Engineering with 120 ECTS credits, with different courses of the Department of Information Technology and Electrical Engineering and the Department of Physics.

Duke University offers a “Quantum Computing Concentration” with two tracks: Software and Hardware. “The Software Track prepares students to program and control quantum information devices and builds on the well-established Software Development Concentration”, and “The Hardware Track focuses on the design, fabrication and testing of quantum devices”. The Quantum Computing Concentration is available as part of a research-oriented Master of Science (MS) degree, or an industry-focused Master of Engineering (MEng) degree. The quantum information courses included are: ECE 590: Introduction to Quantum Engineering, ECE 523: Quantum Information and Computation, ECE 590: Quantum Information Theory y ECE 590: Quantum Error Correction.

QuSoft (Research Center for Quantum Software) offers master programs, including courses about: Quantum Computing, Quantum Cryptography, Quantum Information Theory, y Quantum in Business and Society.

The University of Chicago offers bachelor’s and PhD degrees in quantum information science (QIS) fields through the Pritzker School of Molecular Engineering (PME) and the Physical Science Division (PSD).

The University of Wisconsin–Madison offers a master’s degree in quantum computing,

The University of Queensland (UQ) is launching Australia’s first quantum technology master program for students.

4 Proposal for Quantum Computing education

Following the analysis of the international reference curricula, as well as other international and national curricula, it has been observed that quantum informatics is not treated systematically and transversally in computer engineering plans. There are currently curricula or specific courses for quantum computing, but not within the computer engineering plans.

Therefore, this work proposes a subject of quantum informatics composed of several subjects, which could be included in the curricula of Computer Engineering, in order to achieve this specialization.

The proposed name for the subject is 'Quantum Information' and consists of 6 courses. Below are the proposed courses with a list of descriptors for each of them.
We propose the inclusion of quantum courses in all the computing disciplines. We guess a cross-cutting "Quantum Technology" (QT) Knowledge Area (KA) could be created, including six different units with their topics:

QC: Quantum Computing (6 credits)

- Fundamentals of quantum mechanics
- superposition and entanglement
- Qubits and their measurements
- Quantum error correction
- Quantum computers
- Teleportation and quantum networks

QP: Quantum Programming (6 credits)

- Quantum Logic
- Microarchitectures, compilers and programming languages for quantum processors
- Main quantum gates
- Quantum circuits design
- Translation of quantum circuits to quantum code
- Main quantum algorithms: Shor factorization, Grover search, etc.
- Complexity of quantum states

QSD: Quantum System Development (6 credits)

- Quantum software development methodologies
- Analysis and design of quantum systems
- Implementation and integration of quantum and classical systems
- Continuous improvement and integration in the development of quantum systems
- Quantum systems testing
- Evolution and maintenance of quantum software

QAI: Quantum Support for Artificial Intelligence (3 credits)

- Quantum algorithms for machine learning
- Resolution of optimization problems with quantum computing
- Quantum clustering

QS: Quantum Security (6 credits)

- Fundamentals of cybersecurity
- Notions of classical cryptography and limitations
- Quantum cryptography
- Entanglement-based security protocols
- Security of quantum cryptography

QIS: Quantum Information Systems (3 credits)

- Areas of application of quantum systems.
- Legal and ethical aspects of quantum computing
- Government and strategic alignment of quantum information systems
- Operation of quantum information systems

In Table 1 we summarize the inclusion of the various quantum knowledge units in the different ACM/IEEE/AIS/IFIP Curricula; we have also considered a "Data Science" one, because it is becoming common in some countries.

Table 1. Mapping of the proposed courses regarding the exiting curricula

Computing Curriculum	**Subjects**					
	QC	**QP**	**QSD**	**QAI**	**QS**	**QIS**
Computer Engineering	x	x				
Computer Science	x	x		x		
Information Systems			x		x	x
Information Technology		x	x			x
Software Engineering		x	x			x
Cybersecurity	x				x	x
Data Science	x	x		x		

5 CONCLUSIONS

Quantum computing is already a reality, and it is becoming an engineering matter, not only a theoretical issue. This is the case not just as regards hardware, computers or networks; it is also true with respect to software and system development and security. Quantum technology also has a great influence in AI/ML.

Considering all that has been set forth above, it is obvious that it is time to react. It is time to propose and gradually incorporate some units into the different Computer Science curricula if students are to be prepared for the quantum world. These units should be developed between academia and industry in order to fulfil the needs of new positions needed by companies.

Those in leadership in government and in universities must drive the incorporation of quantum subjects in bachelor's, master's and PhD degrees. They must also encourage professors to retrain, and to learn the possibilities and special characteristics that quantum computing could offer.

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