Supply and Demand in the Training of Quantum Software Engineering Workforce

Oferta y Demanda en la Formación de Personal para la Ingeniería de Software Cuántico

Oferta e Procura de Formação de Pessoal em Engenharia de Software Quântico

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Summary. - Quantum Technologies are experiencing significant growth due to substantial investments made by governments worldwide. These investments aim to enhance global competitiveness in this field and position countries as key players. However, facing the changes of this new paradigm requires an increment in the workforce with specialized expertise in Quantum Technologies, particularly in the area of Quantum Computing. In this paper, we present a concise overview of the current quantum computing education offers and an outline of the current job offer landscape. We highlight essential elements for individuals interested in building a career profile in quantum software engineering, including understanding the professional requirements that experts and companies have established. The main goal of this paper is to offer an overview of the current educational and professional landscape in the quantum software engineering field, empowering the next generation of software engineers to thrive in a quantum technology-driven future that will profoundly impact human lives.

Keywords: Quantum Computing; Quantum Software Engineering; Education and Training; Competence Framework.

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Resumen. - *Las tecnologías cuánticas están experimentando un importante crecimiento gracias a las cuantiosas inversiones realizadas por los gobiernos de todo el mundo. El objetivo de estas inversiones es mejorar la competitividad global en este campo y posicionar a los países como actores clave. Sin embargo, afrontar los cambios de este nuevo paradigma, requiere de un incremento de personal con conocimientos especializados en Tecnologías Cuánticas, particularmente en el área de la Computación Cuántica. En este artículo, presentamos una visión concisa de las ofertas actuales de formación en computación cuántica y un esbozo del panorama actual de ofertas de empleo. Destacamos los elementos esenciales para las personas interesadas en construir un perfil profesional en ingeniería de software cuántico, incluida la comprensión de los requisitos profesionales que han establecido los expertos y las empresas. El objetivo principal de este artículo es ofrecer una visión general del panorama educativo y profesional actual en el campo de la ingeniería de software cuántica, capacitando a la próxima generación de ingenieros de software para prosperar en un futuro impulsado por la tecnología cuántica que tendrá un profundo impacto en la vida humana.*

Palabras clave: *Computación cuántica; Ingeniería de Software Cuántico; Educación y Formación; Marco de Competencias.*

Resumo. ***-*** *As tecnologias quânticas estão a registar um crescimento significativo graças a investimentos substanciais por parte dos governos de todo o mundo. O objetivo destes investimentos é melhorar a competitividade global neste domínio e posicionar os países como actores-chave. No entanto, para fazer face às mudanças deste novo paradigma, é necessário um aumento do número de pessoas com conhecimentos especializados em tecnologias quânticas, nomeadamente no domínio da computação quântica. Neste artigo, apresentamos uma visão concisa das actuais ofertas de formação em Computação Quântica e um esboço do atual panorama de ofertas de emprego. Destacamos os elementos essenciais para as pessoas interessadas em construir um perfil profissional em engenharia de software quântico, incluindo a compreensão dos requisitos profissionais estabelecidos por especialistas e empresas. O principal objetivo deste artigo é fornecer uma visão geral do atual panorama educativo e profissional no domínio da engenharia de software quântico, capacitando a próxima geração de engenheiros de software para prosperar num futuro orientado para o quantum que terá um impacto profundo na vida humana.*

Palavras-chave: *Computação Quântica; Engenharia de Software Quântico; Ensino e Formação; Quadro de Competências.*

1. Introduction. - The principles of quantum mechanics were established in the early 1900s. Since then, quantum information theory and hardware advances have made quantum computing a reality. Quantum computers use quantum bits (qubits) as the minimum unit of information instead of the bits of classical computers. Qubits exhibit two important properties of quantum mechanics: superposition and entanglement. Superposition allows qubits to be in multiple states simultaneously until they are measured. Entanglement enables a qubit to be related to another qubit, so their states cannot be described independently. Due to these properties, quantum computers can resolve the problems considered hard for today's computers [1].

Given this advantage, it sounds logical to start using this kind of computer for computationally hard tasks. However, current quantum computers are noisy and susceptible to errors, limiting their practical utility for complex computations and requiring sophisticated error correction techniques to mitigate these problems. Big efforts in the scientific community and enterprises are being made in order to get reliable quantum computers. Globally, substantial funding rounds are underway for projects focused on quantum technology developments, with particular emphasis on the creation of trustworthy quantum computers.

Nevertheless, to use them in a practical manner, it is also needed the development of efficient quantum algorithms and processes (software) to be run on those quantum machines. Likewise, as software engineering has shown, developing those algorithms is not enough since modern software solutions are complex systems that are based on a multi-layered infrastructure, using tools and techniques that enable software engineers to create high-quality solutions. Most of these elements in the field of quantum computing are in their early stages [2].

Applying software engineering to this new type of software is an emerging topic, which consists of bringing the benefits of software engineering to quantum software development. This innovative area, Quantum Software Engineering (QSE), is beginning to emerge as a relevant topic in the worldwide academic and technological forums, such as the "International Workshop on Quantum Software Engineering" held as part of the ICSE conference, or the "IEEE International Conference on Quantum Software" held as part of the IEEE Services conference, or the "Quantum Software Engineering and Technology Workshop" organized as part of the IEEE Quantum Week, or the "Latin American Workshop on Quantum Software Engineering" (Taller Latinoamericano en Ingeniería de Software Cuántico - TLISC).

However, additional efforts are needed to make progress in this emerging field of quantum computing [3]. Today, there is still a low critical mass of researchers and therefore a need to train new researchers and students in the specific aspects of QSE. The amount of resources needed to develop and test quantum solutions is still significant, so there is a need to pool efforts between groups and institutions interested in this field. In addition, the inherently interdisciplinary nature of quantum development, with fundamental contributions from mathematicians and physicists, requires collaborative approaches. Therefore, it is interesting to understand what knowledge and requirements are necessary to train and guide the new generation of quantum software engineers.

This article provides a brief overview of some of the existing educational offerings for training personnel in the field of quantum computing, specifically in quantum software engineering, as well as outlining the knowledge and professional requirements that future quantum software engineers must possess to apply for jobs in the quantum computing industry.

The paper is structured as follows. Section 2 describes the background, presenting the current financial initiatives of countries regarding quantum technologies. Section 3 presents the educational offerings and principal key concepts for quantum software engineers. Finally, Section 4 details the conclusions of this work.

2. Background. - Quantum computing initiatives around the world are experiencing significant growth and investment as researchers, governments, and private companies recognize the potential of quantum technology to revolutionize various industries. These initiatives encompass a wide range of activities, including research and development efforts, investment in infrastructure, and the formation of strategic partnerships. This investment is managed by public-private collaborations to accelerate the development of this new area. By 2023, global investment in quantum technologies

was estimated at USD 38.6 billion [4].

One example of an investment actor is the European Union which, through its Commission, has carried out a project to achieve the implementation and development of Quantum Computing in Europe through public funds. These projects are encompassed under the Quantum Flagship initiative.

Quantum Flagship is a large-scale, long-term research initiative launched in 2018 by the European Commission. This initiative aims to bring quantum technologies closer to research institutions, industry, and investors. To achieve this, the Quantum Flagship initiative has a budget of e 1 billion [5].

Under this initiative, there are projects in various fields such as communications and computing. Among communication projects, can be highlighted the QIA (Quantum Internet Alliance) [6] and the OPENQKD (Open European Quantum Key Distribution Testbed) [7]. In the field of quantum computing, the OpenSuperQ (An Open Superconduction Quantum Computer) project, whose mission is to create an open, hybrid, high-performance quantum computer of up to 100 qubits, and the NEASQ - NExt ApplicationsS of Quantum Computing project, which aims to foster the development of quantum applications that take advantage of existing quantum computers (NISQ) to address real problems in areas such as energy, computing and medicine, stand out [8].

In addition, countries such as Spain are developing their own projects, as in the case of Quantum Spain, which is investing e 60M to promote a national quantum computing infrastructure [9] or Germany, investing e 3 billion action plan in 2023 to strengthen its leadership in quantum research by developing a universal quantum computer by 2026 [4].

As a result of these investments, Europe has become one of the key players in quantum computing start-up investment [10].

Considering this, it is reasonable to recognize that achieving the objectives of these ambitious investment projects, along with the growth of the quantum computing start-up ecosystem and other global initiatives, necessitates an immediate demand for a skilled workforce. This workforce should comprise competent graduates who can provide the industry with specialized expertise in various areas of Quantum Technologies. In order to accomplish this, it is essential to provide robust educational programs that can cultivate specialized professionals in various domains of Quantum Technologies, including Quantum Computing and the even more focused field of Quantum Software Engineering as well as identify the professional qualifications that these specialists should possess based on the role they play in the industry.

3. Supply and Demand in the Training Quantum Software Engineering Workforce. - The continuous advancement in the development of quantum computing must be accompanied by an expansion of the quantum computing talent pool capable of meeting the demands of academia and industry for a quantum-ready workforce. This requires initiatives to cultivate a skilled pool of professionals equipped with the knowledge and expertise necessary to drive progress in the field of quantum computing.
In this section, a brief review of the current educational offerings in quantum computing, as well as the expected requirements for future quantum software engineers, is presented.

3.1. Education. - Further research in the field of quantum computing is necessary if the aim is to achieve the implementation of this new technology in the productive sectors. To achieve this, it is necessary to increase the number of qualified people who can participate in projects related to the development of quantum computing, in particular by developing research projects in the field of quantum software engineering.

The main objective of the educational offer is to provide the necessary technical expertise to apply for a job in the current quantum computing industry. As shown in the work of Maninder Kaur and Araceli Venegas-Gomez [11], there are different ways to get a job in quantum technology, and not only technical skills are needed, but also the so-called soft skills. In the article by Maninder Kaur and Araceli Venegas-Gomez [11], the best way to achieve this goal is to

participate in post-bachelor training programs. Whether through a combination of traditional learning pathways (masters, PhDs) and shorter, hands-on training with participation in real-world projects.

Currently, the academic offer on the subject of quantum computing is growing. Various training platforms, such as EdX or Udemy, and universities and organizations such as IBM, Google, and Microsoft offer courses and master's degrees focused on this area. However, most of these offers are focused on general introductory aspects or deal with quantum computing from a low level. In a few cases, such as the University of Chicago course offered at EdX [12], or the courses offered by the University of Castilla-La Mancha [13] or the University of Extremadura [14], the focus is on the basic aspects of Software Engineering, such as algorithm development, use of development platforms and simulation tools, application of classical software techniques to quantum environments, among others.

Within the framework of the creation of training programs, the Quantum Flagship initiative, which has presented the Quantum Technology Education portal [15], is noteworthy. This ambitious initiative has the fundamental objective of establishing a solid learning ecosystem that is essential for the dissemination and education of society with regard to quantum technologies. Another goal of the Quantum Flagship initiative for the years 2023-2026, is to foster the creation of a pan-European ecosystem of academic institutions and create an incentive structure for cooperation [16].

According to the work of Zhao [17], there are several key elements that every future quantum software engineer must understand and learn. These elements are:

- A concise overview of the key principles that underpin quantum computation. This topic encompasses essential concepts such as superposition, entanglement, interference, and quantum measurement.
- A description of qubits and fundamental quantum gates and their operations. Special attention should be given to quantum parallelism, which enables quantum computers to execute multiple calculations concurrently.
- A representation of quantum circuits and algorithms.
- An introduction to quantum algorithms focuses on existing examples such as the Shor or Grover algorithms.
- An overview of quantum hardware technologies elucidating the current state of quantum hardware development.
- An introduction to quantum programming languages and current software development kits.
- An initiation to quantum error correction and fault-tolerant quantum computing, explaining noise and decoherence concepts and error correction algorithms.
- An overview of quantum software applications in real-world use cases.
- A hands-on experience by presenting challenges in Quantum Information Processing.
- Practical Labs, Simulations, and Applied Projects for students to assess comprehension and potentially refine teaching methods.

Against this background, we see that efforts in developing quantum software course initiatives are needed to address the relative scarcity in the educational offer in the aspects of Quantum Software Engineering.

3.2. Careers Profiles. - In order to boost the development of quantum technologies and, in particular, those related to the field of Quantum Software Engineering, there must be professionals with appropriate training. This aspect is important, and the training line must be aligned with the generation of these new specific profiles. There is a document, European Competence Framework for Quantum Technologies (ECFQT) [18] that forms part of the Quantum Flagship project. This document sets out a scenario of professional profiles with certain competencies and skills in quantum technologies. These profiles are intended to serve as examples of the competencies that a person should acquire through training programs in preparation for employment in the industry. Also, in this document provides a general description of a Quantum Hardware/Software specialist, "someone who knows the big picture of the technology, related applications, and has an advanced understanding of the underlying quantum concepts (physics/mathematics/information theory), a role that has different characteristics in 'traditional' roles depending on experience".

According to the ECFQT document, future professionals in the field of quantum computing must possess a series of knowledge and skills in some areas of quantum technologies according to their professional roles. In the case of Quantum Hardware-Software Specialists, these core skills and knowledge are the following:

- Having a foundational theoretical understanding of quantum physics principles (fundamental concepts, mathematical frameworks, qubit dynamics) and the underlying physical principles of quantum technologies (atomic physics, quantum optics, solid-state physics serving as the groundwork for quantum technologies). This knowledge enables the description and analysis of real-world issues using mathematical models, the selection of appropriate quantum methods for problem-solving, and the assurance that quantum physical criteria are satisfied.
- Advanced expertise in a specific aspect of quantum technology and a keen understanding of the interrelationships among various facets of quantum technology and classical systems. Proficiency in integrating methods, including those for hybrid quantum systems, and the capability to enhance or expand systems, amalgamate a quantum core with diverse components into a (hybrid) system or application (both hardware and software), and oversee quantum technology manufacturing processes. Cutting-edge knowledge of a particular facet of quantum technology and its interconnections with diverse facets. Proficiency in innovating within the realm of quantum technology, whether it involves the core, system, or application, and the capacity to evaluate and appraise solutions while pushing the boundaries of current technology.
- Familiarity with diverse potential applications and methodologies, along with their respective advantages and disadvantages, as well as relevant providers and experts. Specialized expertise in a chosen quantum technology application or specific application domain. Proficiency in evaluating and selecting the most suitable application or approach for a given problem or scenario.

As outlined in the European Competence Framework for Quantum Technologies [18], the educational journey of Quantum Hardware-Software specialists should begin with advanced qualifications in the traditional/classical field, followed by self-directed learning and participation in master's programs that encompass Quantum Technology.

Upon examining current opportunities in Quantum Computing on platforms such as LinkedIn[7]or The Quantum Consortium[8], it becomes evident that the majority of positions are centered around the foundational aspects of Quantum Computing. However, there is a growing trend of job offerings that necessitate classical software knowledge and skills. Many of these positions require a master's degree, a minimum of two years of experience, and proficiency in the English language.

4. Conclusions. - Quantum computing is a disruptive computing paradigm that offers solutions to challenges beyond the reach of classical computers. To effectively harness the power of quantum computers, the development of quantum software is paramount. As the demand for skilled professionals in this field grows, there is an urgent need for individuals with the necessary knowledge and expertise to fill job vacancies in the coming years.

To address this need, a concise overview of current educational opportunities in quantum computing and quantum software engineering is provided. It also examines the competencies required to excel as a quantum software specialist, which cover a wide range of capabilities, from basic theoretical knowledge to specialized expertise in specific areas. The paper also highlights the importance of understanding the connections between quantum and classical systems, as well as the ability to assess and select appropriate applications for real-world scenarios, which the future quantum software engineers should possess.

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4. Discussion of the results
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