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A report on teaching a series of online lectures on quantum computing from CERN

Elías F. Combarro[1,2] · Sofia Vallecorsa[2] · Luis J. Rodríguez-Muñiz[3] · Álvaro Aguilar-González[3] · José Ranilla[1] · Alberto Di Meglio[2]

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Abstract
Quantum computing (QC) is one of the most promising new technologies for High Performance Computing. Its potential use in High Energy Physics has lead CERN, one of the top world users of large-scale distributed computing, to start programmes such as the Quantum Technology Initiative (QTI) to further assess and explore the applications of QC. As a part of QTI, CERN offered, in November–December 2020, a free, online series of lectures on quantum computing. In this paper, we report on the experience of designing and delivering these lectures, evaluating them in the broader context of computing education and training. Traditional textbooks and courses on QC usually focus on physical concepts and assume some knowledge of advanced mathematical and physical topics from the student. Our lectures were designed with the objective of reducing the prerequisites to the bare minimum as well as focusing on hands-on, practical aspects of programming quantum computers and not on the mathematical analysis of the algorithms. This also allowed us to include contents that are not usually covered in introductory courses, such as quantum machine learning and quantum annealing. The evaluation of the reception of the lectures shows that participants significantly increased their knowledge, validating the proposed approach not focused on mathematics and physics but on algorithmic and implementation aspects.

Keywords Quantum computing · HPC · Education · High energy physics

✉ José Ranilla
ranilla@uniovi.es

Extended author information available on the last page of the article

1 Introduction

The European Organization for Nuclear Research, most commonly known as CERN (from French *Conseil Européen pour la Recherche Nucléaire*), is one of the research institutes with highest computational needs in the world. For instance, the experiments of the Large Hadron Collider (LHC) produce about 90 petabytes of data every year and other, non-LHC-related experiments contribute another 25 petabytes of data per year[1]. For this reason, CERN has always been one of the biggest promoters and users of High Throughput Computing (HTC) and, more recently, High Performance Computing (HPC) technologies in the world.

Quantum computing (QC) [35] is a computing paradigm that exploits properties of subatomic particles, such as superposition, entanglement and interference, to perform certain tasks with a speed-up over what is possible with classical computers. Chief among quantum algorithms are Shor's celebrated method for factoring integers [43] and Grover's famous search algorithm [25], which are, respectively, exponentially and quadratically faster than the best available classical counterparts.

In the last few years, an increasing effort has been made to develop and build quantum computers capable of solving practical problems. In late 2019, researchers at Google announced that they had succeeded in running a task on a quantum computer that would be infeasible to perform with even the most advanced classical supercomputer available [5]. These hardware improvements have gone hand-in-hand with the proposal of new quantum algorithms which can be used for High Energy Physics (HEP) computational tasks and with the development of initial prototypes for concrete problems in the field [27, 42].

At CERN, the research activities around quantum information processing technologies crystallized in 2020 in the creation of the Quantum Technology Initiative (QTI), which encompasses the areas of quantum computing, quantum communication, quantum sensing and quantum simulation. One key aspect in the activities of CERN's QTI is the creation and promotion of educational resources in these areas, that are still relatively unknown among researchers and HPC users.

As a part of such educational effort, from November the 6th until December the 18th 2020, CERN offered a weekly series of online lectures called "A Practical Introduction to Quantum Computing: From Qubits to Quantum Machine Learning and Beyond". The lectures were webcast on CERN's website and also recorded and later published on both CERN's Document Server (CDS) and CERN's YouTube channel, reaching several thousand people from all over the world and quickly becoming the most popular CERN's lecture videos ever by a wide margin (cf. Sect. 5.1).

The main novelties of this series of lectures are reducing the mathematical prerequisites to a bare minimum (just some basic linear algebra) and focusing on the task of practical quantum computer programming rather than on physical implementation aspects or on complexity analysis of the algorithms. This helped in reaching a rather large audience with different backgrounds, many of them with no prior

[1] https://home.cern/science/computing/storage.

knowledge of quantum physics. Also, we introduced some topics which are not usually taught in introductory QC lectures (such as quantum annealing, variational algorithms for optimization problems and quantum machine learning; see Table 1 and Fig. 5), but that can be used with current quantum hardware and help highlight the practical applications of quantum computing.

In this work, we report on the experience of designing and running such lectures in the broader context of CERN's quantum computing activities and of HPC education and training in general. We also analyse the impact of the lectures through the results of a survey taken by a large numbers of the course participants who largely praised the teaching approach, something that makes us conclude that this method may be valid for teaching quantum computing to students without a previous background on quantum theory.

The rest of the paper is organized as follows. Section 2 describes CERN's computational needs, its involvement in large-scale computing infrastructures and HPC, and introduces CERN's Quantum Technology Initiative. The challenges and opportunities of teaching QC are discussed in Sect. 3, while Sect. 4 describes the design and contents of our QC lectures as well as their practical implementation. The lectures are evaluated in Sect. 5, where we present the questions of the participant survey and we analyse the results of the answers. Finally, in Sect. 6 we draw some conclusions of the whole experience and its relationship to the wider task of HPC education.

2 CERN and large-scale computing infrastructures from the grid to quantum

The European Organization for Nuclear Research, or CERN, was founded in 1954 with the purpose of providing for "[...] collaboration among European States in nuclear research of a pure scientific and fundamental character, and in research essentially related thereto" [1]. CERN vocation for knowledge sharing, education and promotion of peaceful scientific and social values is therefore a cornerstone of the Organization.

The importance of computing technologies for research and information sharing led in 1989 at CERN to the definition by Tim Berners-Lee of the Hypertext Transfer Protocol (HTTP) that marked the invention of the World-Wide Web and the scientific, economic, and social revolution that in less than fifteen years gave rise to most of the large-scale computing and data infrastructures we know today. In the past 30 years, CERN has actively contributed to evolving the international computing and data sharing infrastructures to support the computational needs of the High-Energy Physics community, but also for the more general benefit of broad scientific research. Grid Computing and Grid infrastructures [22] were deployed at the beginning of this century and since 2006, starting year of the LHC, have allowed the community to execute billions of simulations and data analysis jobs for its four LHC experiments, ATLAS, CMS, LHCb, and Alice.

Although the Worldwide LHC Computing Grid (WLCG) infrastructure has worked remarkably well until now and is expected to work well for quite a few more years, the computing and storage requirements for the upcoming High-Luminosity Large Hadron Collider (HL-LHC) programme represent a considerable challenge, which has prompted in the past few years the HEP community to explore new computing paradigms and technologies. The interest in applications of machine learning and deep learning techniques for simulation, track reconstruction, and data classification has triggered an intense activity of research in accelerated computing architectures (GPUs, FPGAs, IPUs, TPUs, etc.) and HPC infrastructures through several initiatives, including the CERN openlab, started in 2001 with the mandate of setting up R&D projects in support of the physics research programmes. Today, CERN openlab runs more than 30 different projects in accelerated computing technologies, cloud and HPC infrastructures, artificial intelligence, and quantum computing.

In 2020, CERN openlab promoted the creation of the Quantum Technology Initiative (QTI) to explore the possibilities of the main four areas of today's quantum technologies, computing, sensing and metrology, communications, and quantum simulation and information processing, for the High Energy Physics community in general and for CERN in particular.

The creation of an initiative for quantum technologies comes naturally to an institution like CERN for several reasons. First, CERN is in the unique position of having in one place the diverse set of skills and technologies—including software, computing and data science, theory, sensors, cryogenics, electronics, and material science—necessary for a multidisciplinary endeavour like Quantum Technologies (QT). CERN also has compelling use cases that create ideal conditions to compare classic and quantum approaches to certain applications and exploit the possibilities offered by High Performance Computing resources to support large-scale quantum computing simulations.

The main objectives of the QTI are therefore to define a strategy to assess the long-term benefits of quantum technologies, set up concrete R&D project to evaluate and contribute to the advancement of the state of the art, and to establish an international academic, education, and training programme in collaboration with leading experts, universities, and industry to expand awareness and build skills in this emerging field.

One of the rst activities in this direction is the introductory series of online lectures that we describe in detail in the following sections, after explaining some of the unique challenges found when teaching quantum computing.

3 Teaching quantum computing: challenges and opportunities

Quantum computing [35] is a computational paradigm that uses properties of subatomic particles to achieve speed-ups over classical algorithms for certain tasks. The minimal information unit in QC is the qubit, which in its more general form can be in a superposition, i.e. a linear combination

$$\alpha|0\rangle + \beta|1\rangle$$

where α and β are complex numbers such that $|\alpha|^2 + |\beta|^2 = 1$, and $|0\rangle$ and $|1\rangle$ form an orthonormal basis in a two-dimensional Hilbert space. These basis elements are the analogous of the 0 and 1 values that a bit can have in classical computing and are, also, the only possible results that we can obtain when we measure a qubit. Moreover, such a measurement gives a probabilistic result, with $|\alpha|^2$ being the probability of obtaining $|0\rangle$ and $|\beta|^2$ being the probability of obtaining $|1\rangle$. This measurement produces a collapse of the qubit state, which will subsequently be $|0\rangle$ or $|1\rangle$, according to the result just obtained.

When we combine several qubits, the possible values of the system are the normalized elements of the tensor product of the individual qubits Hilbert spaces. Again, these states can be superpositions of the basis elements. If we have n qubits, the dimension of the Hilbert space is 2^n and the system state can be a non-trivial combination of all the possible binary strings of length n, an exponential advantage over the classical case.

The operations that we can perform on the qubits state are given by unitary transformations, that is, linear functions which preserve the inner product and, hence, the normalization condition. This linearity of the operations, together with the possibility of working with superpositions of the 2^n basis states, allows us to evaluate functions on an exponential number of points with just one call, something that is usually called "massive quantum parallelism".

Quantum parallelism by itself does not offer an advantage over classical computers because the retrieval of the results (and subsequent collapse of the state) is still stochastical. However, when used together with other properties of quantum states, such as entanglement and interference, it can lead to the definition of quantum algorithms that achieve a speed-up over their classical counterparts. For instance, Shor's algorithm for integer factorization [43] is exponentially more efficient that the best classical algorithm that has been discovered for the same task, while Grover's algorithm [25] achieves a quadratic advantage over any possible classical algorithm for the search problem in the black-box setting.

Quantum algorithms, however, are notably different from classical ones. To their probabilistic nature, we need to add the fact that all operations, with the exception of measurements, are reversible. Moreover, some of the basic ingredients of these quantum algorithms, such as superposition, entanglement and interference, lead to properties that are famously far from being intuitive and that sometimes have even been called paradoxical [4, 30]. One striking example (which is especially relevant when comparing classical and quantum programming) is the impossibility of copying quantum information because of the no-cloning theorem [18, 45]. In addition to these intrinsic conceptual difficulties, the design and analysis of quantum algorithms use notions that are at the intersection of many different fields, including Physics, Mathematics, Computer Science and Statistics.

All this makes the task of teaching quantum computing a challenging one, especially when the prospective students have backgrounds which cover only part of the concepts required to describe and study quantum algorithms (for instance, if they come only from the field of Computer Science or Software Engineering). Moreover, many of the available teaching resources and scientific papers use terminologies and adopt approaches that are only accessible for students with a certain background [41], imposing an almost insurmountable barrier to a more general audience.

The last few years have seen a growing interest in quantum technologies and a dramatic increase in investments in the field, both from governments and from private companies [26]. As a consequence, the demand of highly qualified workers with quantum computing and quantum engineering skills has also increased remarkably, and it has been reported [23, 37] that traditional graduate, master and PhD programs are sometimes not being able to train all the professionals needed to fulfil these positions. This has led to claims of a “shortage” [32, 33] or even a “quantum bottleneck” [38] in the industry.

In this context, several researchers [7, 23, 31, 34, 39, 44] have designed and proposed guidelines for graduate and undergraduate curricula that can help train the quantum information researchers, programmers and engineers of the future. For instance, the authors of [23] mention that

> *there is still a large number of challenges in developing effective pedagogy to train students who are familiar with classical algorithms in the different paradigm associated with quantum algorithms*

and suggest that

> *one thing that a higher-education institution could do is introduce an intro-level quantum course focusing on either the hardware or algorithms aspects of quantum information science. Such a course would have appeal as both general interest as well as be useful for a variety of science, technology, engineering, and math majors.*

Similar recommendations are given in [7, 31, 34, 39, 44], which also report successful experiences on teaching introductory QC courses to students with different backgrounds (including Computer Science and Software Engineering majors), with a hands-on approach and a focus on implementing quantum algorithms on quantum simulators and actual quantum computers. Their results show that this methodology, tried at different educational levels and in different countries, is useful to engage the audience and help them learn the fundamentals of quantum programming even if they have no prior knowledge of quantum mechanics.

Two of the authors of this paper have experience on teaching, at the graduate level, quantum information processing topics with comparable methodologies and with results that are consistent with those cited above. For these reasons, a similar approach was used to guide the design of CERN’s online, introductory lectures on quantum computing, whose goals and contents we describe in detail in the following section. The high, worldwide reach that our lectures achieved, put us in a privileged perspective to evaluate this approach to QC teaching with a bigger, more diverse group of students than any of the initiatives cited above, something that we do in Sect. 5.

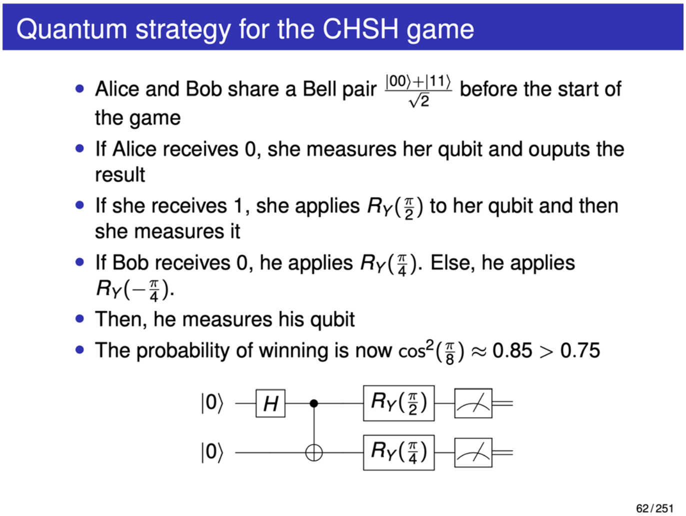

Fig. 1 Actual slide used in the lectures. The mathematical derivation of the winning probabilities in the CHSH game is replaced by a circuit that, as the students checked with the help of Quirk, gives the correct results

4 A practical introduction to quantum computing: CERN's online lectures on quantum computing

CERN's introductory lectures on quantum computing were conceived, from the very beginning, to be accessible for an audience as wide as possible. We drew heavily from the QC teaching experience of two of the authors of this paper[2], who have been delivering courses that merge quantum information processing and HPC topics since 2018 at the Universities of Oviedo, Almería and Castile-La Mancha, in Spain, as well as on-demand courses for several private companies. All these courses had been designed with guiding principles along the lines of those mentioned in [7, 23, 31, 34, 39, 44], aiming to tackle the challenges discussed in Sect. 3. The founding principle was to characterize the lectures as a mixture of a non-formal online education [17] and science dissemination approach [19], due to being framed within CERN's organization. Thus, this led us to formulate two complementary directives that, in turn, shaped the contents and format of the present series of lectures.

The first one was to reduce the prerequisites to a bare minimum. Although the lectures were delivered from CERN, the intended audience was not restricted to researchers with a solid background in quantum physics. In fact, a great fraction of the target public for the lectures came from IT departments inside and outside CERN. Thus, we only assumed previous knowledge of basic linear algebra. Moreover, throughout all the lectures, we adopted an axiomatic approach,

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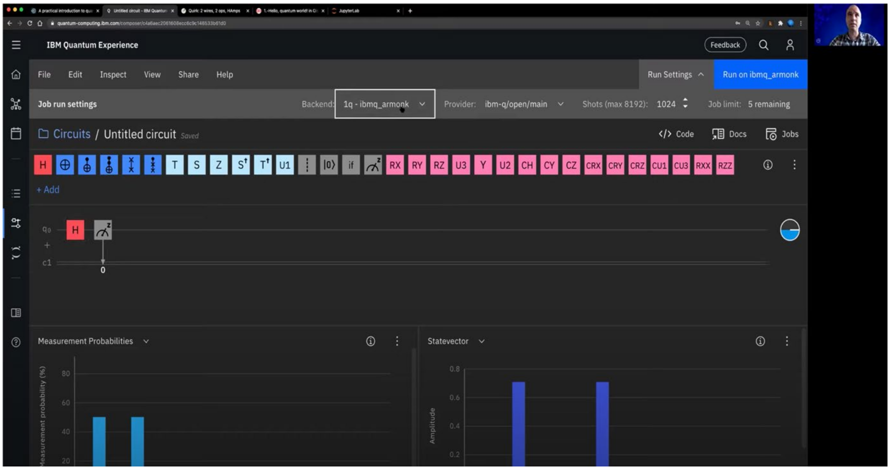

Fig. 2 One moment in the live lectures. The lecturer, in the top right corner, is explaining how to use an actual quantum computer to execute a simple quantum circuit

describing the elements of quantum computing (qubits, unitary transformations and measurements) as if they were abstract data types and operations and without explaining their physical implementation. This approach is analogous to the way in which modern computer programming courses are taught (with no reference to the physical equations governing the electronic elements which form a computer) and it is the one recommended, for instance, in [2, 7, 34, 39]. We also reduced the number of mathematical proofs, replacing them with sketches of computations and referring the interested students to more detailed treatments from a list of recommended resources. Figure 1 illustrates this in the case of the explanation of the CHSH game. Instead of the usual approach of showing the detailed computation of the winning probabilities when entangled qubits are used, we provided a quantum circuit that later was checked by the students, with the help of Quirk, to give the correct results.

The second directive was to focus on actual implementations of all the protocols and algorithms covered in the lectures. We strongly believe that, for quantum computing to become a transformative technology, practical quantum applications must be produced in the near/medium term. In order for this to be possible, a strong understanding of the principles of quantum information processing must go hand-in-hand with a deep knowledge of the practical aspects of quantum programming. This vision is very close to that proposed in [34] and requires the use of a programming environment in which the students can run actual quantum programs on both simulator and actual quantum hardware. In our lectures, we used both, as illustrated in, for instance, Figs. 2 and 4.

In addition, this applied approach liberated us from focusing too much on the mathematical formalism and allowed us to cover topics such as quantum variational algorithms for optimization problems, quantum annealing or quantum machine learning, that are rarely taught in introductory QC courses.

These two directives were clearly stated in the title of the lectures, *A Practical Introduction to Quantum Computing*, with the "practical" and "introduction" aspects corresponding to the second and first guidelines, respectively. The rest of this section is devoted to explaining in detail how we translated these two directives into the design of the format, contents and teaching materials of the lectures.

4.1 Format of the online lectures

The course was organized as a series of seven weekly, live online lectures that ran from the 6th of November until the 18th of December 2020. The lectures were delivered by one of the authors of this paper[3] who participated in a Zoom call with around 50 researchers and students associated to CERN (see Fig. 2). Each lecture had a duration of two hours (from 10:30 am to 12:30 pm, Geneva time) and was also broadcasted live from CERN's website. This webcast was free to watch and available from anywhere in the world (see Sect. 5 for more details on the origin of the audience). It was typically followed by several hundred people live each week (see Sect. 5.1).

In addition to the live Zoom session and the free webcast, all the lectures were recorded and published on both CERN's Document Server (CDS)[4] and CERN Lectures YouTube Channel[5], with the aim of reaching as wide an audience as possible. The schedule of the lectures, with just two hours per week, was also decided so the students could have the opportunity of catching up, by watching the recorded lectures, if they happened to miss one (or several) of them. These recordings reached several thousand people each, an order of magnitude bigger than the live audience following the lectures (cf. Sect. 5.1).

The participants in the live Zoom session had the chance of interacting with the instructor at any moment, in order to ask questions and request clarifications. Those students following the lectures through the webcast or the recorded sessions were invited to submit questions by email. A selection of the most frequent and interesting questions were answered by the instructor at the beginning of each lecture.

4.2 Contents of the lectures

As previously mentioned, the series of lectures was designed to be an introduction to quantum computing that could be followed by any person with only knowledge of basic linear algebra. This guideline, together with the limited amount of time available (14 hours total), made the decision of what contents to include in the lectures a difficult and crucial one.

On the one hand, the basic elements of the model of quantum computation (qubits, unitary transformations, measurement, superposition, entanglement,

[3] Elías F. Combarro.

[4] https://cds.cern.ch/.

[5] https://www.youtube.com/channel/UCwXkOx0EuKBR5m_OOiaZRUA.

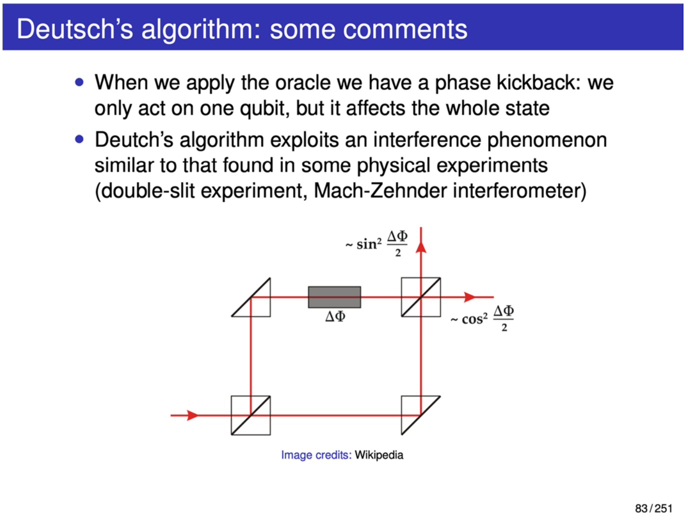

Fig. 3 Actual slide used in the lectures. The Mach-Zehnder interferometer illustrates the operation of Deutsch's algorithm

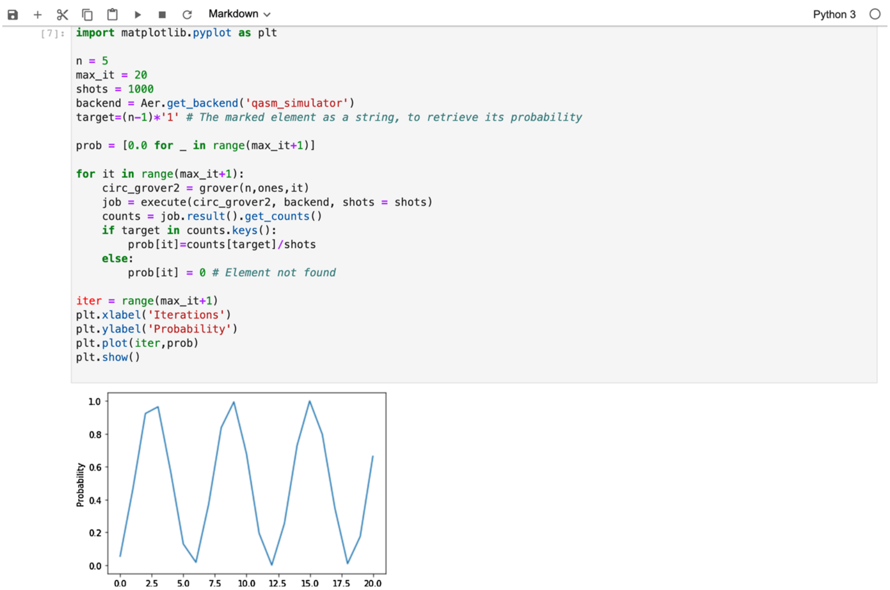

Fig. 4 Detail of one the programs used in the lectures to exemplify the probability of finding a marked element with Grover's algorithm

interference, quantum parallelism...) are unavoidable and must be delivered with special care because they constitute the basis of the inner workings of quantum algorithms. On the other, as stated in our second directive, we wanted this to be a practical course, with a focus on protocols and methods that can be used with quantum

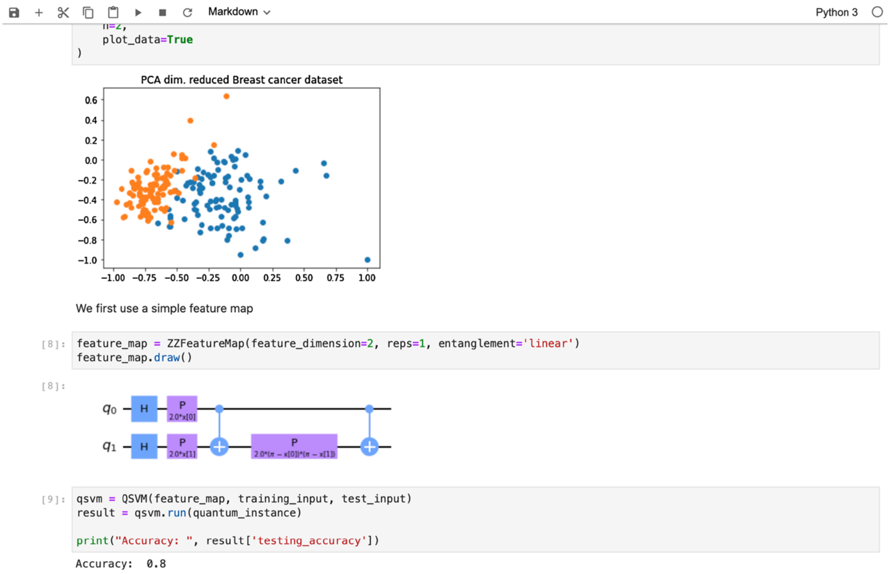

Fig. 5 Detail of one the programs used in the lectures in which a quantum support vector machine is applied for a classification task

computers and simulators, so paying only attention to the theoretical aspects of quantum computing was not an option.

The solution we adopted was to introduce each theoretical concept together with an application. For instance, the concept of superposition was illustrated by the possibility of generating random bits with a single-qubit circuit (cf. [12]) (see Fig. 2), the idea of entanglement was exemplified with the CHSH game [11] (see Fig. 1), and the use of interference and its use in quantum computations were explored with a connection between the Deutsch algorithm [15] and the Mach-Zehnder interferometer experiment [46] (see Fig. 3).

One difference of our lectures with other approaches to teaching quantum computing at the introductory level is that we expended a large fraction of the time explaining concepts and examples which use just one or two qubits. In fact, the first three lectures were devoted to this few-qubit systems and only in the forth session did we introduce the idea of a general, n-qubit system. This may seem strange, especially because of the reduced number of lectures of our series, but this approach allow us to treat more complicated algorithms such as Grover's search [25] (see Fig. 4) or Shor's factorization method [43] (see Fig. 6) in a way such that the students can relate the new ideas to the concepts that they have interiorized in simpler situations.

Another particularity of our lectures is that, in addition to algorithms that can be found in most quantum computing textbooks (such as Grover's, Shor's or Deutsch-Jozsa's [16] methods), we also devoted some of the lectures to introduce more modern algorithms, such as the quantum approximate optimization algorithm [20], the variational quantum eigensolver [36] or recent proposals in

Table 1 Detailed contents of "A Practical Introduction to Quantum Computing: from qubits to quantum machine learning and beyond"

Lecture	Title	Contents
1	Introduction	What is quantum computing?
		Applications of quantum computing
		Hardware and software for quantum computing
		Elements of the quantum circuit model
		Introduction to the IBM Quantum Experience
2	One- and two-qubit systems (Part 1)	Quantum key distribution with the BB84 protocol
		Two-qubit gates
		The CHSH game
3	One- and two-qubit systems (Part 2)	Quantum teleportation
		Superdense coding
		Deutsch algorithm
4	Multiqubit systems	Multiqubit gates and universality
		Quantum parallelism
		Deutsch-Jozsa algorithm
		Grover algorithm
		Shor algorithm
5	Quantum algorithms	Quantum adiabatic computing and quantum annealing
	for combinatorial optimization	Introduction to D-Wave Leap
		Quantum approximate optimization algorithm
6	Quantum variational algorithms	Variational quantum eigensolver
	and quantum machine learning	Quantum support vector machines
		Quantum neural networks
		Quantum generative adversarial networks
7	The future of quantum computing	Quantum error correction
		What is quantum supremacy?
		Prospects for quantum computing

The title of each lecture links to the webpage where the slides, code and recordings can be freely accessed

the field of Quantum Machine Learning, such as the Quantum Support Vector Machines [28] or the Quantum Generative Adversarial Networks [47] (see Fig. 5 for an example of the kind of applied implementation of these algorithms used in the lectures). This was particularly helpful in achieving our objective of offering practical content, because it allowed us to present examples rooted in High Energy Physics applications, including some in which researchers from CERN and CERN openlab have actively worked (see [8–10, 21, 27]).

The concrete contents of each of the seven lectures can be seen, together with links to each lecture web page where the materials and recordings can be found, in Table 1.

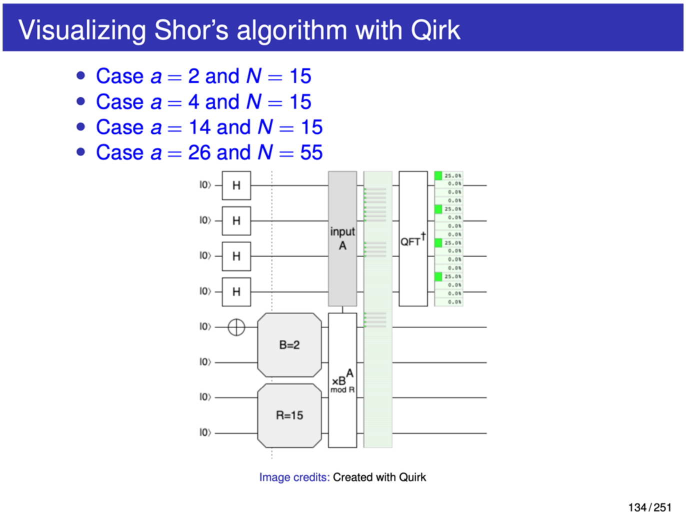

Fig. 6 Actual slide used in the lectures. Notice the links to already implemented circuits for Shor's algorithm that the students can interact with and modify to observe the change in results

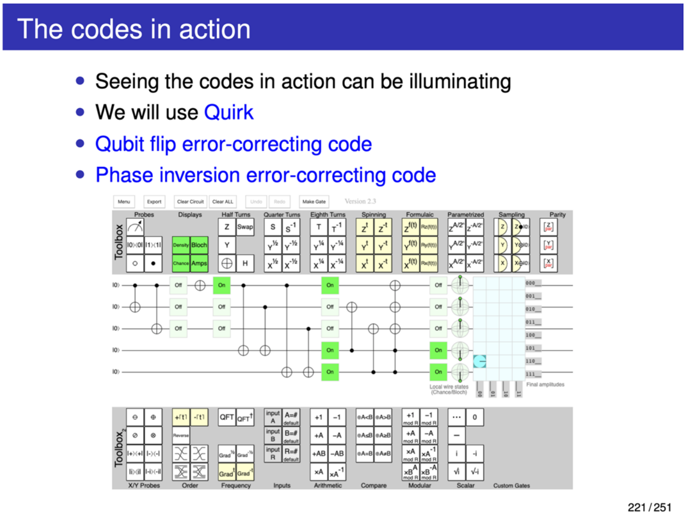

Fig. 7 Actual slide used in the lectures. The links take the students to visual implementations of quantum error correcting codes that they can easily interact with to learn about the type of errors that can be detected and corrected with each code

4.3 Teaching materials and resources

Several different types of teaching materials were shared with the students through the web pages of the lectures[6]. The first one was a set of 251 slides (see Figs. 1,

6 https://indico.cern.ch/event/970903/.

3, 6 and 7 for actual examples or access the whole set of slides through the links in Table 1) that were used by the instructor during the live sessions. Some of the content of these slides is an adaption of previously existing materials that two of the authors of this paper[7] had used in related courses taught, at the graduate level, at the Spanish universities of Oviedo, Almería and Castile-La Mancha. This material was reviewed, adapted and translated into English and constitutes about 90% of the slides used in Lectures 1 through 4. All the slides used in Lecture 6 and most of the ones used in Lectures 5 and 7 were created specifically for this course.

A second type of material that we provided to the students was a set of Jupyter notebooks and Python programs with implementations of the algorithms and protocols studied in the lectures (see Figs. 4 and 5 for two examples). Almost all the implementations were done using IBM's Qiskit [3]. The only exception was the use of the D-Wave Ocean Python library [14] to show how to solve optimization problems with quantum annealing. A total of 16 notebooks were available to the students. Of them, 10 were adapted from material previously used at the Spanish universities mentioned above and the other 6 were created from scratch, specifically for the lectures.

All the programs were completely functional and ready to be run on quantum simulators and actual quantum devices and, in fact, live demonstrations of all of them were done during the lectures (see Fig. 2). For that, we used The IBM Quantum Experience [29], which offers free cloud access to simulators and to quantum computers of up to 16 qubits, and D-Wave's Leap [13], which allows to use two different quantum annealers to run quantum programs for one minute per month.

In addition to The IBM Quantum Experience and D-Wave's Leap, the Quirk simulator [24] was extensively used to help visualize geometrical properties of quantum states and simple quantum circuits. Pre-constructed circuits were provided to the students through web links that lead to implementations in the simulator. In Figs. 6 and 7, we show two examples of slides in which links to already implemented circuits for Shor's algorithm and quantum error correcting codes are provided. These implementations are interactive, so the students can easily modify the parameters and immediately observe the effect in the results.

A list of recommended books and other resources was also made available to the students through the web pages of the lectures (see Table 1 for links to the web page of each of the lectures, where the materials can be freely downloaded).

5 Evaluation of the lectures: reception, survey and results

In this section, we evaluate the lectures by taking a look at their reception and by analysing the results of a feedback survey that we run at the end of the lectures.

[7] Elías F. Combarro and José Ranilla.

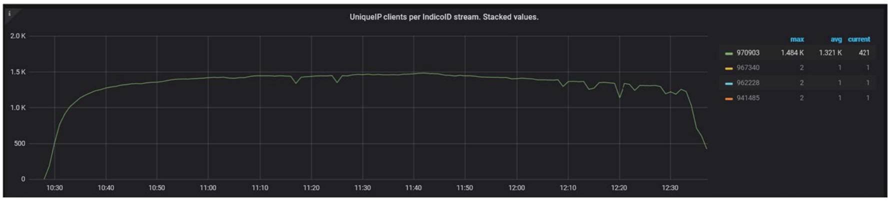

Fig. 8 Monitoring system for the live streaming platform during the first lecture

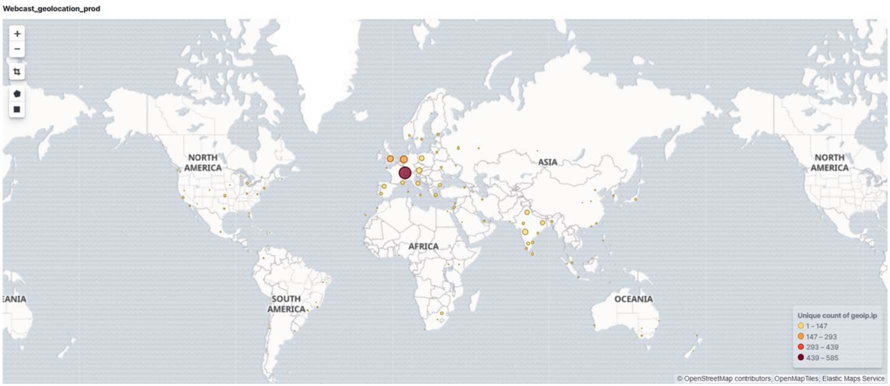

Fig. 9 Map showing origin of attendants to the first live lecture

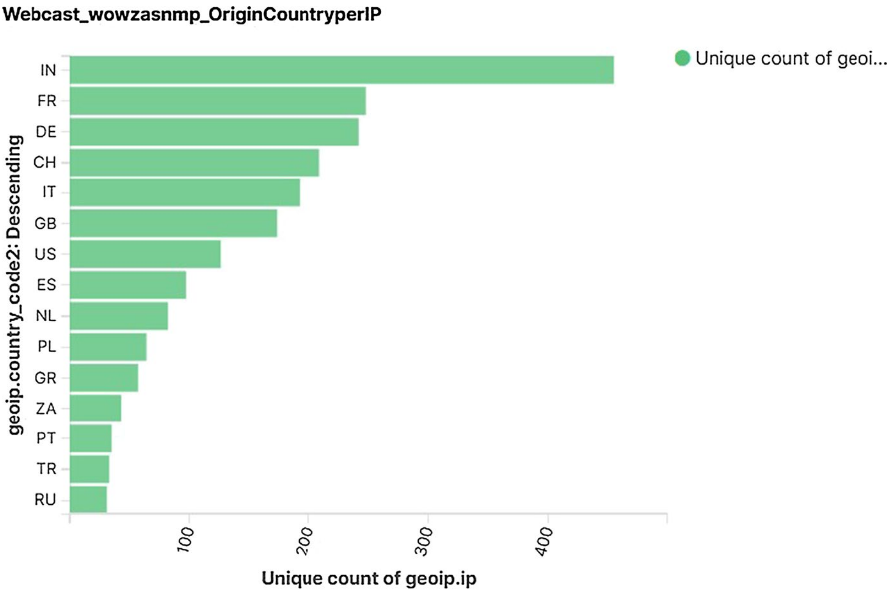

Fig. 10 Countries of origin of attendants to the first live lecture

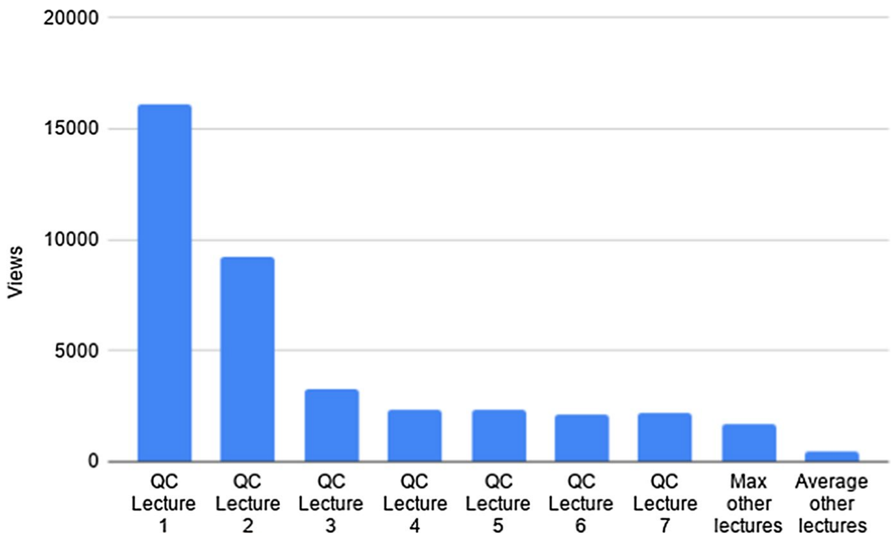

Fig. 11 Views of the QC lectures compared to other videos in CERN's YouTube lectures channel

5.1 Reception

The lectures were officially announced on CERN's website[8] on the 2nd of November 2020, four days ahead of the first lecture. They were also featured on CERN's and CERN openlab's social media accounts, including Twitter, Facebook and LinkedIn. The announcement was quickly echoed by HPC, IT and QC news websites, including HPC Wire[9], ZDNet[10] and TechRepublic[11]. The news announcement of CERN's official website was the most popular article on the site for several days. Four months later, the CERN tweet[12] celebrating the World Quantum Day (April 14th) and relaunching the lecture series was still the main driver of internet traffic to the CERN web site for the entire week.

The first lecture was watched live by almost 1,500 people who remained connected for the whole two hours (see Fig. 8) and who watched from all over the world (see Figs. 9 and 10), even from countries like USA on which it was the wee hours of the night. The subsequent sessions saw a reduction in audience until a stable figure of about 200 people per lesson was reached. This reduction was probably caused by

[8] https://home.cern/news/announcement/computing/online-introductory-lectures-quantum-computing-6-november.

[9] https://www.hpcwire.com/off-the-wire/cern-hosting-online-introductory-lectures-on-quantum-computing-beginning-nov-6/.

[10] https://www.zdnet.com/article/whats-quantum-computing-cerns-new-free-online-course-offers-you-the-answer/.

[11] https://www.techrepublic.com/article/get-your-quantum-computing-questions-answered-during-7-free-online-classes/.

[12] https://twitter.com/CERN/status/1382295115755094016

some drop-outs, but also by the popularity of the recorded versions of the lectures, available both on CERN's lectures channel at YouTube[13] and on CERN's Document server (CDS)[14], which offered more flexibility for the students. At the moment of writing this paper, the first lecture was been watched more than 16,000 times on YouTube.

In fact, the recordings have proved to be significantly more popular than any other content in CERN's Lectures YouTube channel. Excluding the lectures of the quantum computing course, the videos on that channel have been watched on average about 458 times with a standard deviation of 413 views, while the least popular of the quantum computing lectures has been watched more than 2,100 times. In fact, the seven most popular videos in the channel are the seven lectures of the quantum computing course, with the next one having just 1,666 views (see Fig. 11 for a graphical representation of the data). We would like to remark that the channel includes lectures not only on physics, but also on statistics, computer science and cryptography, and features lecturers as renowned as Vinton Cerf, Bruce Schneier or recent Nobel Prize winner Andrea Ghez.

Although it is difficult to convert YouTube view statistics to actual students following the lectures, the fact that the numbers stabilize around 2,100 views after the fourth lecture makes us confident that a sizeable fraction of the people initially interested in the material actually completed the whole series of lectures. This includes students who were not able to attend the live sessions and even people who only learnt about the lectures when they were already finished.

5.2 Survey

Given the nature of the lectures (massive, open, non-compulsory, and without assignments or certificates), in order to obtain feedback from attendants it was needed to apply another instrument. Thus, we prepared a survey with questions about the lectures and about the way the participants use computational resources in their work, research and studies.

The questions and their possible answers can be seen in Tables 2 and 3.

The survey was run on Indico,[15] and it remained open for answers from December the 11th 2020 until January the 12th 2021. 187 answers were received, and 3 of them were not considered, since they were mostly blank; thus, the final sample size was $N = 184$. As none of the questions was mandatory, the number of answers to each question varies from one to another. Data were analysed with IBM SPSS 24 and also displayed by using Google Sheets.

[13] https://www.youtube.com/channel/UCwXkOx0EuKBR5m_OOiaZRUA.

[14] https://cds.cern.ch/.

[15] https://indico.cern.ch/.

Table 2 Questions in the feedback survey

Question	Possible answers
Age	A number between 1 and 99
Region (single choice)	Africa
	Asia
	Europe
	North/Central America
	Oceania
	South America
Gender (single choice)	Female (including transwomen)
	Male (including transmen)
	Non-binary
	Neuter
	Other
	Prefer not to disclose
Occupation (multiple choice)	Student
	Academic (university)
	Researcher
	Teacher (non university)
	Computer scientist/Programmer
	Engineer
	Other professional
	Unemployed
Fields of interest (multiple choice)	Biology/Biotech
	Chemistry
	Computer science
	Engineering
	Finance
	Mathematics
	Physics
	Other
How did you learn about the course? (multiple choice)	Announcement on CERN official website
	Announcement on other website
	Announcement on CERN social networks
	Announcement on other social networks
	I received an email
	Someone told me about the course
How did you follow the course? (multiple choice)	Live webcast
	CDS (Cern Document Server) recording
	CERN's YouTube channel
	Zoom live session
What was your previous quantum computing experience/knowledge before the course?	Number from 0 (None) to 5 (High/advanced)
What computer science techniques and tools do you use for your work/studies? (multiple choice)	None

Table 2 (continued)

Question	Possible answers
	Artificial Intelligence
	Computer security/cryptography
	Databases
	Embedded programming
	High Performance Computing (parallel/distributed/GPUs...)
	Other
What computing environments do you use for your work/studies? (multiple choice)	None
	Desktop/Laptop
	Local cluster
	Cloud computing
	Supercomputer
	Quantum computer

5.3 Results

Within the context variables (age, location, gender or current occupation), we found that the average age of the participants was 40.93±15 years old, being 40 years old the median. As it can be shown in Fig. 12, there were two modes, one 20-25 years old, and the other one 40-45 years old. That means undergraduate or recently graduated students and people with a more defined professional background.

Gender distribution was strongly unequal, having 88.0% men, 8.7% woman and 3.3% preferring not to disclose. That unbalanced distribution prevented us from gender-based differentiated analyses, since they would be non-significant. However, it confirms the technology gender gap [40] and the need of positive actions to reduce it [6].

Despite having an international audience, as it was confirmed by the reception data, the majority of the survey respondents came from Europe (60.3%), followed by Asia (20.7%), Northern/Central America (9.8%), Southern America (6%), and Africa (1.6%). As box-plots in Fig. 13 show, people from Asia and Africa were significantly younger than the rest. The European majority is probably an effect of the reach of the announcements and the CERN distribution lists, together with the time difference.

As for the current occupation, Fig. 14 shows the frequency of each option. We have to remark that the occupation was multiple-choice, and the most frequent combination was Computer Scientist/Programmer and Engineer (3.8%). Regarding the fields of interest, Fig. 15 shows the distribution, with a clear prevalence of Computer Science, followed by Physics and Mathematics. Moreover, the most frequent

Table 3 Questions in the feedback survey (part 2)

Question	Possible answers
I think that quantum computing will be useful for me... (multiple choice)	In my studies
	In my research
	In my work
	In my teaching
	As general, useful knowledge
	None of the above
Thinking about the computational techniques that you currently use... (single choice)	I do not use computational techniques for my problems/tasks
	I do not think that quantum computing will substitute
	or complement any of the computational techniques that I currently use
	I think that quantum computing can complement other techniques
	that I currently use (for instance, Clouds, HPC, AI accelerators...)
	I think that quantum computing can completely substitute other techniques
	that I currently use (for instance, Clouds, HPC, AI accelerators...)
After following the lectures, what will you say is your current quantum computing knowledge/experience?	Number from 0 (None) to 5 (High/advanced)
Please rate the APPROACH/METHODOLOGY of the lectures	Number from 1 (I did not like it at all) to 5 (I loved it)
Please rate the CONTENTS of the lectures	Number from 1 (I did not like them at all) to 5 (I loved them)
Please rate the PROGRAMMING RESOURCES of the lectures	Number from 1 (I did not like them at all) to 5 (I loved them)
Please rate the TEACHING MATERIALS of the lectures	Number from 1 (I did not like them at all) to 5 (I loved them)
Please rate the EASE OF USE/ACCESS of the lectures	Number from 1 (I did not like it at all) to 5 (I loved it)
Please rate the POSSIBILITY OF ASKING QUESTIONS BY EMAIL	Number from 1 (I did not like it at all) to 5 (I loved it)
Did you contact the teacher or the organizers to request information or ask questions about the course?	Yes/No
What did you like/not like about the course?	Free text
What other quantum technology topics would you like to see treated in future courses?	Free text

multiple-choice was the triple combination Computer Science, Mathematics and Physics (9.8%), followed by Computer Science and Engineering (8.2%).

These variables help us to have an overall picture of the participants, so that we can affirm that there are very heterogeneous profiles among the attendees.

CERN's communication channels were the way from which 28.2% of the participants knew about the lectures (website 14.6%, and social networks 13.5%, respectively). But most of the respondents knew from other websites different from CERN's one (34.2%), and other social networks (20.6%). Surprisingly direct communication from someone else was the source in 25% of the cases, and email reached 11.9% of the participants. The way to follow the lectures was distributed among CERN's YouTube channel (45.1%), CDS recording (43.4%) and Live

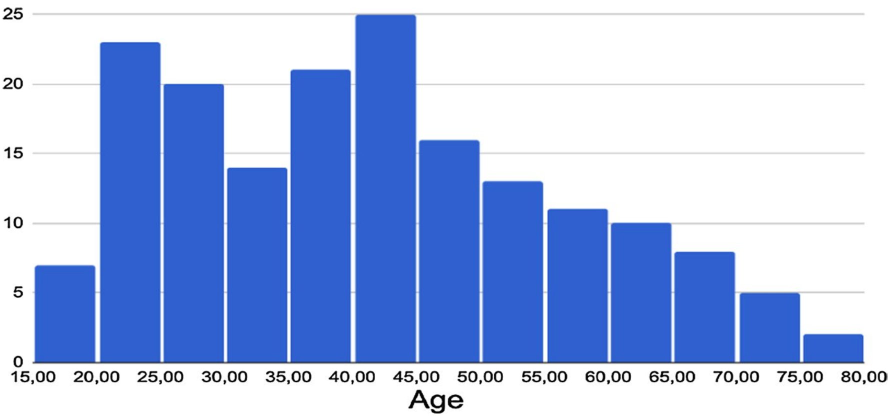

Fig. 12 Age distribution

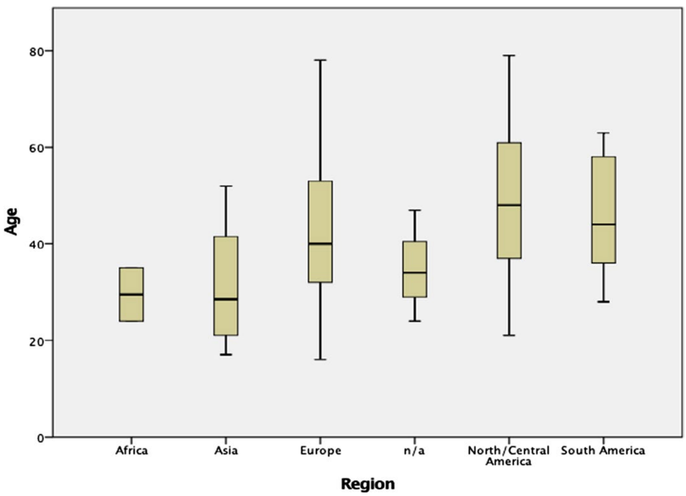

Fig. 13 Age distribution by region of origin

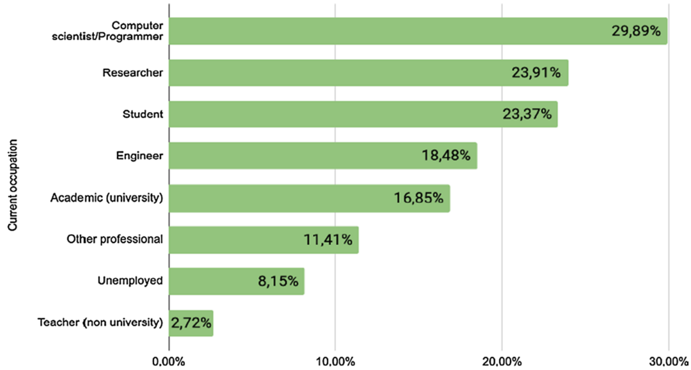

Fig. 14 Distribution of the current occupation

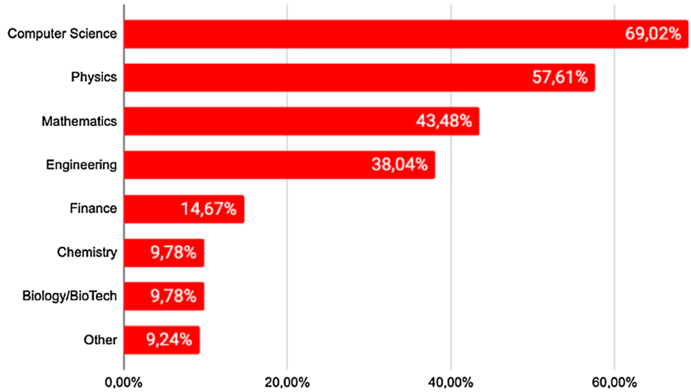

Fig. 15 Distribution of the field of interest

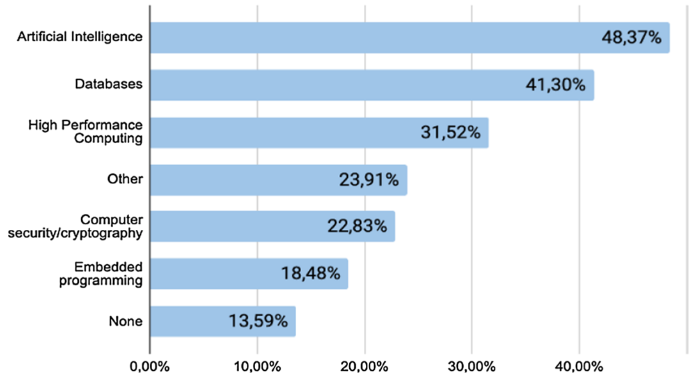

Fig. 16 Distribution of the used computer science techniques and tools

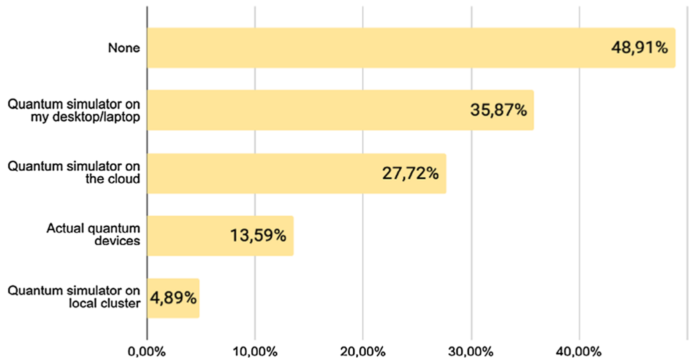

Fig. 17 Distribution of the used QC resources

Table 4 Use of QC in the future

Question	Percentage
I do not think that quantum computing will substitute or complement any of the computational techniques that I currently use	9.2%
I do not use computational techniques for my problems/tasks	18.5%
I think that quantum computing can complement other techniques that I currently use (for instance, Clouds, HPC, AI accelerators...)	59.2%
I think that quantum computing can completely substitute other techniques that I currently use (for instance, Clouds, HPC, AI accelerators...)	6.5%
No answer	6.5%

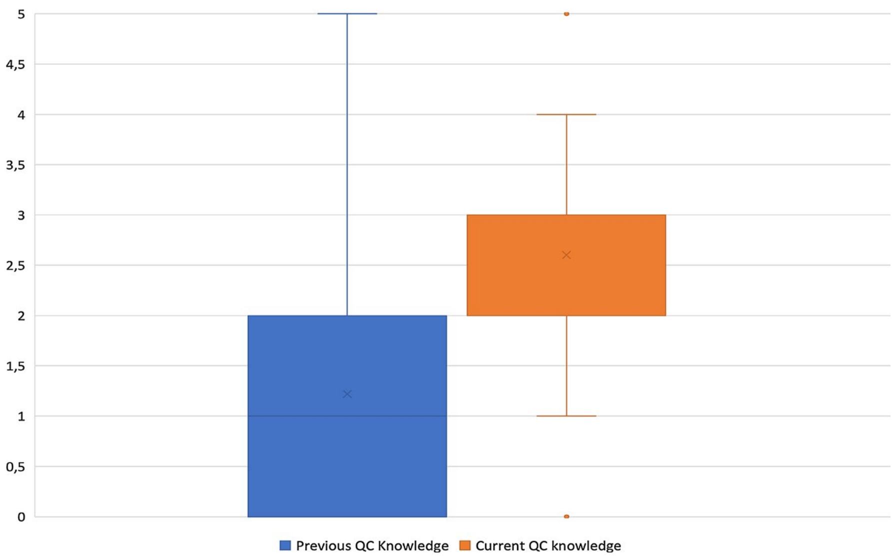

Fig. 18 QC knowledge before and after the lectures

webcast (41.8%). Obviously, many people combined different ways, thus, 13% followed the lectures by CDS and YouTube, 7.6% by webcast and YouTube, and 5.4% combined CDS, YouTube and webcast.

Figure 16 shows the distribution of the type of technology that participants used for their work or studies. Apart from the prevalence of Artificial Intelligence and Databases users, it is also interesting to underline that the most frequent combination (8.2%) was Artificial Intelligence and High Performance Computing.

As regards the computer environment used by participants, almost all used Desktop/Laptop (94%), far followed by Cloud computing (25.5%), Local cluster (25.5%) and only 13.6% used Quantum computer. The most frequent environment combination was Desktop/laptop with Cloud Computing (12.5%).

Figure 17 shows the answers about the used QC resources. As a half of the participants did not use any quantum computing resources, this distribution remarks the novelty of the lectures for the audience. The most frequent combinations were desktop/laptop and cloud simulator (8.7%) and desktop, cloud and quantum devices (5.7%).

More than two thirds of the participants considered that QC can be complementary or substitute of the techniques they were using. Table 4 displays the distribution of the answers to this question (which was single-option).

The most interesting result, considering the goal of the lectures, concerns participants' perceived knowledge. When asked for the knowledge about QC before and after completing the lectures, Fig. 18 shows how participants perceived that it significantly increased. Focusing on the mean value, it increased from 1.22 to 2.6 (marked by "x" in Fig. 18), and both median and mode increased from 1 to 3 (Wilcoxon signed rank test, for paired values, provided a p-value $p < 0.001$). These results highlight a great efficiency of the lectures in terms of self-perceived knowledge gain.

Moreover, significantly perceived increase in knowledge gain (Fig. 18) was consistent for both the whole and the subsamples: there were not differences among groups of participants (we omit statistical test for simplicity) depending on their occupation, field of interest, or QC environment, except in one case: we detected that participants currently occupied as researchers perceived a significantly lower (p-value $p < .05$) knowledge gain than the rest, but with an average knowledge gain of 1.14 points out to 5. Being an expected result (since researchers were assumed to have a greater prior knowledge), it is relevant that even researchers perceived such an important knowledge gain.

The answers to the question "What did you like about the course?" also seem to validate our hypothesis that teaching QC with a programming-focused approach can be helpful when reaching a heterogeneous audience with no previous knowledge of quantum physics. Some of the many comments that highlight this aspect are the following:

- "I really liked the simplicity with which such complex topics were proposed in such a short time"
- "I like the practical approach adopted by the instructor. Even if I did not fully get the theoretical concept, I can see its code and how it works, which really

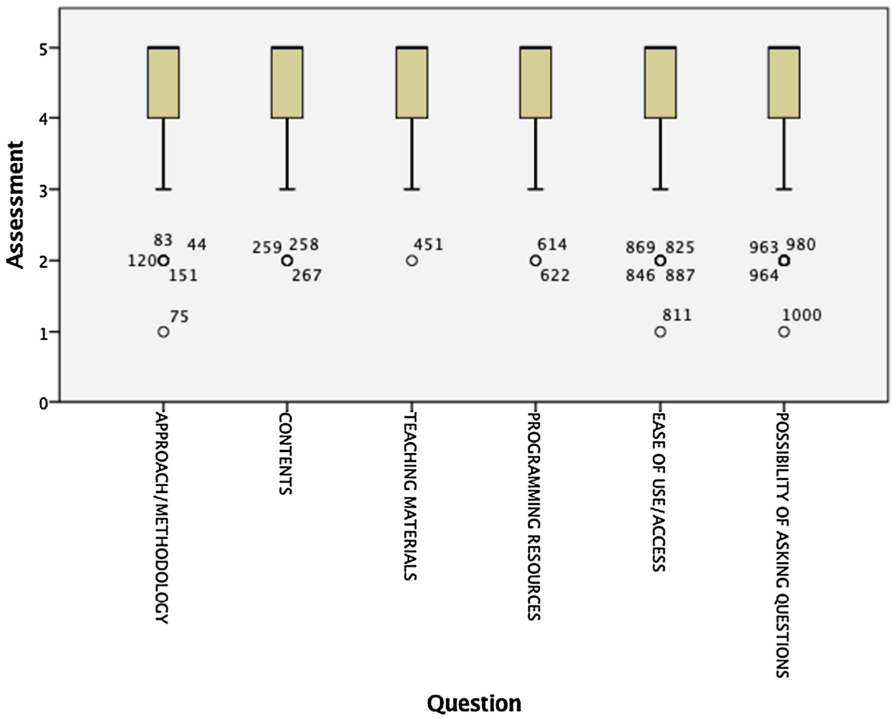

Fig. 19 Distributions of the Likert-scale questions assessing the lectures

helped me to better understand the materials. I read so many books and articles about many of the topics covered in this lecture series, however, I enjoyed this series the most because of its practical approach. This lecture series introduced me to so many software tools (e.g., Quirk) and IBM Quantum Experience , and I am so grateful for that".

- "The lecturer is clearly experienced in both lecturing and the subject. I appreciated the applied focus of the lectures which makes the abstract topic concrete".
- "I loved the materials that were used in the lab. I think the instructor did an awesome job at making a subject that could be difficult to comprehend, something that I now enjoy and feel I am learning more about. I am sad the class is ending next week. ! Thank you!"
- "For me personally, the perfect balance between overview, theory and practice; between approachability and depth of discussion".
- "I was impressed by the items which were included which achieved a very nice balance between explication of the basics, and suitable emphasis on advanced topics, such as error correction".
- "I liked the information on programming resources as well as the inclusion (though very brief) of some of the more advanced (and current) topics".
- "Clear explanation of concepts (I had troubles in understanding them on traditional books)"

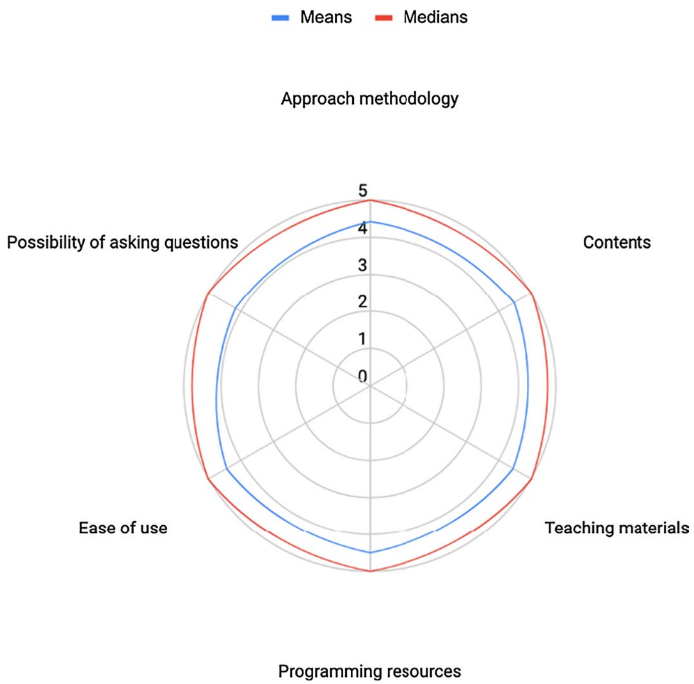

Fig. 20 Means (*blue*) and medians (*red*) of the questions for assessing the lectures

- "Quantum computing is very vast and interdisciplinary subject. Teacher did awesome job going through almost every important aspect of quantum computing. Some topics which I had already studied for about 4-5 times but still unclear to me, these lectures made those very easy for me to understand. Teacher's way of explaining a topic is one I have never seen before and it's great. I would like to study more from them. Big respect for you sir. Thanks a lot".
- "it was very useful to see how the different algorithms were implemented".

The six Likert-scale questions about the assessment of the lectures provided very high values, both in mean and median, as it is displayed in Figs. 19 and 20. The medians reached 5 points in all the questions. Except in one case, means ranged between 4.44 and 4.5 points, with standard deviations less than .8. Only when assessing the possibility of asking questions some extreme values increased the standard deviation up to 1, producing a 4.18 points mean, which is still very high.

Differences in the assessment depending on different factors were analysed. The outputs of the six assessment Likert-scale questions did not follow a normal distribution (Kolmogorov–Smirnov with Lilliefors correction provided p-values $p < .001$); therefore, U Mann–Whitney test for medians was considered in all the cases, with p-values $p < .05$ for significance. In most of the cases, there were no significant differences; thus, for simplicity, we only refer to significant cases. First, regarding the current occupation, participants from universities scored significantly higher than the rest the teaching materials and the ease of use/access of the lectures. This fact endorses the quality of the materials and their usability, since it comes from people with teaching experience in tertiary education. Second, when considering the field of interest, those interested in mathematics and in physics scored significantly higher than the rest the possibility of asking questions. Our hypothesis is that the computational approach followed in the lectures provoked this interest. Third, as for the computer science techniques and tools currently used, participants using Artificial Intelligence scored significantly lower than the rest the contents of the lectures. That fact was expected, since it is obvious than working with AI made participants more familiar with some of the contents.

There are other two relevant outcomes. One is that participants using cloud computing as their computing environment scored significantly higher both the approach/methodology and the contents of the lectures. Another one that participants using quantum simulators as computing environment scored significantly higher than the rest in three questions: contents, teaching materials, ease of use/access. We consider this as a positive assessment of the lectures since they are advanced users, so even when the assessment was very positive in mean and median for the whole sample, it is even more positive in some aspects for advanced users. Both positive results lead us to affirm that participants have been able to learn thanks to the contents of the lectures and the specifically designed approach.

It is also important that participants considering QC as useful for their studies scored significantly higher than the rest both the contents and the programming resources. Particularly, the higher score for programming resources among students is relevant since it was one of the novelties of the lectures compared with previous ones about QC. On the other hand, participants considering QC useful for their research scored significantly higher than the rest the possibility of asking questions. Thus, interaction among speaker and attendants is revealed as a strength in the design of the lectures.

We compared the association between the different modalities of the computer science techniques used and the question about possible uses of QC in the future ("Thinking about the computational techniques that you currently use..."), as well as between that question and the field of interest. The most relevant association detected was when Artificial Intelligence was considered. In this case, Cramér's V coefficient was .297, which can be assumed as an considerably big value (empirical values over .3 are usually accepted to be relevant), and, hence, it remarks the association, on the one hand, between participants not using AI and the two negative answers ("I do not use computational techniques for my problems/tasks" and "do not think that quantum computing will substitute or complement any of the computational techniques that I currently use"), and, on the other hand, between participants using AI and the two positive answers ("I think that quantum computing can complement other techniques that I currently use" and "I think that quantum computing can completely substitute other techniques that I currently use"). Additionally, there is a weak association between the possible uses of QC and the current use of High Performance Computing (Cramér's $V = .271$, which is close to .3); in particular, the association is similar to that detected when AI was considered: HPC users tend to answer in the positive ("I think that quantum computing can complement other techniques that I currently use" and "I think that quantum computing can completely substitute other techniques that I currently use") more than non-HPC users. This is not surprising because HPC users are also associated (Cramér's $V = .35$) to AI users, as well as to participants using local clusters ($V = .38$).

6 Conclusions

A series of lectures on quantum computing was successfully implemented and delivered online from CERN as part of the institution's Quantum Technology Initiative. The approach was eminently practical and assumed almost no previous knowledge (other than basic linear algebra) from the students. The lectures were very well-received, and the recordings of the seven sessions are now the most popular videos ever on CERN's Lectures YouTube channel, where each of them has more than 2,100 views (and some of them over 9,000 times). This fact endorses that the approach, not focused on mathematics and physics but on algorithmic and implementation elements, is a useful methodology, with great acceptance by the participants, who repeatedly mentioned this aspect on their answers to a satisfaction survey.

In [39], it was pointed out the need of empirical studies discussing the educational approach to QC for people with different backgrounds. The current work highlights this dark aspect, by providing evidence about a specific informal approach by using a large worldwide sample of people with very different background and interests.

Even when, as expected, computer scientist was the most frequent occupation and computer science the most frequent field of interest, participants represented a varied sample of professional profiles. This fact clearly indicates the cross-sectional importance that QC is gaining. Moreover, after the lectures, the possibilities of QC as a future computing technique were acknowledged but two thirds of the participants.

The most important result from the survey is that the perceived knowledge about QC increased very significantly and all the aspects about methodology, contents and materials were very highly scored. The pertinence of this result is remarked since the perceived knowledge gain is almost 1.4 out of 5 points in almost all the groups, an only a little lower for participants occupied as researchers. Hence, this confirms that the followed approach is valid for introducing QC among a mixed population of practitioners. This is especially relevant because our lectures reached a wider and more diverse audience than previous studies available in the literature.

Another remarkable conclusion is that, even with a limited number of teaching hours, the approach of focusing on algorithmic and programming aspects of quantum computing, paying relatively less attention to the mathematical formalism and physical implementations, allowed us to cover topics that are considered "advanced" and not usually taught in introductory QC courses, such as variational algorithms, quantum annealing and quantum machine learning.

For the future, it would be interesting to study the possibility of exporting some of the methodological aspects used in these lectures to other QC teaching initiatives.

In view of the results, we consider that this approach helps in introducing this difficult subject to a wide and diverse audience, as shown by reaching several thousand people from all over the world and receiving very high scores in our satisfaction survey. Thus, it is very likely that a similar methodology could be used by other researchers and instructors to teach quantum computing to students with no previous background in quantum physics.

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Authors and Affiliations

Elías F. Combarro[1,2] · Sofia Vallecorsa[2] · Luis J. Rodríguez-Muñiz[3] · Álvaro Aguilar-González[3] · José Ranilla[1] · Alberto Di Meglio[2]

Elías F. Combarro
efernandezca@uniovi.es

Sofia Vallecorsa
Sofia.Vallecorsa@cern.ch

Luis J. Rodríguez-Muñiz
luisj@uniovi.es

Álvaro Aguilar-González
aguilaralvaro@uniovi.es

Alberto Di Meglio
Alberto.Di.Meglio@cern.ch

[1] Computer Science Department, University of Oviedo, Oviedo, Spain

[2] CERN openlab, CERN, Geneva, Switzerland

[3] Department of Statistics and O.R. and Math Education, University of Oviedo, Oviedo, Spain