Journal of Physics: Conference Series **2297** (2022) 012018 doi:10.1088/1742-6596/2297/1/012018

Quantum technologies: a course for teacher professional development.

C. SUTRINI[1,a], M. MALGIERI[1,b], C. MACCHIAVELLO[1,c]
[1]*University of Pavia, Physics Department, Via Bassi 6, 27100, Pavia, Italy*
a claudio.sutrini01@universitadipavia.it
b massimiliano.malgieri@unipv.it
c chiara.macchiavello@unipv.it

Abstract. We present an educational path for teacher professional development whose primary purpose is to enhance physics teachers' knowledge and awareness of topics related to quantum computation and quantum information, and of their relevance for technological advancement. Besides their objective importance, also stressed by several authors and projects, the choice of topics not traditionally covered in the final year physics curricula also arises from the concrete possibility of developing a multidisciplinary path, able to represent under a unified perspective several subjects treated in secondary school physics and mathematics.
The project is realized in the context of the Italian PLS (Plan for Science Degrees) and the education section of the Quantum Flagship. Due to the limitations related to the COVID-19 pandemic it was entirely delivered in the form of synchronous distance learning and was attended by around 30 teachers. Asynchronous discussion was performed using both generally available tools (Google drive, forms etc.) and a dedicated online forum set up on the servers of the University of Pavia. We discuss the structure of the educational path and the results of the first part of the course whose purpose was describing the transition from classical to quantum computation. In general, from both the written pre-questionnaire and the mid-course interviews, strong appreciation and fascination emerge for the cultural significance of the introduced topics and connections.

1. Introduction

Several authors in Physics Education Research (PER) have stressed the importance of bringing some of the most relevant physics concepts lying at the basis of the so called "second quantum revolution" available to secondary school physics teachers and, in perspective, to students [1,2]. In many cases, the work in PER has consisted of designing individual activities, in the form of games or laboratory experiments, to illustrate concepts such as entanglement or quantum cryptography [3]. In our work on teacher professional development, we have instead chosen to inspect the whole physics and mathematics curriculum in search of a longitudinal perspective, mainly based on computation, which could culminate in the treatment of quantum information topics. The goal is clearly ambitious given that in most European educational systems quantum physics is a recent addition to the physics curriculum, often only a few selected topics are covered [4] and, in general, more research is needed to develop strategies to help students overcome learning difficulties at secondary school level [5]. Thus, our approach was instead to attempt, by means of a course providing common grounds and motivation, the formation of a community of practice [6] motivated to longitudinal and inter-disciplinary curriculum innovation towards the objectives of the Quantum Flagship [7]. The main idea is that there is a dialectic between physics, mathematics and logic that is somehow deeper than the three disciplines in their own individual development; that is, the idea that the process is more relevant than the event, idea that distinguishes the diagrammatic approach to quantum physics [8], and which could be adopted in many other disciplines. This dialectic was born in a primitive form already in archaic times when the concept of calculation was strongly linked to real physical elements such as abacus stones. The development of the mathematical-logical syntactic paradigm finds its realization with the advent of computers, which produces a much stronger overlap between the discourse on computation and the physics of real systems. However, in the pioneering works of Turing the necessary logic for the construction of algorithms is the classical one, and the corresponding classical physics for their implementation is substantially implicit. In the 70's and 80’s, on the other hand, a profound reflection develops on the physical problems of computation and on the possibility to use quantum mechanics to encode and manipulate information in a way that will turn out to be deeply different and innovative in comparison to what was previously done.

2. Structure of the educational path

The Educational path has a total duration of about 20 hours and is structured according to the following steps summarized in Table 1: 1) introduction to physics problem of classical computation; 2) building the quantum logical language and the origin of quantum algorithms; 3) introduction to entanglement and development of quantum protocols.

Table 1. Structure of the educational path.

Introduction	Building	Development
Physics problem of computation	QP with Stern-Gerlach device From bit to qubit – Quantum circuits Quantum algorithms	Entanglement Bell’s inequalities No-cloning theorem Quantum protocols (Dense coding, quantum teleportation) Cryptography

The first four meetings took place in October and November 2020; the other four will be organized during the following February and March. This article will mainly describe the first part of the educational path, planning to elaborate on the second part in a later paper.

2.1. Physics problem of computation

The first reflections on the thermodynamics of computation, related to Bennett's works [9], allow to introduce and develop reversible logic and reflect on the relationship between logic gates and entropy. Bennett's plan [10] requires to demonstrate the thermodynamic reversibility of the calculation by following a very precise path, which we have retraced during the lesson:

> *“A proof of the thermodynamic reversibility of computation requires not only showing that logically irreversible operations can be avoided, but also showing that, once the computation has been rendered into the logically reversible format, some actual hardware, or some physically reasonable theoretical model, can perform the resulting chain of logically reversible operations in a thermodynamically reversible fashion”*

From the start, logical operations can be described in terms of physical systems, as Feynman did in [11] by representing the "and" and “or” operations in terms of the rules of binary addition on rows of pebbles. The relationship between physics, logic and computation, discovered through this simple example, allows us to introduce the classical logic gates, along with a new circuital language that will be used in all the following lessons (See Figure 1), while maintaining a connection between logical operations and physical systems. The next step in reinforcing the connection between physics and computation is the demonstration that reversible logic does not require a necessary theoretical minimum of energy dissipation, since theoretically the only thermodynamically irreversible operation is the erasure of information (Landauer's principle). The birth of reversible logic and the corresponding operators [12] is the first formal step towards an extension, both necessary and intuitive, from classical logic to what we may improperly call "quantum logic". This passage, although touching less known authors and topics in physics and computation, is historically well founded, essential to the consistency of the teaching sequence, and implies a profound reflection on the link between computation and the physical support used to perform it. Through the introduction of reversible logic it can be shown how the division into preparation, transformation and measurement begins to manifest itself, and while classically its consequences are not deep, it will become fundamental in the quantum field.

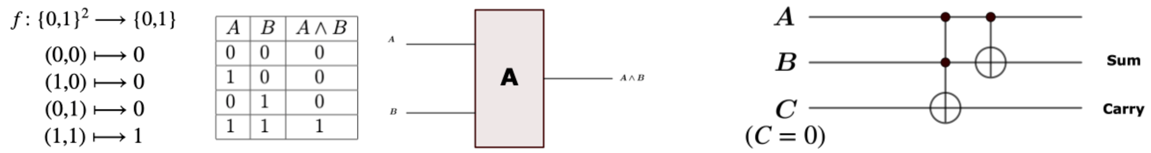


Figure 1. (left) Boolean function, truth table and circuital representation of AND logic gate. (right) Reversible circuit of binary addition

Bennett's demonstration of the reversibility, in principle, of the process of copying a bit using the example of a one-domain ferromagnet [9] is also very interesting, both (as it was originally presented) as a concrete example of application of Landauer’s principle, and for the possibility to link it to the quantum no-cloning theorem.

At the end of this first meeting, teachers should begin to become aware of the possibility to establish a close relationship between physics, logic and computation [13], and perhaps of the educational possibilities implied by problematizing and exploiting such link. In fact, the topics discussed can be an interesting starting point for reflecting on educational paths in physics and mathematics to be implemented in the first three years of high school (insights into classical logic, thermodynamics, computation, matrix algebra).

2.2. Quantum Physics with Stern-Gerlach device

The second meeting is organized in collaboration with the educational research area of Insubria University whom we worked with for a Summer School on quantum computation for high school students. With the aid of the Quvis simulations [14] of the Stern-Gerlach device, it was possible to bring the concept of preparation of states, evolution and measurement into the quantum context by means of the appropriate formal language, both in the Dirac notation (which is introduced contextually to the analysis of two-level systems) and in matrix computation. This aspect is a very important tool for subsequent use in the computational and informational field. In particular, the use of two-level systems [15] – which implies the adoption of a spin first approach well established in PER – allows to perform the transition from the concept of a bit to a quantum bit - the qubit - and to introduce logical operators acting on them. In the last part of the lesson, it was possible to explore more in depth the role of probability in quantum measurement, the issue of incompatible observables, and the concept of quantum interference with the analogy of the Stern-Gerlach device and the double-slit experiment with photons.

2.3. From bit to qubit – Quantum circuits

This third lesson allows us to extend the physical problem of computation to quantum systems. The initial motivation arises from R. Feynman's considerations about the simulation of physical systems [16]: "What kind of computer are we going to use to simulate physics?" and even before that, "what kind of physics are we going to imitate?". The route we explore with teachers, is that if we want to imitate quantum physics, the natural choice is to renounce both classical logic and classical probability.

To understand this fundamental aspect, we have first described, using the language of set theory, the basic structure of classical physics, and then shown how propositional logic and probability can be constructed as theories concerning subsets of the set *S* of possible states of classical physics [15]. The image in Figure 2 can be read equivalently in the three disciplines with simple terminological substitutions: a proposition, in fact, is a true or false (1 or 0) statement about a certain property, i.e. whether or not the value of a physical quantity satisfies certain conditions; similarly, a random variable on event space can take one of the experimental outcomes. It should be evident how much this description can allow for multidisciplinary educational paths well before the fifth year of study.
Awareness of a structural connection between physics, proposition logic and probability theory emphasizes even more the fact that the spin properties and the double-slit photons experiment need a critical review of both logical connectives and probability theory. On one hand, the existence of incompatible properties in quantum physics raises for example the problem of the truth value of the conjunction of propositions about the spin values for a single quantum object on different axes. On the other hand, quantum experiments suggest the necessity of an interference term when computing probabilities for events which can realize through mutually exclusive paths, a term inexplicable by classical probability theory. Furthermore, one possible educational advantage in using this approach, is that, based on our previous experience [17], the sudden realization by students that quantum mechanics may be at odds with classical proposition logic and ordinary probability theory may cause them to reject the theory as absurd and wrong, since they typically perceive proposition logic to be hierarchically superior to physics. However, the gradual construction of an intertwined link between classical mechanics, proposition logic and probability, puts these theories at least on equal grounds from an epistemological point of view, and may help students more easily accept the consequences of adopting quantum mechanics as a fundamental physical theory.

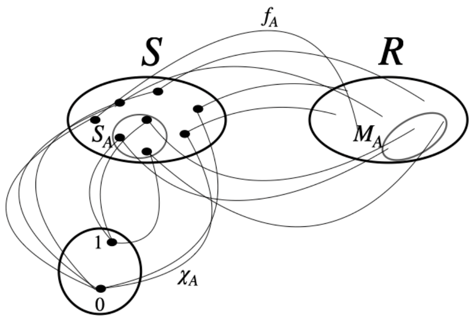
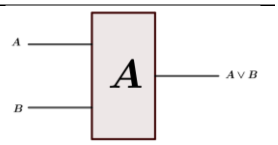
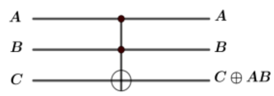
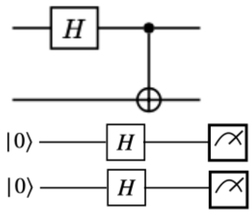


Figure 2. In physics, a proposition is a true or false statement about a certain property, i.e. whether or not the value of a quantity (a function f_A from the phase space *S* to **R**) satisfies certain conditions. Similarly, in probability theory, a proposition is a true or false statement about the value of a random variable, and the possibility of constructing probabilities is granted by the existence of a measure on *S*. The link with propositional logic is thus immediate.

Table 2. From classical to quantum computation.

	Information coding (preparation)	Logic gate (transformation)	Decoding of information (measurement)	Circuital representation
Classical logic	Bit 0, 1	Boolean functions $f:\{0,1\}^n \longrightarrow \{0,1\}^m$ $Not, And, Or...$	Confirms the value of the bit on which it acts. We obtain a bit of classical information	
Reversible classical logic	Bit 0,1	Invertible Boolean functions $f:\{0,1\}^{n+m} \longrightarrow \{0,1\}^{n+m}$ $Toffoli, Fredkin$	Confirms the value of the bit on which it acts. We obtain a bit	

Journal of Physics: Conference Series **2297** (2022) 012018 doi:10.1088/1742-6596/2297/1/012018

			of classical information	
Classical computation	Classical state (potential)	Diodes, transistor	Measurement instrument (circuit element) of the potential	
Quantum logic	Qubit $\|\psi\rangle = \alpha\|0\rangle + \beta\|1\rangle$ $\|\alpha\|^2 + \|\beta\|^2 = 1$ $\alpha, \beta \in C$	Unitary operators $X, Or, And, H, Z \ldots$	It randomly chooses one of the two eigenvalues associated with the basis qubit states. We get a bit of classical information	
Quantum computation	Quantum state Spin $\|\uparrow\rangle$, $\|\downarrow\rangle$ Polarization $\|V\rangle$, $\|H\rangle$	Different experimental realizations	Measurement devices (intrinsically probabilistic)	

By using two-level systems, we can then generalize the concept of the classic bit to quantum bit - a qubit - and study some logical operators that act on them (See Table 2). The generalization allows us to establish a correspondence between Boolean functions, describing classical connectives, and unitary operators describing the evolution of a system in quantum physics. All the objects involved in the formalism used also have a simple circuital representation [8], which may be seen as one of the distinctive features of our approach. The possibility of working on new and strongly decontextualized symbolic representations allows the development of an autonomous and complete language that we believe can be of great interest and help for the more in-depth exploration characterizing the second part of the educational path.

The probabilistic interpretation of qubits makes it possible to introduce composite systems and the tensor product fairly and introduce multi-qubit logic gates. The action of logic gates has been described both in Dirac notation and with matrices. An in-depth understanding of the correspondence between circuit element, the Dirac and the matrix formalism, and the physical systems that implement them, is an essential part of learning and grasping the concepts introduced.

Some exercises were left for the teachers to familiarize with the new language introduced. The teachers' answers were put into the prepared folder and corrected in the next lesson.

2.4. Quantum algorithms

The last lesson of the first part is devoted to the introduction of two quantum algorithms: Deutsch' and Grover's algorithm [18,19]. The algorithm concept in our educational path is used not only as a mere symbolic manipulation but also in the close connection it may have with the physical world [20]. This allows the proposed algorithms to be studied on three decreasing levels of abstractness: the circuital-representational level, the formal algebraic level and, finally, their ultimate interpretation on the level of physical theory (in Figure 3 we can see a representation combining the first and last levels above described).

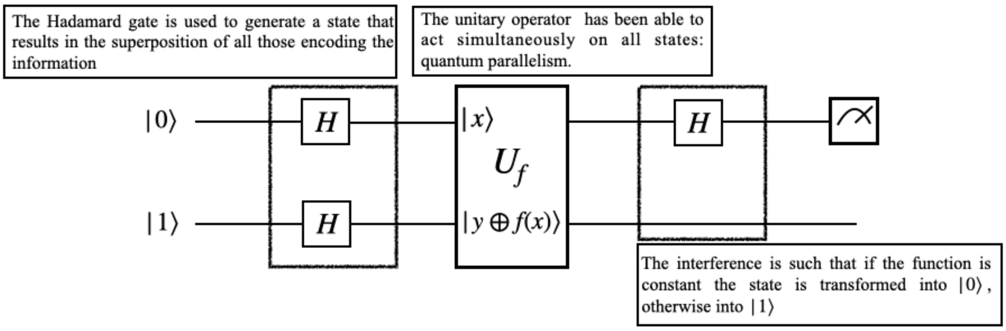


Figure 3. Deutsch Algorithm circuit

The generalization of the Deutsch-Jozsa algorithm has been presented in the form of a "Bank Robbery" problem by translating the example described in [21] into formal and circuit language.
This last meeting concludes the first part of the course. The two algorithms contain most of the concepts covered and allow the use of quantum superposition and quantum interference so that the advantage in quantum computation becomes evident.

2.5. Second part: entanglement
The next 10 hours of the course will be devoted to entanglement and its role in the quantum theory of communication. In the second part of the course, Bell entangled states are introduced through the newly developed circuital language. These states are sufficient to study some pioneering quantum protocols, crucial in current quantum technological applications, explaining the most significant aspects of entanglement: dense-coding, quantum teleportation, quantum cryptography. We will deal with these aspects in depth in a second paper.

3. Context and data collection
The course was organized in the context of the Italian PLS-Piano Lauree Scentifiche (Plan for Science Degrees) and the education section of the Quantum Flagship. We divided the twenty hours planned in two parts: first 10 hours in October and November; the second part in February and March. Due to the restrictions imposed in response to the COVID-19 pandemic, all lessons, although initially planned as a traditional classroom course, were performed in synchronous distance learning. Interaction between teachers was limited, and the means of delivery were, approximately, 80% frontal lesson, 10% full group discussion, 10% teachers performing individual activities such as exercises or answering questions, which were discussed immediately afterwards.

Within the first part of the course, we collected data by several means:

- 23 pre-questionnaires completed, touching both disciplinary aspects and items related to personal engagement and involvement
- Sheets with solutions to problems and exercises produced by teachers during the course, and answers to on-the-fly clicker type questions given during one lesson of the course
- Semi-structured interviews with four volunteering teachers

3.1 Pre-test data
The pre-questionnaire was organized into three parts: 1) general questions about the teacher's career and their routines in the teaching of QP; 2) most specific questions about the topics close to those covered in the course or most in general about QP; 3) four specific problems on the polarization of light.

3.1.1. General question. From the part of the questionnaire collecting general information on the participating teachers, we learn that the teachers are equally divided between graduates in physics and in mathematics; that almost all of them work in science-oriented high schools; and that in their schools, students are required to develop only basic computer skills at most. Almost all of them teach following the textbook approach: photons and the photoelectric effect, the Compton effect, Bohr's model of the atom and interpretation of atomic spectra, De Broglie's hypothesis and wave-corpuscle dualism, wave-particle dualism, Schrödinger's equation, energy levels, wave functions and probability waves, Heisenberg's uncertainty principle; this can also be seen in part from the topics addressed (See Figure 4).

3.1.2. Questions about specific topics. As we can see in Figures 5 and 6, teachers consider the topics covered to be very significant for their professional development; they are less convinced of the role these topics might play for their students; finally (Figure 7) there is a good propensity to create longitudinal or multidisciplinary educational paths.

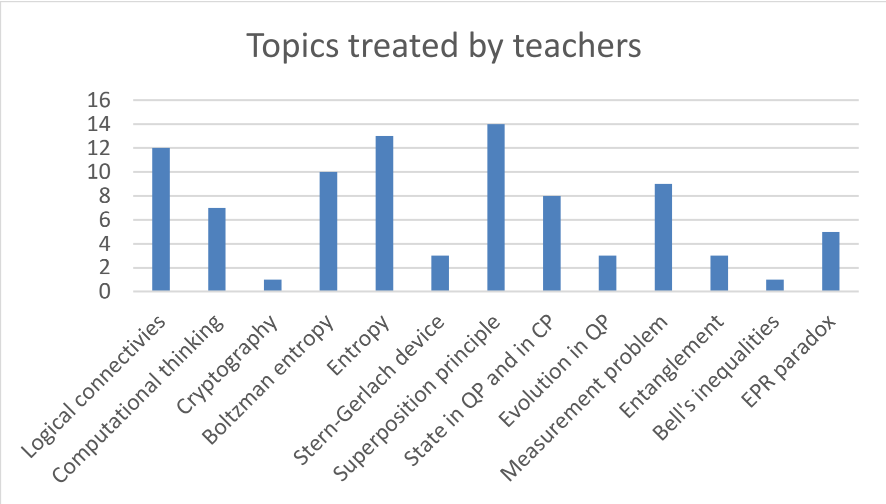


Figure 4. Topics treated by teachers in their own respective classes

3.1.3. Specific problems about polarization. We have proposed to teachers two problems about the polarization of classical light and the same again in a single photon. About half of the teachers attempt to provide a solution (not always correct) to problems in which light is treated as a classical electromagnetic wave; few answer the corresponding single-photon questions. The problems will be modified to deal with electron spin and presented again at the end of the course. One example of problem proposed to teachers was the following:

N photons polarized at 45 degrees encounter three successively arranged polarizers at 90, 45 and 0 degrees respectively. Ideally, how many photons will be detected on average beyond the last polarizer? Explain in detail.

It will be interesting to compare such data with the post-test data.

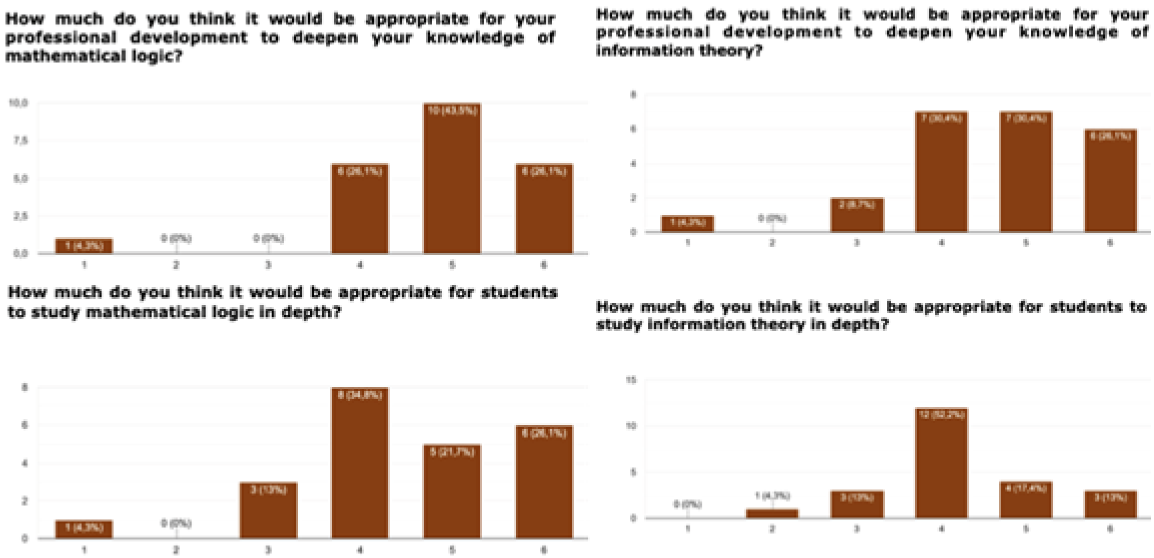


Figure 5. Comparison of what teachers *a priori* think about the role of mathematical logic and information theory for their professional development and how appropriate they think it is for students to study these topics.

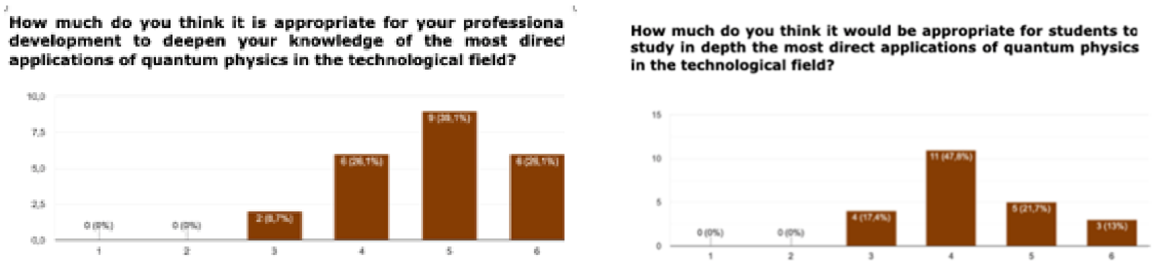


Figure 6. Similar comparison about direct applications of quantum physics in the technological field.

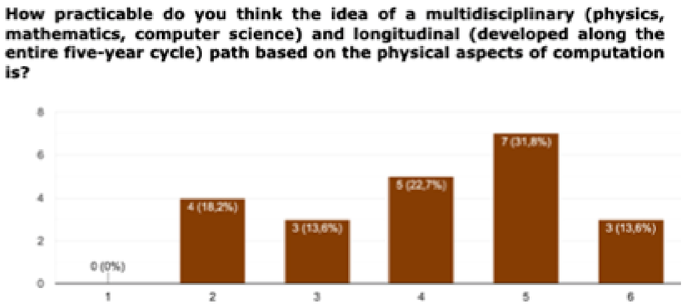


Figure 7. Propensity to create longitudinal and multidisciplinary educational paths in pre-test

3.2. *Sheets produced by teachers*

Only eight teachers among the participants carried out and handed in the proposed exercises. All of them correctly used both Dirac notation and matrix algebra to describe the proposed circuits.

3.3. Semi-structured interviews

We created a matrix for mapping interview questions onto research questions [21]. After the initial questions, we have divided the interview protocol matrix into four parts:

- specific questions about the topics
- didactic feasibility of the proposed topics, multidisciplinarity and cultural impact
- questions about the formalism used and circuital language
- questions related to lessons and materials.

Each section has some general research question to arrive at key questions that interested these first interviews. The transcription of interviews has been included in the matrix for analysis and comparison. A priori coding scheme [22] is developed out of course goals and two of our assumptions: the topics covered would have been interesting especially for mathematics graduates; the possibility of introducing the topics before the final year would have made them more practically usable in teaching. For a possible generative coding, we will wait for the end of the second part of the course and the final interviews. As interview ends, we provided the participant an opportunity to raise any issues not addressed.

3.3.1. Specific questions about the topics treated. Regarding mathematical logic, everyone acknowledges that it is not taught in great depth and is only linked to set theory and propositional calculus in the first year. Teachers after the course believe it would be appropriate to expand the weight of the topic, but this seems not easy in a school context that seems to progressively assign lesser and lesser importance to it. The cultural importance of introducing non-classical logics is recognized. The strong link proposed between logic and the thermodynamics of computation has caused surprise and difficulty, in particular to the two teachers with a degree in mathematics. All teachers recognize the effectiveness of the introduction to QP through the Stern-Gerlach device, but some would prefer to use polarization because it is a topic already known to students.

The formalism used for the introduction to quantum computation is considered suitable for high school students if appropriately trained, and it is seen to be very positive especially by the two mathematics graduates. The abstractness of language, however, raises the problem of immediate physical interpretation. This aspect is even more evident in the study of the two proposed algorithms, whose computational aspect seem, in part because of their complexity, to be prevailing on its physical aspects.

3.3.2. Didactic feasibility, multidisciplinarity and cultural impact. The interviewees generally agree on the high cultural value of the proposal, and the importance of a multidisciplinary approach for the education of future scientists. However, they recognize the introduction of these topics into the traditional curriculum as problematic, unless some of the content is *deeply* revised from the early years. The possibility of introducing topics linked to very recent technological developments is viewed as a likely source of students' engagement. Particular importance was attached to the cultural impact of the course, and that the two teachers with a degree in mathematics, in their free final remarks, stressed the great impact that the topics covered had had on their desire to study and explore QP and on a new vision of the world arising from it. Here are the words of a teacher:

"I was pleased to have attended the course because it allowed me to see a new way of thinking that I did not know, and it made me aware of the need for me to be trained in this regard, and that the students also need to be stimulated because contemporary physics is working on these things. It made me realize how much I don't know and that I need to be trained in this area. This unfortunately comes in a year when there are so many other problems. I don't think I can do that in my class. I'm sorry. For the future, however, I think it's something I should definitely consider."

3.3.3. Formalism and circuital language. Teachers were able to see the concepts introduced with both matrix algebra and Dirac notation. They showed no difficulty in accepting both and in thinking that they can also be introduced to their students from the early years of high school. Finally, the value of circuit representations is recognized, although the references to physics are not always explicit. Doubts remain as to how long it will take for all students to achieve satisfactory results.

3.3.4. Lessons and materials. The interviewees complained about the difficulty of following two and a half hours in the afternoon after teaching in distance learning in the morning. The particular condition due to the pandemic seems to make the course more difficult to follow. Nevertheless, the demands are adequate for a course that certainly has the claim of not being superficial.

4. Conclusion

We presented the first part of a course for teacher professional development introducing some of the most relevant physics concepts connected to the “second quantum revolution”. The course attempts to make explicit the dialectic between physics, mathematics and logic in order to inspect the whole physics and mathematics curriculum in search of a longitudinal perspective, mainly based on computation, which could culminate in the treatment of quantum information topics. The part described is based on the need to review the highly symbolic aspect of computation and information and show the aspects of the physical systems. This approach aims to go further than the classical paradigm capable of describing logic and probability consistent with physics and to make evident the need for a critical approach. The result is the possibility of using two-level systems to encode information in a new way and develop a logic that presents itself as an extension and overcoming of the previous one. The resulting representative circuit language allows the physical processes underlying quantum technologies to be described rigorously and intuitively. They thus become a means of grasping the most significant aspects of the quantum paradigm. From the initial questionnaires completed by 23 teachers, we can deduce that they introduce quantum physics to their students in a traditional way, but that they are extremely interested in the topics of the second quantum revolution for their own professional development. More resistance was exhibited to the possibility of including them in a traditional curriculum. The interviews carried out at the end of the first four meetings show a strong appreciation for the cultural value of the topics dealt with and the approach given to the course.

5. Authors’ ORCID iD

Massimiliano Malgieri, 0000-0002-9254-2354
Chiara Macchiavello, 0000-0002-2955-8759

6. References

[1] Pospiech G 2009 Teaching quantum theory—between the photoelectric effect and quantum information *Physics Curriculum Design, Development and Validation* Proceedings of the GIREP 2008 Conference, Cyprus.
[2] Dür W and Heusler S 2014 Visualization of the invisible: the qubit as key to quantum physics *Phys. Teach.* **52**(8), 489-492.
[3] López-Incera A, Hartmann A. and Duer W 2020 Encrypt me! A game-based approach to Bell inequalities and quantum cryptography *Eur. J. Phys* **41**(6), 065702.
[4] Stadermann H K, van den Berg E and Goedhart M J 2019 Analysis of secondary school quantum physics curricula of 15 different countries: different perspectives on a challenging topic *Phys. Rev. Phys. Ed. Res.* **15**(1), 010130.
[5] Krijtenburg-Lewerissa K, Pol H J, Brinkman A and Van Joolingen W R 2017 Insight into teaching quantum mechanics in secondary and lower undergraduate education *Phys. Rev. Phys. Ed. Res.* **13**(1), 010109.
[6] Wenger E 1998 Communities of practice: learning as a social system. *Syst. Think.* **9**(5).
[7] Riedel M, Kovacs M, Zoller P, Mlynek J, and Calarco T 2019 Europe’s quantum flagship initiative. *Quant. Sci. Tech.* **4**(2), 020501.

[8] Coecke B, Duncan R, Kissinger A, and Wang Q 2016 Generalised compositional theories and diagrammatic reasoning *Quantum Theory: Informational Foundations and Foils* (Springer, Dordrecht) pp. 309-366.
[9] Bennett C H 1982 The thermodynamics of computation—a review *Int. J. Theor. Phys.* **21**(12), 905-940.
[10] Bennett C H 1988 Notes on the history of reversible computation *IBM Journal of Research and Development*, *32*(1), 16-23.
[11] Feynman R P 2018 *Feynman lectures on computation* (CRC Press)
[12] Fredkin E and Toffoli T 1982 Conservative logic *Int. J. Theor. Phys.* **21**(3-4), 219-253.
[13] Isham C J 2001 *Lectures on quantum theory Mathematical and structural foundations* (Allied Publishers)
[14] St. Andrews University, QuVis simulations. https://www.st-andrews.ac.uk/physics/quvis/
[15] McIntyre D H Manogue C A and Tate J 2012 *Quantum mechanics: a paradigms approach* (Boston: Pearson)
[16] Feynman R P 1982 Simulating physics with computers *Int. J. Theor. Phys*, **21**(6/7).
[17] Malgieri M Onorato P and De Ambrosis A 2017 Test on the effectiveness of the sum over paths approach in favoring the construction of an integrated knowledge of quantum physics in high school. *Phys. Rev. Phys. Ed. Res.* **13**(1), 010101.
[18] Deutsch D 1985 Quantum theory, the Church–Turing principle and the universal quantum computer *Proc. Math. Phys. Eng. Sci.*, **400**(1818), 97-117.
[19] Grover L K 1996 A fast quantum mechanical algorithm for estimating the median. *Preprint quant-ph/9607024*.
[20] Hill R K 2016 What an algorithm is. *Philos. Technol.* **29**(1), 35-59.
[21] Rudolph T 2017 *Q is for quantum* (Kindle paperbacks)
[22] Castillo-Montoya M 2016 Preparing for Interview Research: The Interview Protocol Refinement Framework. *Qual.* **21**(5).
[23] Otero V K and Harlow D B 2009 Getting started in qualitative physics education research. *Reviews in PER*, **2**(1).