A teacher professional development course on quantum technologies: discussion of results

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Abstract. We first present the evaluation of a professional development course for in-service teachers on quantum technologies which was initially presented at the GIREP Malta 2020 webinar about halfway into its development. The primary purpose of the course was to enhance physics teachers' knowledge and awareness of topics related to quantum computation and quantum information, and of their relevance for technological advancement. However, our choice was not to present such topics as a simple addition to high school physics in the final year, but rather to inspect the whole physics and mathematics curriculum in the search for a longitudinal perspective, roughly based on the relationship between physics and computation, which could culminate in the treatment of quantum information topics. In the present contribution, we will focus on the educational outcomes of the course in terms of teacher appreciation, interest level and judgement of usefulness coming from both a final questionnaire and individual interviews. We will also describe a follow-up course structured to frame the topic from the standpoint of curriculum design and action research projects currently underway.

1. Introduction

The European Quantum Flagship [1], one of the most important joint research efforts of the European Union, is centered on the development and diffusion of quantum technologies. In parallel with frontline research, a clear focus of the Flagship since its inception in 2018 is the promotion of educational actions on the subject at all levels. Based on the collaboration between the groups of Quantum Information and Communication, and Physics Education, the Department of Physics of the University of Pavia offered in 2020-21 a course for teacher professional development on quantum technologies aimed at increasing teachers' awareness and competencies on topics related to the second quantum revolution. The structure and main innovative features of the course have been discussed at the GIREP Malta 2020 webinar [2]. We remind that in our work on teacher professional development, we have chosen to inspect the whole physics and mathematics curriculum in the search for a longitudinal perspective, mainly based on computation, which could culminate in the treatment of quantum information topics. The main idea is that there is a dialectic between physics, mathematics and logic that remains hidden in traditional teaching, as it is essentially focused on the individual development of each discipline. This interplay had been recognized, although in a primitive form, already in archaic times when the concept of calculation was strongly linked to real physical elements such as abacus stones. A deeper awareness of the aforementioned connection develops in the 70's and 80's, with a profound reflection on the physical problems of computation and on the possibility to use quantum mechanics to encode and manipulate information in different and innovative ways.

In the present contribution, we first provide in Section 2 an overview of current research on teaching quantum technologies and quantum information science, a highly active research area, and discuss the connections of such research with our own. Next we report on a professional development course based on this longitudinal and interdisciplinary approach that was organized in the context of the Italian PLS-Piano Lauree Scentifiche (Plan for Science Degrees) and the education section of the Quantum Flagship. The course was structured into three parts: a first basic sequence of 20 hours on the fundamental topics of quantum computation and communication, whose educational outcomes are discussed in Section 3; a follow-up part of 10 hours, attended only by teachers interested in starting action research projects, focusing on the educational challenges in teaching-learning quantum technologies, the design of active-learning strategies for overcoming these challenges, and the introduction of a physical context suitable to describe quantum systems and devices that can possibly encode and process information (Section 4); finally, the ongoing co-design sessions and action research projects with teachers are briefly discussed in Section 5. Being aware that asking teachers to directly discuss quantum information and communication topics in the regular curriculum would require a profound cultural revision and a steep learning curve, we instead directed their efforts on the design of teaching-learning sequences based on an exploration of the connections between physics concepts and the problem of computation at different school grade levels. 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.

2. Previous research on teaching-learning quantum technologies and information science

In recent works, a number of authors have proposed courses, tools and strategies in an effort to advance the scope of education to quantum mechanics (QM) in secondary school to include topics related to the "second quantum revolution" [1]. For example, Walsh et al [3] have designed and tested a one year high school course on quantum computing based on classical wave optics, with a focus on hands-on experiments and simulation activities adopting an inquiry-based approach, and the contextual introduction of new topics and competencies (such as the matrix formalism, or Python programming skills) when needed for the completion of students' inquiry projects. Satanassi et al. [4] developed a quantum computing course for high school students based on the general idea of leading students to follow the evolution of computational thinking in human history, from the most primitive computing machines, and ending with quantum computers and algorithms. The final part of their course uses a spin first approach, with the re-interpretation of Stern-Gerlach experiments in terms of information input (the state preparation), information processing (the state evolution) and information output (the measurement) playing a central role as a bridge from basic QM to quantum computation. Pospiech [5] proposes a course on QM for the German high school, in which quantum computing and quantum cryptography are introduced as rich technological contexts in which the fundamental concepts of quantum theory (e.g. superposition, entanglement, incompatibility, measurement) find their full development and application. According to the author, teaching QM in the context of quantum technologies has positive reflexes on conceptual understanding, on students' ability to construct consistent mental models, and on the epistemological acceptance of QM as an ordinary physical theory.

Research-based course proposals based on a hands-on approach for different targets, ranging from secondary school students [6] to undergraduates with little or no physics background [7] have very recently appeared in the educational literature. However, while research on the teaching and the learning of quantum physics is a well-developed field within physics education [8, 9]; and student difficulties at different levels, both in general and in connection with different teaching approaches, have undergone significant clarification, quantum technology and information science represents still a largely uncharted territory. There is a need to build effective programs and to design curricula for diverse student populations and educational levels, identifying goals and challenges according to the context at hand. Recently, quantum computation experts from both academia and industry signed an open letter [10] calling for an earlier start of education in quantum computer science in the academic career and recommending the involvement of education experts in curriculum development. An early introduction of such topics was also the subject of a recent educational survey [11] in which interviewed instructors in quantum information science expressed interest in research-based instructional materials, while displaying a remarkably wide range of opinions on the desirable content and prerequisites of future undergraduate courses. In Ref. [12], the authors identified the core ideas for quantum computing courses suitable for computer science students with superposition and entanglement of qubits, quantum computer, quantum algorithm, and quantum cryptography. The present work represents part of a larger program, which will be pursued in future works, aimed at defining the contours of a possible educational reconstruction of quantum computation and communication topics suitable for secondary school students. Since we believe that any such project is doomed to failure if it is not grounded on a community of motivated teachers, our work has started from the attempt to build such community, and most importantly, listen to teachers' perspectives and needs concerning the content. Although there are obvious similarities and parallelisms with some of the proposals in the literature, in particular Refs. [4,5], our work, as described in Ref. [2] originated mainly for a deep analysis of the subject matter, the search for an historical-epistemological route to make the content in principle accessible to secondary school students, and the attempt to exploit as much as possible the educational connections of the topic, both in a longitudinal sense, within the physics curriculum (e.g. connecting the debate on the second principle of thermodynamics, through the Szilard analysis of a single-molecule heat engine [13] to the discovery of Landauer's principle) and in an interdisciplinary sense, mainly, but not exclusively, with the mathematics curriculum on themes related to logic and probability.

3. Introductory sequence and educational outcomes

The initial part of the course had a total duration of about 20 hours and was 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	Entanglement
	From bit to qubit – Quantum circuits	Bell's inequalities No-cloning theorem
	Quantum algorithms	Quantum protocols (Dense coding, quantum teleportation)
		Cryptography

It was attended by around 30 teachers which reduced to about 17 after the introductory part. 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. At the end, we collected data by several means:

- 14 post-questionnaires completed, touching both disciplinary aspects and items related to personal engagement and involvement
- Semi-structured interviews with volunteering teachers

3.1 Post-course questionnaires

As shown from Figure 1 in general teachers displayed a strong appreciation for the topics covered, particularly on the second part about entanglement which using the formalism of logic gates can be treated in a formally rigorous and conceptually meaningful way. We note positive answers about having dealt with the course topics and the importance they could potentially have for the students. On the other hand, we also note a significant degree of scepticism about the possibility of introducing them into the curriculum, either just in principle, or adopting a longitudinal and multidisciplinary perspective (See Figures 2 and 3).

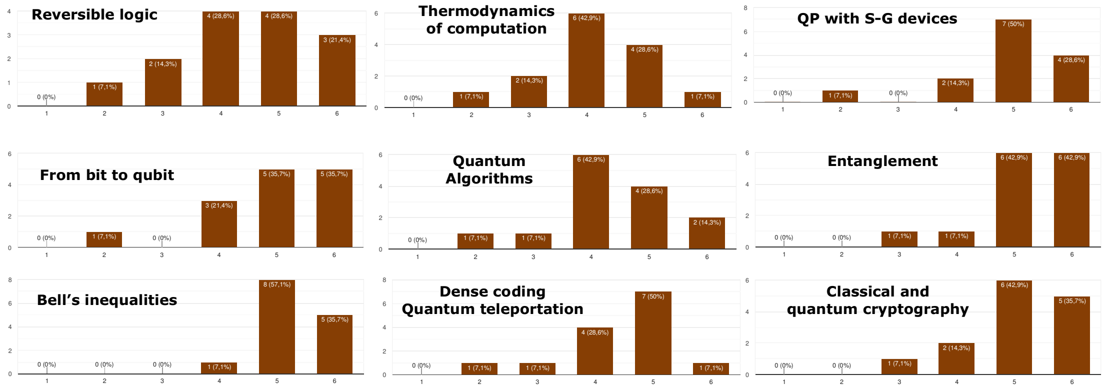

Figure 1. Interest level about topics introduced.

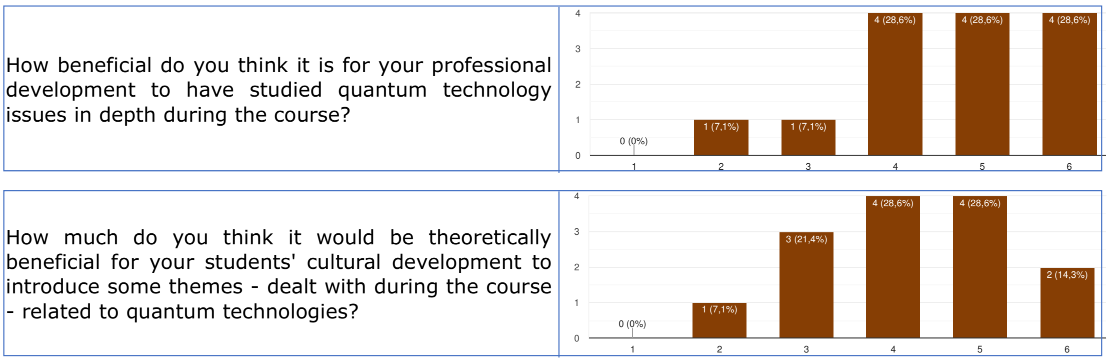

Figure 2. Teachers' opinion on whether themselves and students can benefit from instruction in quantum technologies.

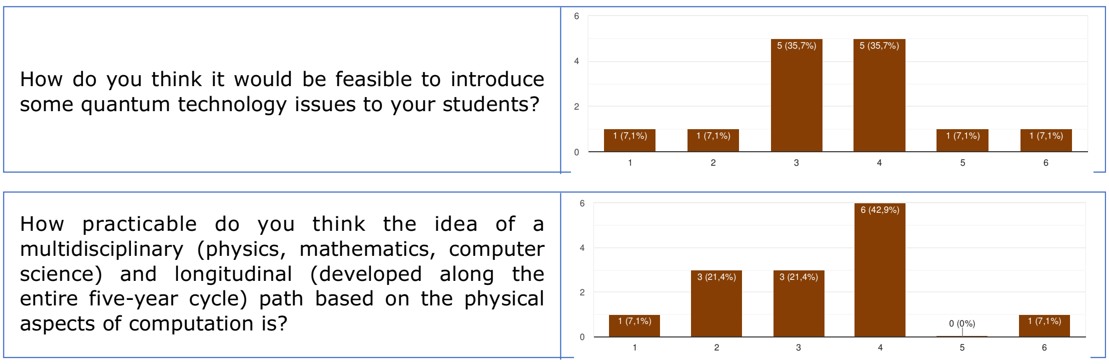

Figure 3. Propensity to introduce the topics of the second quantum revolution into the curriculum in general, and from the perspective of a longitudinal and multidisciplinary approach.

It is also extremely interesting that teachers found the circuit language introduced productive to relate physical phenomena, mathematical formalism and syntactic representation (See Figure 4).

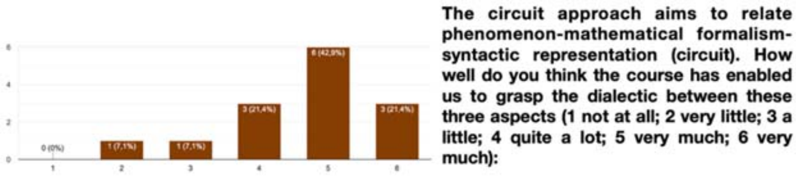

Figure 4 The importance of the circuital representation.

Although the teachers greatly appreciated the materials prepared and shared (lecture recordings and slides) and found the lessons as well structured and interesting as they had hoped at the beginning (Figure 5), they struggled to create a shared community of practice during the course, and teacher-to-teacher or collective online communication did not happen to any significant extent, notwithstanding the instruments we provided the group with (community forum, google drive folders).

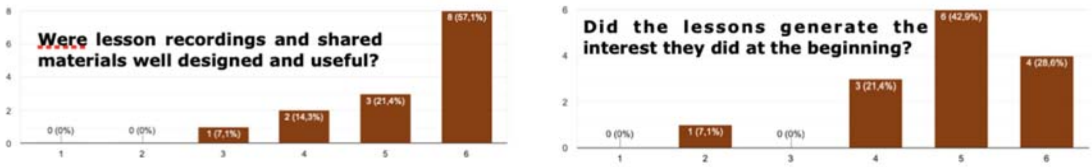

Figure 5 Quality of shared materials and level of satisfaction with respect to expectations

3.2 Semi-structured interviews
Between the initial sequence and the follow-up course, some teachers were individually interviewed for direct feedback on their appreciation of the topics covered and the aspects that improve or decrease their inclination to design experimentations with students. Some results based on such interviews were presented in a previous paper [2]. Here we restrict our attention to the four interviews to teachers followed the activities to the end. The elements that these interviewees had in common can be summarized as follows:

1. All teachers stated it was extremely difficult to deal with such advanced topics during the school term and also in distance learning. Nevertheless, the cultural impact of what had been proposed was fundamental in motivating them to follow as best they could and to engage in further development.
2. Teachers were interested in the physical grounding of the course, which made use of optical devices for implementing logic gates, algorithms and quantum protocols. Especially for physics graduates, this counterbalanced the excessive abstraction sometimes felt in the typical presentations of themes of quantum computing.
3. Teachers reported, with variable emphasis, the progressive tendency to homologation of all classes in high school, which reduces spaces of teacher freedom available for experimenting novel approaches and underlined the additional difficulty in introducing innovation in the final year of secondary school, which is the most strictly regulated because of the need of a common basis for the final exam.
4. All teachers asked for further help in the reconstruction of the content for instruction, and to be able to study and modify the teaching-learning sequences that our group had simultaneously proposed to some self-selected high school students [14]. In doing so, they also stressed the importance of continual close interaction and collaboration with researchers.

4. Follow-up course

After the initial sequence, we asked teachers who were available and willing to continue their professional development how work could be most profitably organized in the coming months with the aim of bringing some of the topics covered in class. The teachers' requests we report were the basis for the subsequent actions taken by the research team to continue the collaboration.

1. Teachers requested time to review and study the materials introduced, and the organization of further meetings devoted to questions, clarifications and additional information.
2. All teachers asked for further help in the reconstruction of the content for instruction based on preliminary teaching-learning sequences already designed by our group, but so far tested only with self-selected, motivated secondary school students.
3. Teachers were interested in preparing simplified materials trying to identify at least minimal learning paths to propose to students, taking into account the heterogeneity of classes.

4.1 Organization of the follow-up course

The follow-up part of the course was organized into five meetings and with some specific aims: 1) clarifying the educational issues and challenges behind the design of a teaching-learning sequence, in particular those related to the progressive acquisition, during the secondary school curriculum, of the prerequisites needed for quantum technologies; 2) exemplifying the implementation of these principles of design in terms of active-learning strategies that are feasible at high school level; 3) developing more in detail a physical context suitable to describe quantum systems and devices that can possibly encode and process information (photon polarization).

In the first meeting, we discussed the results of research on student understanding of quantum physics, highlighting three different kinds of learning challenges that need to be taken into account: interpretive difficulties, conceptual fragmentation, and epistemic challenges. In theory change from classical to quantum physics, basic terms of the former, such as 'measurement' and 'state', undergo a shift in meaning, giving rise to interpretive difficulties (see [15] for difficulties with quantum measurement). In addition, students struggle to overcome knowledge fragmentation on the quantum model, as attested by the strong context-dependence of their reasoning even after long periods of instruction on the topic [16]. Last, learning quantum physics requires students to renounce a set of basic beliefs about nature at a time, depriving them of important resources in building a plausible mental model of quantum systems and processes [17]. We explained to teachers that an awareness of research findings about domain-specific learning challenges can provide them with reliable guidelines in the design of instructional materials on the topic.

In the second and third meeting, we presented a teaching-learning sequence designed to help students overcome these different challenges. For this purpose, we revised an educational path presented in Pospiech et al., Section 4 [18]. The sequence is set in the context of the linear polarization of light, involving a repeated alternation of empirical explorations of the phenomenon and related devices (polarizing filters, birefringent crystals, etc.) at a macroscopic level, and model building activities at the level of single photons. We illustrated how the challenges were addressed by means of various kind of active-learning strategies grouped as *knowledge revision activities*, *knowledge integration activities*, and *exploration of epistemic practices.* The first set involves the revision of basic terms of classical physics such as physical quantity, measurement, state, vector, superposition, interference, whose quantum versions represent the conceptual and mathematical tools needed to cope with a course on quantum technology. The second introduces and develops the framework of the 'relations between properties', i.e., the rules that determine the acquisition, the loss and the retention of definite values of observables in the measurement process. The knowledge of these relations allows students to analyze measurement not only in the context of photon polarization, but also in other physical situations (e.g., the hydrogen atom), by means of already known instruments, in order to help students overcome fragmentation without introducing sophisticated mathematical constructs. The third is the operationalization of historically significant practices of the theoretical physicist - e.g., thought experiments, interpretation of known laws within new models, etc. - in terms of inquiry-based activities. These activities are used for helping students accept the quantum description of the world as a plausible and reliable product of their own inquiry. In these meetings, we showed several examples of ways in which basic design needs can be translated into concrete activities that can be experienced in the classroom.

In the last two meetings, we put the work done in the context of photon polarization at the service of quantum technologies, describing how to use already known experimental tools (birefringent crystals) and new ones (phase shifters) to build logic gates acting on a polarization encoded qubit (fourth lesson). In the fifth lesson, we introduced the last device (non-polarizing beam-splitter), which allowed us to discuss dual-rail encoding. Finally, we showed how this set of tools can be used to realize two-qubit gates, circuits and algorithms such as Deutsch's and Grover's, and, as a result, how mathematics, physics and the concrete realization of technological networks can be integrated into an interdisciplinary perspective.

4.2 Significance and role of the follow-up course

The five meetings following the course were essential to enable teachers to revise the concepts learned in terms of teaching methods that can be implemented in the classroom. The following is an interesting commentary by one of the teachers:

"The first course was a very significant, complex course: a course for teachers that was held at a higher level so that we could then reconstruct the concepts for the students. Translating into a educational sequence requires confronting with others, reflecting and concretely preparing the activities: you can't do it alone."

Teachers also underlined that a decisive step for them was to start reflecting autonomously on possible educational paths to bring in class part of the topics discussed.

Synthetically, some distinctive features of the second part of the course which contributed to its perceived productivity were as follows:

1. Each meeting was attended by 5 or 6 teachers, and based each time on their needs and requests
2. Since topics had already been introduced it was possible to focus on more specific parts making the approach more accurate
3. The topics introduced were presented in the light of an educational reconstruction for teaching
4. Each topic was treated with the continual prospect of evolving into a teaching experiment the following year.

These features led to more participation during the meetings, more questions and more observations made by the teachers even though they were still carried out in distance learning. All this allowed a qualitative leap in the relationship between the researchers and the teachers, as a prelude to the activities in action research projects that are still being carried out.

5. Co-design and action research projects

At the end of the follow-up course those teachers who intended to start autonomous experimentations based on the course materials were divided into thematic groups and started discussing between themselves and with tutors in the perspective of planning and performing didactic proposals in the context of their own classrooms. Considerations related to the dynamics of the various class-groups and the teachers' own level of interest and appropriation of the course materials guided each teacher in choosing the target classroom and the general theme for their first experimentation. From the start, participants were encouraged to work within a proper action research perspective, i.e. the well known phases of planning, execution, observation, reflection, evaluation [19]; and were introduced to the basics of the Model of Educational Reconstruction (MER) [20] as a general guideline for the design of teaching-learning sequences. It is however emphasized that, from the perspective of action research, the primary goal is not the production of new knowledge, not even knowledge in education research (although it may be gained as a byproduct in some cases) but self-development and the improvement of one's own educational practice [21]. Three groups were formed, to work on proposals concerning respectively a) quantum computation and communication; b) the thermodynamics of computation and the Landauer principle; and c) the connection between classical logic, probability and experimental outcomes. Such proposals are intended for the fifth, third, and first year of high school respectively. In the preparatory phase for the educational planning, the guiding role of researchers in arranging on the table the various elements contributing to the design (historical and epistemological analysis of the science content, relevant research literature, possible difficulties which students could encounter) and the instruments for evaluation of the sequence was still relevant, but work is proceeding towards a progressively higher level of autonomy by the teachers. At the present time, for teachers belonging to the group a) described above, the experimentation is ongoing in classrooms; for group b), teachers are in the final phase of the design of educational sequences, and group c) is in the preliminary phase.

6. Conclusions

We presented the outcomes of a professional development course for in-service teachers introducing some of the most relevant physics concepts connected to the "second quantum revolution". The course was greatly appreciated by teachers, and interest was reportedly high for all the treated topics. Teacher's willingness to translate the course content into educational practice was not very high (about 30% of the initial participants is now involved in the design of research-action projects). However, the result appears encouraging if compared with the outcomes of typical professional development activities on modern physics [22]. It emerged from interviews and recordings of meetings that the teachers involved in the action-research projects all shared certain similarities: strong engagement for the proposed topics; appreciation of the cultural value of the proposal for students; the aim to propose new curricular education paths disseminating them to their whole schools and not only in their classes; the aim of including these paths in a perspective of continuity with the previous personal educational choices; the awareness of the importance of discussions with researchers and the time shared with them. Strong personal motivations supported by work with researchers are currently resulting in a progressively higher level of autonomy by the teachers, essential condition for one's professional development.

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