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The challenge of Quantum Manifesto for science education: Designing a teaching module on quantum computers for secondary school students

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Summary. — Among the key activities of Quantum Manifesto there is the formation of a new generation of quantum technology professionals in Europe through focused education at the intersection of different STEM and socio-economical disciplines and by strengthening public awareness of key ideas and capabilities. How can young people be guided to grasp the essence, potential and social implications of new quantum technologies? This paper presents how the research group in physics education of the University of Bologna is addressing the challenge launched by Quantum Manifesto and is approaching the issue of designing teaching materials on quantum technologies aimed to enable secondary school students to grapple with the second quantum revolution.

1. – The second quantum revolution, an overview

On invitation of the Commissioner for Digital Economy and Society and the Minister of Economic Affairs in The Netherlands, a European academic team in 2016 wrote a document entitled *Quantum Manifesto* (`https://qt.eu/app/uploads/2018/04/93056_Quantum-Manifesto_WEB.pdf`). It represents an authoritative call from academy to formulate a common strategy for Europe to stay at the front of what it is called the Second Quantum Revolution. The beginning of this document stresses the extent to which quantum technologies are slowly invading every-day life and seem to lead to radical change.

"Technologies based on the laws of quantum mechanics, [...], will lead to a wave of new technologies that will create many new businesses and help solve many of today's global challenges. [...] Quantum technologies could result in revolutionary improvements in terms of capacity, sensitivity and speed, and will be the decisive factor for success in many industries and markets" [1].

The manifesto continues:

"This Manifesto calls upon Member States and the European Commission to launch a 1 billion euros flagship-scale initiative in Quantum Technology, preparing for a start in 2018 within the European H2020 research and innovation framework programme.

It is endorsed by a broad community of industries, research institutes and scientists in Europe".

As is happening in other parts of the world, like in China and the USA, the development of European capabilities in quantum technologies is expected to create a knowledge-based industry, which will lead to long-term economic, scientific and social benefits. This will result in a more sustainable, more productive, more entrepreneurial and safer European Union. The European Commission officially responded to the Quantum Manifesto call through *The European quantum technologies flagship programme* [2].

The aims of the flagship are i) to consolidate and expand European scientific leadership and excellence in quantum research and innovation project; ii) kick-start a competitive European industry in quantum technologies to position Europe as a leader in the future global industrial landscape; iii) make Europe a dynamic and attractive region for innovate research, business and investments in quantum technologies [2].

As asserted in *The European quantum technologies flagship programm* [2], the current quantum revolution follows the revolution that led the fundamental laws of the microscopic world to be discovered and the quantum theory formulated in the beginning of the 20th century. In the years following the first revolution different technologies (laser and transistor) were designed and developed with the help of quantum mechanics (for example, the band structure of a semiconductor). The Second Quantum Revolution concerns instead technologies that can directly act on an individual quantum state and make use of quantum properties, *i.e.*, superposition principle and entanglement. This revolution has been triggered mainly by two different factors. The first factor concerns the increasing number of start-ups that have been founded to offer quantum technologies to very specialized markets (for example, quantum cryptography devices and software are already on the market). The second factor concerns the large investment in quantum technologies of big global companies as Google, IBM5, Microsoft, etc. They are attracting "the best talents that only a couple of years ago had only the choice between the pursuit of an academic career and the abandonment of the field" [2]. Governments are also taking a cue from the trend and launching large funding programs in the field. In addition to quantum computing, quantum communication is particularly at the top of the agenda of many countries, especially in China, which is planning to invest heavily, managing to launch a satellite with quantum communication devices [3]. The strong urgency for Europe to keep up with quantum technologies global developments is felt by many experts and decision makers. This urge was expressed in the Quantum Manifesto, endorsed by over 3500 stakeholders from abroad community of industries, research institutes and scientists in Europe [1].

To cope with the second quantum revolution, the Quantum Manifesto states that "An ambitious, long-term, flagship-scale initiative combining education, science, engineering and innovation across Europe is needed in order to unlock the full potential of quantum technologies, to accelerate their development and to bring commercial products to public and private markets" (emphasis added).

The program thus includes different dimensions, such as science, engineering and innovation, but a strong importance is also given to the dimension of education. This dimension has the specific objectives of:

- "running educational programmes for a new generation of technicians, engineers, scientists and application developers in quantum technologies;
- running a campaign to inform European citizens about quantum technologies and engage widely with the public to identify issues that may affect society" [1].

Coherently, within the program of the flagship, a first edition of the European Quantum Technologies conference has been held in Grenoble (ETQC19, `https://first-tf.com/eqtc-2019-european-quantum-technologies-conference/`), where also a section explicitly targeted to education was considered. Education means, first of all, to invest competences and resources to prepare a new generation of professionals that are experts in quantum technologies. A new generation of professionals means the need of designing now educational programmes and it implies the product of new teaching materials for both secondary school and university students. Moreover, education means to invest competences and resources to equip the young generation and citizens with knowledge and skills needed to grasp the conceptual basis, the potential and/or the social implications of these new technologies.

This paper shows a module on quantum technologies developed by the group of physics education of the University of Bologna within the I SEE project (`https://iseeproject.eu/`). The I SEE project (Inclusive STEM Educating to Enhance the capacity to aspire and imagine future careers) is a triennial Erasmus + project, started in September 2016 and ended in September 2019, coordinated by the Department of Physics and Astronomy of the University of Bologna. The strategic partnership is composed by institutions coming from four different countries: Italy, Finland, Iceland and the United Kingdom. In particular, the partners are: two universities (the University of Bologna and the University of Helsinki), three secondary schools (the "A. Einstein" High School of Rimini, the Normal Lyceum of Helsinki and the Hamrahlid College of Reykjavik), an Icelandic environmental NGO (Non-Governmental Organization), an association of English teachers (Association for Science Education) and a private foundation in Bologna (Fondazione Golinelli). The overarching goal of the project is to design innovative approaches and teaching modules on STEM (advanced) topics, to improve the students' ability to imagine the future (*future-scaffolding skills*) and aspire to STEM careers [4, 5]. Furthermore, the project aims also to contribute to the complex and articulated debate on the integration of STEM disciplines in *curricula*, taking the original perspective of addressing, through the lens of science education, the issue of imagination of possible futures as a key to encourage the students to aspire to STEM careers. In order to achieve these goals, we developed four modules on three topics that are STEM, future-oriented topic and relevant on the political, social and personal dimension: climate change, artificial intelligence, carbon sequestration and quantum computing.

With our study we tried to respond to the call launched by the Quantum Manifesto. We designed an approach and developed a module on the new quantum technologies for high school students, in order to exploit these new technologies both to reinforce some quantum concepts that could remain abstract and to make the students aware of the fast technological evolution and the new opportunities that it offers. The module designed by the group of Bologna is a re-elaboration of a first version developed by the group of Helsinki. The group of Bologna was composed of different experts belonging to different disciplines:

- a theoretical physicist, Prof. Elisa Ercolessi, expert in quantum computing;
- a researcher in physics education, Prof. Olivia Levrini;
- three post-doc students, one in mathematics education, Dr. Laura Branchetti, one in physics education, Dr. Giulia Tasquier, one in computer science, Dr. Michael Lodi;

- three PhD students, two in Physics, Dr. Giovanni Ravaioli and Dr. Sara Satanassi, and one in Data Science and Computation (Dr. Eleonora Barelli);
- a secondary school teacher with professional expertise in classical computing architectures and algorithms, Prof. Paola Fantini;
- two teachers of the "A. Einstein" High School of Rimini, Prof. Michela Clementi and Prof. Fabio Filippi.

In the next section we present the context, the contents and the approach we developed to introduce and address the topic.

2. – A glance at the module on quantum computation

The first implementation of the module took place between February and March 2019 within an extra-curricular context, the PLS (Piano Lauree Scientifiche) laboratory, organized by the department of Physics and Astronomy of the University of Bologna. The module implementation lasted about 20 hours (six weeks with 3-hours weekly sessions) and involved 25 secondary students (16–17 years old), 15 males and 10 females, from different schools, that had never studied quantum physics before. Figure 1 shows the contents of the activities and their organization.

In this paper we focus on the conceptual and epistemological activities on quantum computing and, in particular, on the approach we developed and implemented in the first three days.

3. – The approach to quantum technologies

When we started to think about the module on quantum technologies, an analysis of the popularized literature showed that the articles, in general, present the quantum computer as a much more powerful calculator because it "uses" a new basic unit (the

	Conceptual and epistemological activities	**Future activities**
Day 1	- History of classical computers - Physics of quantum computer – Part 1 (Stern and Gerlach experiment, introduction of the concept of state, superposition principle, manipulation of state and measurement)	
Day 2	Physics of quantum computer – Part 2 (introduction of two-state systems, the concept of entanglement, notes on quantum cryptography)	Teamwork activity on the Quantum Manifesto to explore implications and applications of quantum computing on research, society, policy, communication
Day 3	Analysis of the quantum teleportation protocol as concrete exemplification of the approach	
Day 4	Introduction to computational complexity	Introduction to Future Studies (FS)
Day 5		Teamwork on future (introduction of the concepts of scenario and back-casting)
Day 6	Presentation of group works	

Fig. 1. – Timetable of activities.

QUBIT) and follows laws different from the classical ones. Behind this, apparently simple, statement, lies the epistemological revolution that characterized the physics of the 20th century and that re-opened the old ontological and epistemological questions about the "foundational laws of nature". In fact, the origin itself of quantum simulators and quantum computers implements the idea that, as Feynmann wrote in his foundational article: "But, what kind of physics are we going to imitate? [...] the physical world is quantum mechanical, and therefore the proper problem is the simulation of quantum physics [...] I want to talk about the possibility that there is to be an exact simulation, that the computer will do exactly the same as nature" [6].

For this reason, when we started to think about the type of activities to develop, some questions emerged to guide us in the design:

a) How can we make students aware of what we mean today with quantum logic gates, quantum circuits, quantum simulators and quantum computers?

b) How can we introduce the new logic in order to foster students to grasp the essence and the potential behind them?

c) How can we make students aware of the transformative power and the impact that these new technologies can have?

In order to answer the first two guiding questions we designed an approach characterized by the choice of two leading threads as the backbone structure of the module:

- the comparison between classical and quantum logic;
- the comparison between experiment and circuit.

Following these two main threads, students were guided to learning the basics concept of quantum physics, to recognizing the potential behind quantum technologies and grasp their transformative essence. In sect. **4**, the contents of the module are described according to this structure.

In order to answer the third question, we developed an activity aimed to make students aware of the impact of these technologies not only on the research dimension but also on the social, ethical, political and environmental dimensions. The activity is described in sect. **5**.

4. – The approach to quantum technologies

The first three days of the module have been designed to build the knowledge necessary to grasp the differences between classical and quantum computers and to outline an overarching image of quantum technologies without getting lost in the physical and mathematical technicalities.

The first meeting was focused on introducing the approach. The lesson was organized in two parts, according to the two leading threads. In the first part, students were led to realize that dealing with quantum computers implies, so far, to refer to simulators and, at the very basis, to quantum physics experiments. From this point of view, they had to expect a difference between the common idea of classical computer and what they would have found in the course on quantum computers: today when one talks about classical computers, he/she mainly refers to the software and the interfaces; when one talks about quantum computers, he/she mainly refers to the physics of its gates and, hence, to the physics of the equipment that realizes the gates. Thus, the part titled *History of classical computers* was organized to show that: a) all the classical computers, from the first to the fourth generation, share the same structure and logic; b) the technological progress led an impressive extension of the memory, the velocity of information processing, the type of input/output devices, but it did not change the basic structure and the basic logic. More specifically, the students were introduced to the von Neumann structure, composed by: The Central Processing Unit (CPU), that includes the arithmetic logic unit, ALU, and a control unit; the Random Access Memory (RAM), an input unit, an output unit; a channel called BUS which links the components together. After that, a special focus has been made on the logic shared by all the classical computers. For this purpose, the concept of BIT, the Boolean logic, the logical gates NOT, AND and OR with their respective truth tables have been introduced and it has been shown that all the mathematical operations (*i.e.*, the sum and the subtraction) can be realized through a combination of those universal logic gates. Special attention has been paid to moving reasoning from a computational perspective to a physical one. A concrete realization of the BIT and logical gates has been shown by reefing to the mechanical example extrapolated from an article published on *Scientific American* by Dewdney. The logic gates and their functioning are realized by an ingenious system of ropes and pulleys represented in fig. 2 [7]. Real and concrete reconstruction of such gates have been presented to the students too.

The lesson on the history of classical computer continued by showing computer evolution from the difference engine, first created by Charles Babbage, to the computer as we know it today, focusing on the technological evolution of the components. In particular, in the first generation the main tools of information processing were the vacuum tubes, in the second the transistors, in the third the integrated circuits and in the fourth sets of integrated circuits called chips. This operation showed that there is a logic, based on the logic of classical physics, that is deterministic and sequential. This overview allowed us to pave the way to enter quantum computers by stressing the revolution that characterizes the changes in the structural logic and by searching for its logic in the basic quantum physics.

To accomplish the presentation of the approach, the second leading thread is introduced: an experiment can be reconceptualized as logical circuit. More specifically, three main phases of an experiment,

preparation of a state - manipulation of a state - measurement,

can be re-interpreted in terms of

input information - information processing - output information.

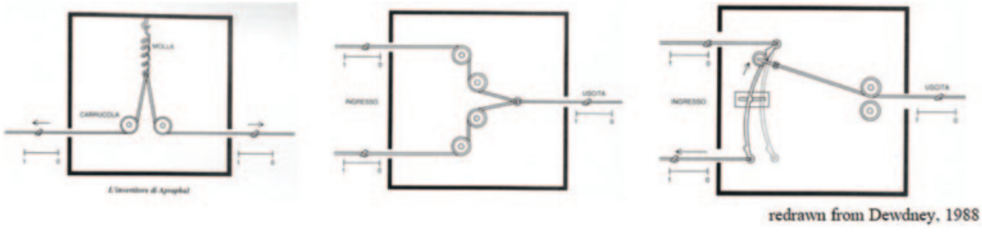

Fig. 2. – Mechanical realization of, from left to right, NOT, OR and AND logic gates [7].

Consistently, the quantum logic gates emerged immediately as a reconceptualization of experimental tools that are used for quantum evolution and measurement. The approach was implemented in the second part of the first meeting starting from the Stern and Gerlach experiment. This experiment has been used to:

a) introduce the concepts of state, that of state evolution/manipulation, in the particular case of a one-state system, and that of measurement;

b) show the new logic that characterizes quantum physics focusing, in particular, on the superposition principle being conceptual and epistemological innovation that marks the difference between BIT and QUBIT;

c) introduce the one-qubit quantum logic gates and the truth table (X, Y, Z and Hadamard gates) by referring to the Stern and Gerlach apparatus.

In the second meeting, two-qubit systems, their manipulation through two-qubit logic gates and their respective truth tables were introduced. Furthermore we discussed the concept of entanglement as a real resource for quantum computation and information. The computational reconceptualization of experiment was used to engage students with the quantum cryptography protocol. Using the simulation of QUVIS (quantum mechanics visualization) project, by the University of St. Andrews (`https://www.st-andrews.ac.uk/physics/quvis/`), we showed students the functioning of the quantum cryptography protocol BB84 and its experimental realization (a representation is in fig. 3). The action of Pockels Cells (PC) and the entire experiment were interpreted as the combination of X, Y or Z logic gates (X, Y, Z) with the inclusion of a circuit that randomizes the polarization.

In the third meeting, the approach was made more and more explicit in the case of teleportation [8]. A step-by-step comparison was built between the main "moments" of the experiment (fig. 4) and the "moments" of the circuit (fig. 5). The experiment we chose refers to the very well-known one realized by the group of Zeilinger in which a state of a photon was teleported from a side to the other of the Danube [9].

In particular, the teleportation experiment was schematized in three crucial steps that have equivalent moments in the circuit. The first important moment is the projection of the two photons (b and c) in a Bell state (fig. 4). From the experimental point of view, states of the photons are transformed by a particular set-up composed by optical fibres, polarization controller and optical fibre beam splitter. From a computational point of view, the states are manipulated by sequencing two logic gates, the CNOT and the Hadamard gate. The second crucial moment regards Alice's measurement. In the

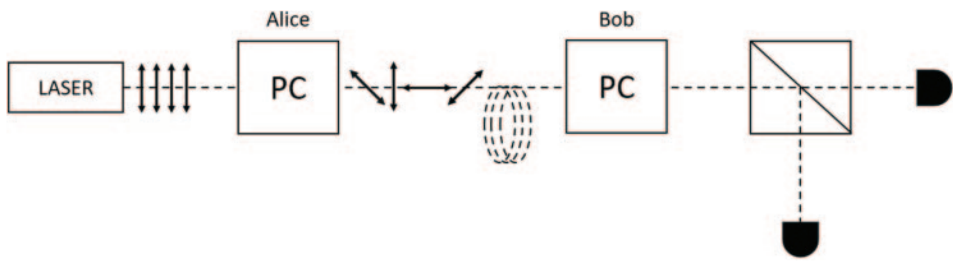

Fig. 3. – Schematic experimental representation of quantum cryptography protocol BB84 (PC - Pockels Cells).

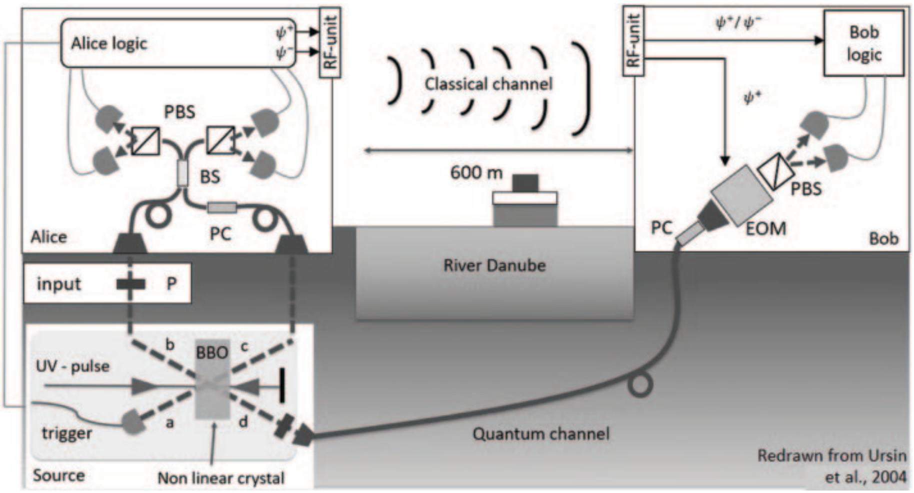

Fig. 4. – Set-up of the teleportation experiment [9]. (BBO: β-barium borate; P: polarizer; BS: Beam Splitter; PBS: Polarizing Beam Splitter; PC: Polarization Controllers; EOM: Electro Optic Modulator.)

experiment, the measurement is carried out through the combination of PBS (Polarized Beam Splitter) and four detectors (fig. 4). This step in the circuit is represented simply by the quantum symbol for the measurement (fig. 5). The third moment consists in the unitary transformation that Bob has to perform in order to recover the state, after that Alice's output is communicated via the classical channel. In the experiment, the state is modified by applying a voltage pulse through the EOM (electro-optic modulator), whilst in the circuit the signal has to be passed through the X and Z gates that correspond to rotations of the state in the Block's sphere. The experimental set-up of quantum teleportation is complicated, so it was not our aim to make students acquainted with the tools that realize it. Our purpose was to help them grasp where the "reality sticks to the circuit" and where the logical arguments can be attached to the real apparatus.

The cultural potential of the activity lies in showing the experiment and the circuit represent different ways to solve the same task, each of them being characterized by its own language, symbolic forms of representation and formalism.

To sum up, from the second part of day one up to day 3, we built an overarching picture to point out how quantum computers are based on a new logic and why, today, referring to them, we are often talking about experiments: quantum devices design to manipulate information and solve problems.

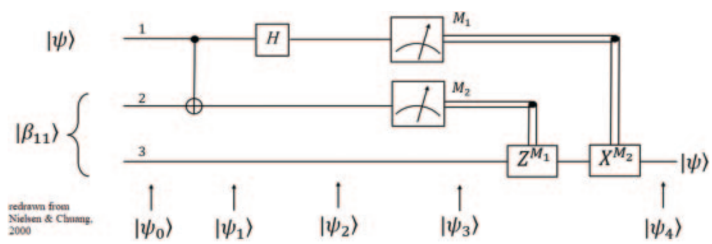

Fig. 5. – Teleportation circuit [10] (H: Hadamard gate).

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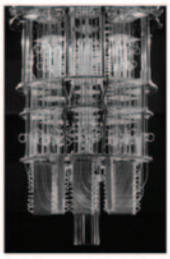

Some definitions:

- ***Quantum simulator***: a controllable quantum system used for the simulation of other quantum systems, as it is possible to control some parameters.
- ***DQS (digital quantum simulator)***: a system that can reproduce a quantum algorithm for simulating another system. Quantum computers are an example: they are universal simulators, as they can *potentially* reproduce any kind of quantum system.
- ***AQS (analogue quantum simulator)***: tangible quantum systems that can replicate other ones. They can simulate a limited class of systems or phenomena. Because they are tangible, one can directly make measurements on them, contrary to DQSs, where states are manipulated through algorithms for obtaining results. In the recent years, different types of AQS models were implemented, and the development of some of them is based on the principles of physics of condensed matter—neutral atoms in optical lattices, cooled and trapped ions, superconducting circuits, et cetera.
- ***Quantum sensors:*** devices that use the superposition principle and/or entanglement in order to obtain higher sensibility and resolution for measurements of gravitational and magnetic fields, time intervals, and fundamental physical constants.

Quantum simulation applies to various scientific and technological fields, from atomic physics and solid-state physics, to high-energy physics and cosmology, and beyond.
Moreover, as it will allow to analyse the properties of certain systems, to select systems with desired properties, and to realise new compounds with desired properties, it will also allow to design new drugs or materials with important features (such as superconductors at high temperatures) that could be used in different fields, such as the energy or the transport ones.

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As far as the environment is concerned, one of the so-called *world's critical problems* is the design of an efficient system for capturing carbon in the atmosphere.
A wide accessibility to quantum computers on one hand and to scientific knowledge on the other is necessary to avoid the creation of monopoles within pharmaceuticals companies, multinational corporations and governmental institutions. It is for tackling these new challenges that we need to educate new generations of technicians and scientists.

Links	Descriptions
https://www.youtube.com/watch?v=qarc7AA4-wM	Short introductive video on the challenges of quantum simulation
https://www.microsoft.com/en-us/research/blog/problems-will-solve-quantum-computer/	Article showing that a QC can be used to reveal the reaction dynamics within a complex chemical system. For example, the analysis of the nitrogenase (an enzyme), which is beyond the capacity of any supercomputer today, will have important consequences on the production of fertilisers
https://qt.eu/discover/applications-of-qt/fertilizer-and-other-quantum-computer-chemistry/	Website showing the objectives of computational chemistry in the development of mathematical models that simulate the behaviour and the properties of complex chemical systems
https://home.cern/news/news/computing/exploring-quantum-computing-high-energy-physics	QC for the challenges in high-energy physics
https://www.cnr.it/it/news/8292/sensori-quantistici-superconduttivi-per-comprendere-la-progressione-della-sla	Use of quantum superconductive sensors in the functional study of the brain
https://qt.eu/app/uploads/2018/04/93056_Quantum-Manifesto_WEB.pdf	Quantum Manifesto

Fig. 6. – An example of worksheet to explore the impact of quantum technologies in the research.

5. – An example of activities: "Quantum computing and..."

Another important aspect, as we highlighted before, concerns the transformative power and impact of quantum technologies. The implications and applications, as the Quantum Manifesto stresses, go beyond the scientific, technological and societal dimensions, and invest dimensions that may appear less related to the problem, such as policy, education, ethics, economy and environment. In order to enable students to recognise this multidimensionality, an activity was designed [11]. The students were guided to explore first hand how quantum technologies, for example, can improve the research and the development in different sectors (*e.g.*, the sector of materials, energy, health, safety and environment), or can create new carriers in the STEM (Science, Technology, Engineering and Maths) fields. Specifically, students were guided to analyse official documents (including excerpts from the Quantum Manifesto), by using four worksheets that we designed on the principal impact areas of quantum technologies: quantum computing and research, society, policy and communication (an example of worksheet is reported in fig. 6).

We asked students to analyse in groups these sheets and to work on the map in fig. 7, trying to think about the connections between their topic and the areas involved and to clarify both the reasons for the connections and the dimensions involved in the problem they found.

Finally students were required to present the results of the work group. From the presentations, both the worksheets and the activity seemed to be effective to enable students to recognize the multidimensionality that characterizes the topic and to develop a critical attitude towards scientific knowledge.

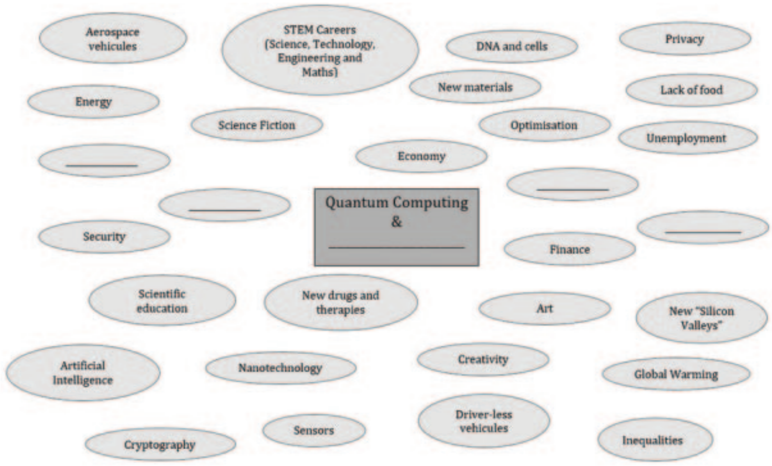

Fig. 7. – Map of the impact and link.

6. – Conclusion

In this paper we described an approach and some teaching activities we developed on quantum computers. Implementation with secondary school students shows its effectiveness and educational potential on two sides. The first one concerns the type of disciplinary and cultural engagement fostered among the students. From an initial analysis of the collected data, it seems that students found an effective and stimulating way to enter the conceptual and epistemic essence of quantum technologies. For example, a student, during a final discussion, said: "[...] it was very interesting the distinction between everyday physics that we study in high school and quantum physics, because we grew up thinking that what surrounds us is classic [...] then when you told us that it is quantum I was a little bit ... confused, because I could not immediately grasp the meaning but now it seems to me clearer [...] consequently a computer that represents and reflects more reality and its logic I think can be [...] (trustful)". From these reflections emerges to what extent the approach was able to touch very profound beliefs about physics and reality, as well as how it was effective to show why new technologies require a deep study on quantum physics as a foundational theory. The second element of education potential concerns the nature itself of quantum technologies and their role with respect to quantum theory. The developed approach pointed out that such new technologies do not simply represent a sort of appendix or a mere application of the theory to be added at the end of the chapter on quantum mechanics. Instead they can become a very fruitful context to both introduce and deepen the concepts of quantum mechanics, and discuss the impact of quantum revolution on society and, thus, prepare them to deal with their futures.

In this moment, the module is implemented for the second time within the PLS laboratory (`http://www.pls.unibo.it/it`). In this second edition, special focus is on the type of intertwinement between physics, computer science and mathematics. The goal is to exploit the module as a fruitful case that can contribute to pointing out a model of interdisciplinarity in STEM fields within the Erasmus+ project, IDENTITIES (`https://identitiesproject.eu/`).

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This article was part of my master thesis and represents the starting point of PhD research work. I would like to thank Professors Olivia Levrini, Elisa Ercolessi and Paola Fantini for their fundamental contribution in the design and implementation of the module.

REFERENCES

[1] de Touzalin A., Marcus C., Heijman F., Cirac I., Murray R. and Calarco T., *Quantum Manifesto*, 2016.
[2] Riedel Max F. *et al.*, *Quantum Sci. Technol.*, **2** (2017) 030501.
[3] Gibney Elizabeth, *Nat. News*, **535** (2016) 478.
[4] Levrini O., Tasquier G., Branchetti L. and Barelli E., *Int. J. Sci. Educ.*, **41** (2019) 2647.
[5] Branchetti L., Cutler M., Laherto A., Levrini O., Palmgren E. K., Tasquier G. and Wilson C., *The I SEE project: An approach to futurize STEM education*, in *Visions for Sustainability*, 2018, https://doi.org/10.13135/2384-8677/2770.
[6] Feynman Richard P., *Int. J. Theor. Phys.*, **21** (1982) 467.
[7] Dewdney Ak., *Sci. Am.*, **258** (1988) 118.
[8] Satanassi S., *Quantum Computers for High School: Design of Activities for an I SEE Teaching Module*, Master's Thesis (Alma Mater Studiorum, University of Bologna, Italy) 2019, https://amslaurea.unibo.it/id/eprint/18157.
[9] Ursin R., Jennewein T., Aspelmeyer M., Kaltenbaek R., Lindenthal M., Walther P. and Zeilinger A., *Nature*, **430** (2004) 849.
[10] Nielsen Michael A. and Isaac Chuang, *Am. J. Phys.*, **70** (2002) 558.
[11] Spada R., *The Second Quantum Revolution: Designing a Teaching-Learning Activity on the Quantum Manifesto to Futurize Science Education*, Bachelor's Thesis (Alma Master Studiorum, University of Bologna, Italy) 2019, https://amslaurea.unibo.it/18360/.