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Quantum Computing for high school: an approach to interdisciplinary in STEM for teaching

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Quantum Computing for high school: an approach to interdisciplinary in STEM for teaching

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Abstract. The paper focuses on a Quantum Computing teaching module for high school students that was designed and implemented within the I SEE Erasmus+ project (https://iseeproject.eu/). The module is discussed as an example of how the S-T-E-M disciplines can be integrated to stress the conceptual, epistemological, and social relevance of quantum computing. We implemented a three-level approach to introduce quantum technologies without getting lost in the technicalities. The approach has allowed us to highlight the difference between classical and quantum computers and to bring out the interdisciplinary character that characterises the new technologies.

1. The I SEE project and the module on quantum technologies

The paper concerns a module on quantum computation that was designed and implemented for secondary school students within the project I SEE (Inclusive STEM Educating to Enhance the capacity to aspire and imagine future careers). I SEE is an Erasmus + project, started in September 2016 and just finished (August 2019), coordinated by the Department of Physics and Astronomy of the University of Bologna (https://iseeproject.eu/). The strategic partnership is composed by institutions coming from four different countries: Italy, Finland, Iceland, and the United Kingdom. The module on quantum computation is an elaboration of a previous module developed by the University of Helsinki (https://iseeproject.eu/i-see-module-on-quantum-computing-and-the-future-of-ict/)

The main objective of the project concerns the design of teaching modules aimed to i) improve students' ability to imagine the future and to aspire to STEM careers; ii) develop *transversal skills* that allow students to play an active, aware and responsible role in the 'society of acceleration and of uncertainty' [10]. The I SEE project is based on the idea that STEM (Science, Technology, Engineering and Math) education can offer a fundamental contribution to enabling the young to develop *future-scaffolding skills*, i.e. skills that enhance their capacity to aspire, envisage themselves as agents of change, and push their imagination towards future careers in STEM [1].

In order to develop *future scaffolding* and *transversal* skills the I SEE partnership has designed and implemented teaching-learning modules on four STEM and cutting-edge topics: climate change, artificial intelligence, carbon sequestration, and quantum computers. The topics have been chosen since they represent real contemporary challenges and are future-oriented and relevant from a political, social, and personal perspective. All the I SEE modules share a common structure, represented in figure 1. From left to right, the five blocks of activities represent i) activities of encountering the focal topic and issues related to future thinking; ii) lab-activities on the scientific core of the module where conceptual knowledge, inquiry practice and epistemological knowledge and practice are intertwined; iii) "bridging" activities aimed to flesh out, from the scientific contents, the constructs or models of causal reasoning

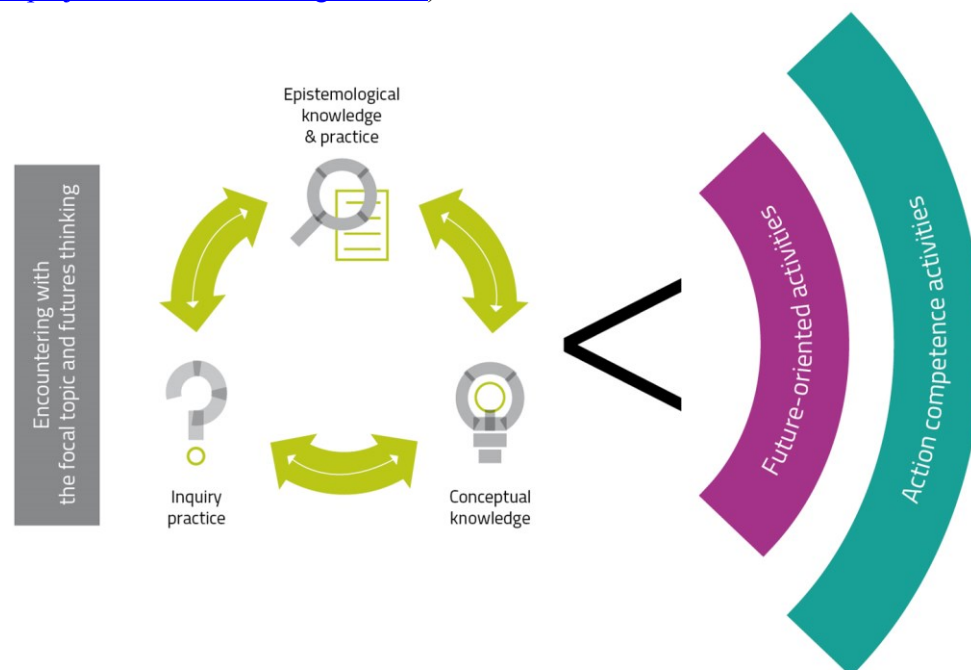relevant for forecast and foresight; iv) future-oriented activities; v) action competence activities (https://iseeproject.eu/i-see-module-guide-o3/).

Figure 1: structure of an I SEE teaching module

The paper is focused on the module of quantum computers, that has been designed to enable students to:

    a) grasp what is meant today by quantum logic gates, quantum circuits, quantum simulators and quantum computers;

    b) recognise the impact and the multidimensionality (dimensions of the research, politics, economy, ethics and so on) that characterises these new technologies.

To reach these goals we developed a three-level approach, described in Section 3.

The module was implemented between February and March 2019 in an extra-curricular course organised by the Department of Physics and Astronomy of Bologna, within a national programme called Piano Lauree Scientifiche, PLS (Scientific Degrees Plan). The programme aims to foster a collaboration between universities and schools to orient and support students in their university career choice. The module on quantum computers was attended by 25 secondary school voluntary students (10 female and 15 male), 17-19 aged (grade 11-12). The students had never studied quantum physics before. The module implementation was articulated in six afternoon slots of three hours each.

The activities of the module were organised to develop, in each lesson:

- *conceptual* skills (about the basic knowledge of quantum physics, such as the concept of state, manipulation/evolution of a state, superposition principle and measurement, quantum cryptography, and teleportation);
- *transversal* skills (such as team working, decision making...);
- *future scaffolding* skills (scenario thinking, foresight, back-casting, action competence).

Table 1 shows the main topics addressed in the six lessons.

Table 1: timeline and structure of the quantum computing module

Day	Concepts-oriented activities	Future-oriented activities
1°	▪ History of computers ▪ The basics concepts for quantum computer (state, superposition principle, Qubit, state evolution and measurement)	▪ Introduction to future's cone
2°	▪ Introduction to multi-qubit systems and entanglement ▪ Cryptography	▪ Future-oriented activity "quantum computing &..."
3°	▪ Quantum teleportation	▪ Delivery of students' output on "quantum computing &..." ▪ "Back to the future"
4°	▪ Classical and quantum problems ▪ Predict, simulate and build future scenarios ▪ Game theory: which interaction between agents?	
5°	▪ Futures and action competence activity	
6°	▪ Delivery of students' outputs on futures and action competence activity	

A wide variety of teaching strategies have been implemented in class: lectures to introduce the concepts, teamwork to solve problems and discuss on conceptual questions of tutorials, teamwork to analyse excerpts from Quantum Manifesto, teamwork to reflect on the societal implications of quantum technologies, as well as collective epistemological discussions, led by a teacher, to stress the revolutionary issues introduced by quantum physics with respect to classical physics (uncertainty and ontological probability, meaning of quantum measurement, entanglement).

In the next sections, before describing the approach (Section 3), we illustrate the framework that motivated the choice of developing a teaching module on quantum technologies (Section2).

2. Theoretical references

In Europe, in 2016, a group of academics, at the invitation of the Commissioner for Digital Economy and Society and the Minister of Economic Affairs in The Netherlands, signed a document called Quantum Manifesto. It represents an authoritative call from academy to formulate a common strategy for Europe to stay at the front of the second Quantum Revolution. Quantum Manifesto aims to bring transformative progress to science, industry, and society in order to "*create new commercial opportunities addressing global challenges, provide strategic capabilities for security and seed as yet unimagined capabilities for the future*" [3].

For these reasons, the Member States and the European Commission are called to launch €1 billion flagship scale initiative in Quantum Technology, launched in 2018 within the European H2020 research and innovation framework programme [3].

To cope with the second quantum revolution, the Quantum Manifesto states that:

"*An ambitious, long-term, flagship-scale initiative <u>combining education, science, engineering and innovation</u> across Europe is needed in order to unlock the full potential of quantum technologies [...]*"

The program thus includes different dimensions, such as science, engineering, and innovation, but 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*" [3].

In Physics Education Research there are many relevant proposes about teaching quantum physics and plenty of studies show that it is possible to significantly introduce the basic concepts that are needed for grasping the conceptual essence of quantum computers. However, there are very few, if any, educational projects, and materials that aim to introduce quantum applications and technologies in secondary schools. On the other hand, at the university level quantum computing is mainly addressed in Master Physics courses (new master curricula in physics have been developed, i.e. Fisica delle Tecnologie Quantistiche at University of Pavia, UNIPV), where it is possible to use highly sophisticated and advanced mathematical and conceptual tools. Therefore literature on quantum computing appears very polarised: on one hand we have popular books where quantum computers are qualitatively described, on the other we have highly specialised texts where the discussion on quantum computers grounds on very advanced physics knowledge and formalism. Moreover, from the research point of view, almost all the published papers are highly specialised and accessible only to experts and it is difficult to find broad reviews that frame the specific studies within a global picture.

In light of this analysis, the research challenge, for us, was to outline an approach to reconstruct the advanced knowledge on quantum computers from an educational point of view, aimed to value the conceptual and epistemological essence, without getting trapped in too technical details.

3. The approach and the design principle

For the design, the problem we started from regards an asymmetry between the classical and the quantum computers: today, in the collective imaginary, the discourse on classical computers concerns the software and the interfaces. To learn to deal with the classical computers does not imply to start from the physical laws according to which hardware and logical gates are realised. The common narrative on quantum computers, instead, requires to start from the basic principles of quantum physics and some exemplar experiments. Why? This asymmetry usually creates a sort of disappointment among the audience when they attend a popularisation conference on quantum computers. The languages and the focus on qubits as superposition states are not what is expected in a conference on "computers". In order to guide a student to compare classical and quantum computers we decided to articulate the discourse along three different levels (the narrative, logical and experimental one) each of which has its own features (specificities) and a specific role.

The first level is the narrative level and consists of a "story" with characters and tasks to perform. It allows building a scenario, to visualise and to contextualise a problem to be solved. This level relies on the student's imagination and helps to pose a problem in an effective and comprehensible way. But it is necessary to distinguish between the narrative level in the classical and in the quantum case.

When referred to classical computers the narrative level is switched on and developed with the goal to make transparent the idea that behind the software there are logical gates materially built on devices that follow physical laws. The devices are historically situated and, throughout the history, they moved from the thermionic valves to the modern microchips. As we will describe below, the story that was used to introduce the classical computers refer to invented devices able to reproduce logical gates through mechanical ropes and pulleys. The main message was that the current opacity of the physical behaviours of the devices in classical computers is the result of a technological development that led the software to become in some sense "THE computer". When referred to quantum computers, the narrative level is switched on and developed to create an overarching leading threat that could allow the students to follow the quantum logics without getting lost in technical and physical details.

The logical level is the core of the argumentation and of the comparison between the classical and quantum computers. This level describes the logic underlying the classical and quantum computers. It

is the level that defines the "rules" with which logic gates and circuits (truth tables) work and their combination to solve a problem (algorithm).

The third level is the technical-mechanistic level. This level is needed since today we are at the beginning of quantum computers and, so far, the concept of quantum simulators and the goal to reach a universal computer are part of the debate. Quantum experiments are indeed very often "THE computers", in the sense that they are the devices used to manipulate information and solve problems. From an educational point of view, this level is also useful to give concreteness to the logical level and to provide the students with the idea of what means, today, to realise a quantum computer.

The use of the three levels made it possible to construct an articulated discourse that sees the interaction of these multiple dimensions: the narrative that builds an overarching vision that allows the teacher and the students to contextualise the single steps in a global vision without getting lost in the details; the logical / mathematical one that structures thought and allows teachers and the students to grasp the essence of the logic with which a problem is analysed and solved through classical and quantum computing; the physical / experimental one that allows finding possible realisations of objects that could remain abstract, in order to "fill them of physical meaning".

The next paragraphs contain how these levels were introduced and developed in the first lectures of the module. Table 2 shows a schematic and temporal articulation of the three level approach in the first lectures of the module.

Table 2: schematic and temporal articulation of the three level approach

Levels	Day 1: History of classical computers	Day 2: Introduction to the physics of quantum computers
Narrative	Introduction of the story of Apraphul island, where "*archaeologists have discovered the remains of an ingenious system of ropes and pulleys that is believed to be the first digital calculator in history*". On the island, classical logic gates and circuits are constructed through systems of ropes and pulleys, where the positions assumed by the ropes in input and output represent the 0 or 1, that characterise the computer binary logic.	Introduction of the story of Alice and Bob, each of whom holding a photon of an entangled (photons) pair and they have a task to address: in the cryptography case Bob has to decipher the encrypted message sent to him by Alice, in the teleportation case Alice and Bob have to teleport the state of a photon from one position to another in the space.
Logical - Mathematical	Introduction of the logic that characterises classical computers and their information processing: the BIT, the Boolean operations, their computational representation (classical logic gates), and their representation through truth tables.	Introduction of the logic that characterises quantum computers and their information processing: the QUBIT, the "new" operation, their computational representation (quantum logic gates), and their representation through truth tables. A particular focus was given to the superposition principle as the reason why a quantum computer can manage much more information than the classical one
Technical-Mechanistic	Introduction of possible experiments corresponding to the logical level: the four generations of computers and the evolution of main tools of information processing (from vacuum tubes to the chips).	Introduction of one of the possible experiments that realise the circuital representation of quantum protocols (cryptography and teleportation).

3.1. History of classical computers

The first lecture focused on classic computer and its evolution. It started by defining what computer science is in terms of structures and procedures for information processing. Then, we retraced the fundamental steps that led to the development of the computer up to what we know today: the basic unit (the BIT) was introduced as well as the main components and the logic that characterises the computation. In the discourse, the three levels were articulated as follows.

The narrative level was switched on through the story of "the ropes and pulleys of Apraphul island", an imaginary island that is the subject of an article by K. Dewdney in the 1988 Scientific American newspaper. The story begins like this:

"*On the island of Apraphul which is located off the north-western coast of New Guinea, some archaeologists have discovered the remains, by way of decomposition, of an ingenious system of ropes and pulleys that is believed to be the first digital calculator in history [...]*" [4]

The article illustrates in a rigorous way how logic gates (such as OR, AND, NOT) and circuits can be constructed through ingenious systems of ropes and pulleys, where the positions assumed by the ropes in input and output represent the 0 or 1 (false / true) that characterise the computer binary logic. The computation is carried out by a mechanical calculator as big as the whole island. The functioning and the problems that could be computed were obviously strictly conditioned by the rules of classical physics. In this way we fostered students to grasp the idea that behind the software there are logical gates materially built on devices that follow physical laws, necessary to understand their functioning.

The logical level was addressed by carefully introducing the classic logic that still characterises computers operation. The main point we stressed is the passage from the mathematical level of Boolean operations and their representation through truth tables to the logical gates. The concept of BIT was introduced to accomplish this passage.
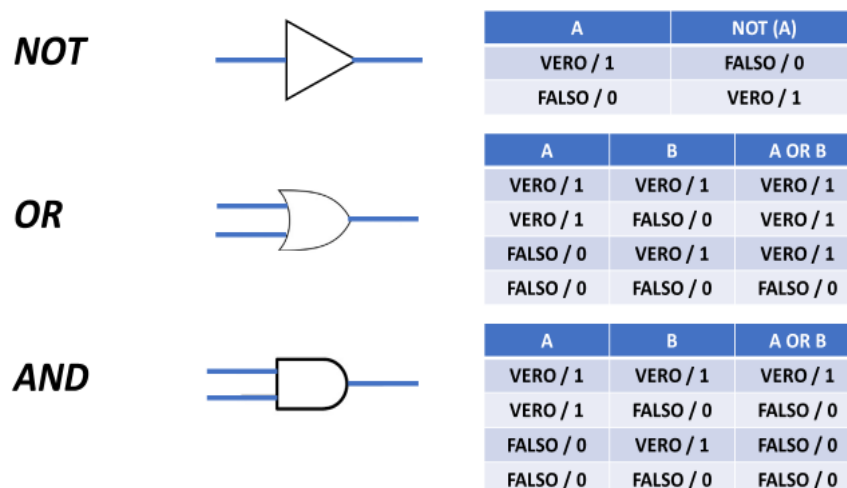

NOT

A	NOT (A)
VERO / 1	FALSO / 0
FALSO / 0	VERO / 1

OR

A	B	A OR B
VERO / 1	VERO / 1	VERO / 1
VERO / 1	FALSO / 0	VERO / 1
FALSO / 0	VERO / 1	VERO / 1
FALSO / 0	FALSO / 0	FALSO / 0

AND

A	B	A OR B
VERO / 1	VERO / 1	VERO / 1
VERO / 1	FALSO / 0	FALSO / 0
FALSO / 0	VERO / 1	FALSO / 0
FALSO / 0	FALSO / 0	FALSO / 0

Figure 2: universal logic gate and truth tables

Particular attention was paid to the fact that:
- the information is processed by the algorithms with a sequence of operations performed sequentially;
- the processing process is deterministic (if well executed the algorithm gives a certain result);
- the two possible states are mutually exclusive (0 or 1 / true or false).

The technical mechanistic level is the level that expresses a possible experimental realisation of the logical level. In this case, passing through the four generations of computers, it was shown how 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 (see figure 3).
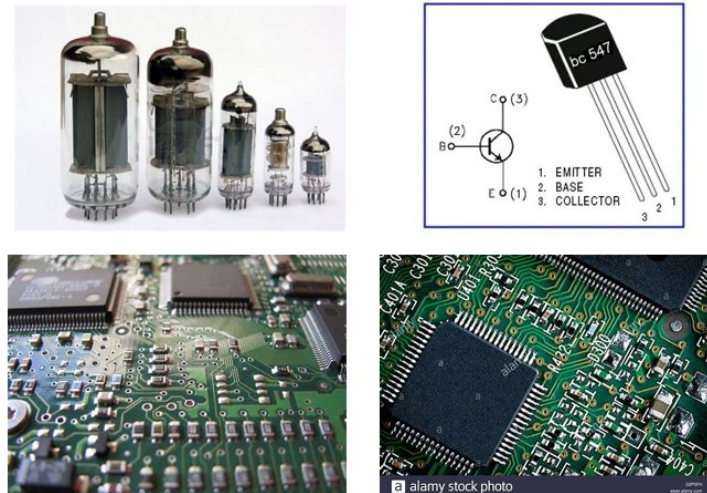

Figure 3: from top to the bottom and from left to right we see vacuum tubes, transistors, integrated circuits, and chips (Source: Google images).

The interaction among the three levels showed in what sense the computers have progressed without changing the basic logic and how technology evolution led the software to be developed to process complex problems that go ever beyond a mere sequential logic through which the machine processes the data. Today's computers are designed according to the potentialities of software or on the basis of the type of the problem to be solved, rather than how the machine works.

3.2. Introduction to the physics of quantum computers

In this section we describe how the three-level approach was followed to guide the students to grasp the sense of a quantum computer.

First of all we introduced the basic concepts of quantum physics, since the students involved in the implementation had never studied quantum physics before.

In order to introduce the basics concepts we chose the *spin-first* approach based on a simplified version of the Stern and Gerlach apparatus (figure 4). The basics concepts that we decided to introduce were the concept of state, manipulation/evolution of a state, superposition principle, QUBIT, and measurement.
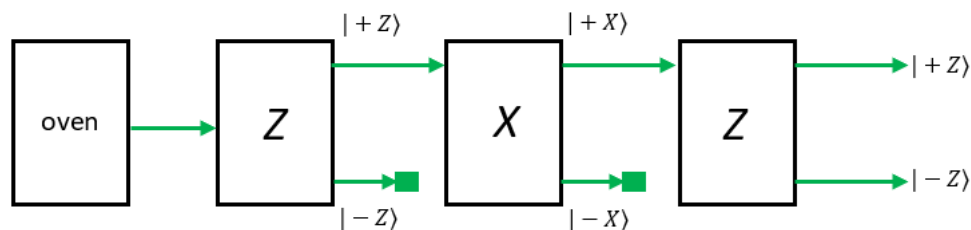

Figure 4: Abstract schema of the Stern–Gerlach experiment (treatment of the book "Modern Quantum Mechanics", J. J. Sakurai [12])

Then, we guided the students to the core idea of the module: to re-conceptualise the foundational Stern and Gerlach experiments in terms of computation. This implied to re-read the three main phases of the experiment ($preparation\ of\ a\ state - transformation\ of\ one\ state - measurement$) in terms of information ($input\ information - processing - output\ information$).

Once the basic concepts were introduced, the concept of entanglement and two quantum protocols of particular interest (cryptography and quantum teleportation) were introduced, through our three-level approach. First of all, we switched on the narrative level, by introducing the story of Alice and Bob, each of whom holding a photon of an entangled (photons) pair. The story foresaw that they had to address a task: in the case of the cryptography Bob had to decipher the encrypted message sent to him by Alice, in the case of teleportation Alice and Bob had to teleport the state of a photon from one position to another in the space.

The logical level consisted of the logic that characterises quantum computers. The concept of QUBIT was therefore introduced, highlighting that, thanks to the superposition principle, a quantum computer can manage much more information than the classical one and the main quantum logic gates with the respective truth tables (CNOT and Hadamard, figure 5) have been shown.
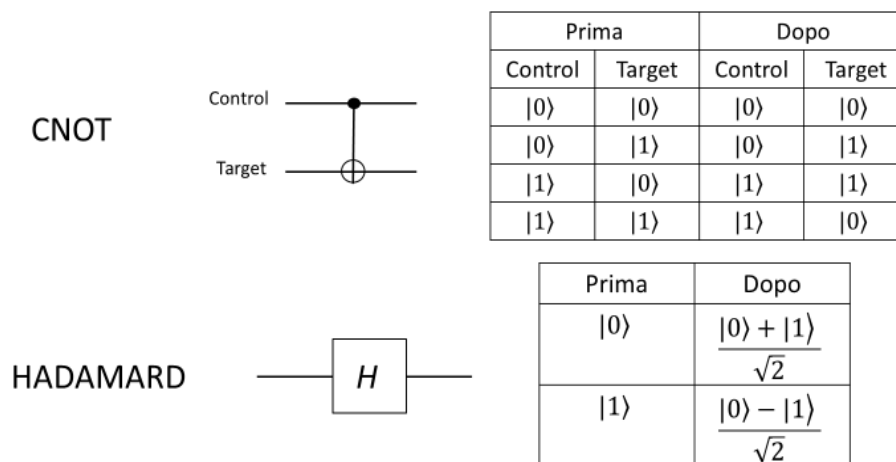

	Prima		Dopo	
	Control	Target	Control	Target
CNOT	$|0\rangle$	$|0\rangle$	$|0\rangle$	$|0\rangle$
	$|0\rangle$	$|1\rangle$	$|0\rangle$	$|1\rangle$
	$|1\rangle$	$|0\rangle$	$|1\rangle$	$|1\rangle$
	$|1\rangle$	$|1\rangle$	$|1\rangle$	$|0\rangle$

	Prima	Dopo
HADAMARD	$|0\rangle$	$\dfrac{|0\rangle + |1\rangle}{\sqrt{2}}$
	$|1\rangle$	$\dfrac{|0\rangle - |1\rangle}{\sqrt{2}}$

Figure 5: quantum logic gates and truth tables

Particular attention was paid to the fact that:
- the information is processed by the algorithms with a succession of operations performed in parallel (performance of calculations simultaneously because of the superposition of quantum states);
- the processing process is probabilistic;
- the state of a system, until a measurement takes place, is described by a vector in the Bloch sphere (figure 6).
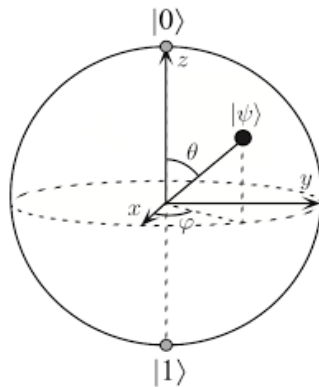
Figure 6: Bloch sphere [9]

The technical-mechanistic level was switched on by introducing one of the possible experiments that realise the protocols of cryptography and quantum teleportation (figure 7). Since the experimental set-up is very complicated, our aim was not to enable students to understand the operation and the functioning of tools such as beam splitter, PBS (Polarized Beam Splitter), Pockels cells, EOM (Electro-Optic Modulator) etc.. They were instead guided to understand that, behind the logical gates and circuits, there is a physical device, and to have the sense of where "reality" sticks to abstract logical discourse.
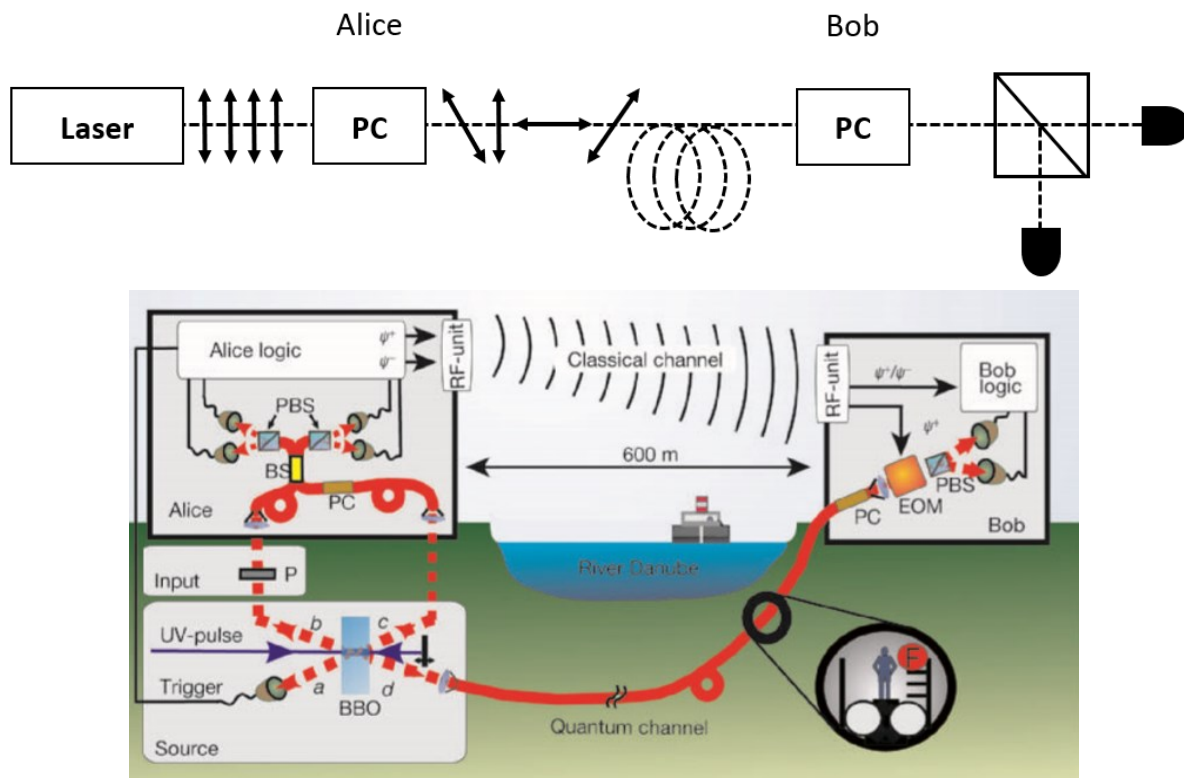

Figure 7: the first image is a schematic experimental representation of the cryptography protocol BB84 (based on the simulation [14]), the second image is the experiment realised by Ursin and Zeilinger, taken from [11]

The interaction between the three levels and the whole discourse has allowed us to highlight what is meant today by quantum technologies. Moreover, this discourse has allowed students not only to dwell

on conceptual and epistemological aspects, but also to take a look at the potentialities of these new technologies.

4. Conclusion

From the first glance at students' reaction, it seems to us that the interaction between the narrative, logical, and technical/mechanical levels has a special potential to stress, from an epistemological point of view, the meaning of quantum computers. Indeed, this multi-layered structure provides, at the same time, imaginative, technical, and logical tools to grasp the sense of quantum revolution. In particular, we can conjecture that the narrative level has the potential to significantly guide a comparison between classical and quantum computer, to contextualise and highlight the needs and the specificity of a new logic based on a new physics. The logical and the technical/mechanical levels seem to be able to provide the necessary conceptual and formal tools to follow the process of computation. Moreover from an epistemological point of view the approach seems significant to show the "experimental method", and the "computational method" as different ways to solve the same task: even though they are equivalent if compared from the results, they represent two different ways to looking at a task, each of them is characterised by its own language, symbolic forms of representation and formalism. Their comparison points out the double nature, physical and computational, of quantum states: these two methods are apparently different, but they give sense to information, in the sense that they attach it both physical meaning (information as photons' polarisation) and mathematical meaning (information as a qubit). All these conjectures will be tested against the data we have collected.
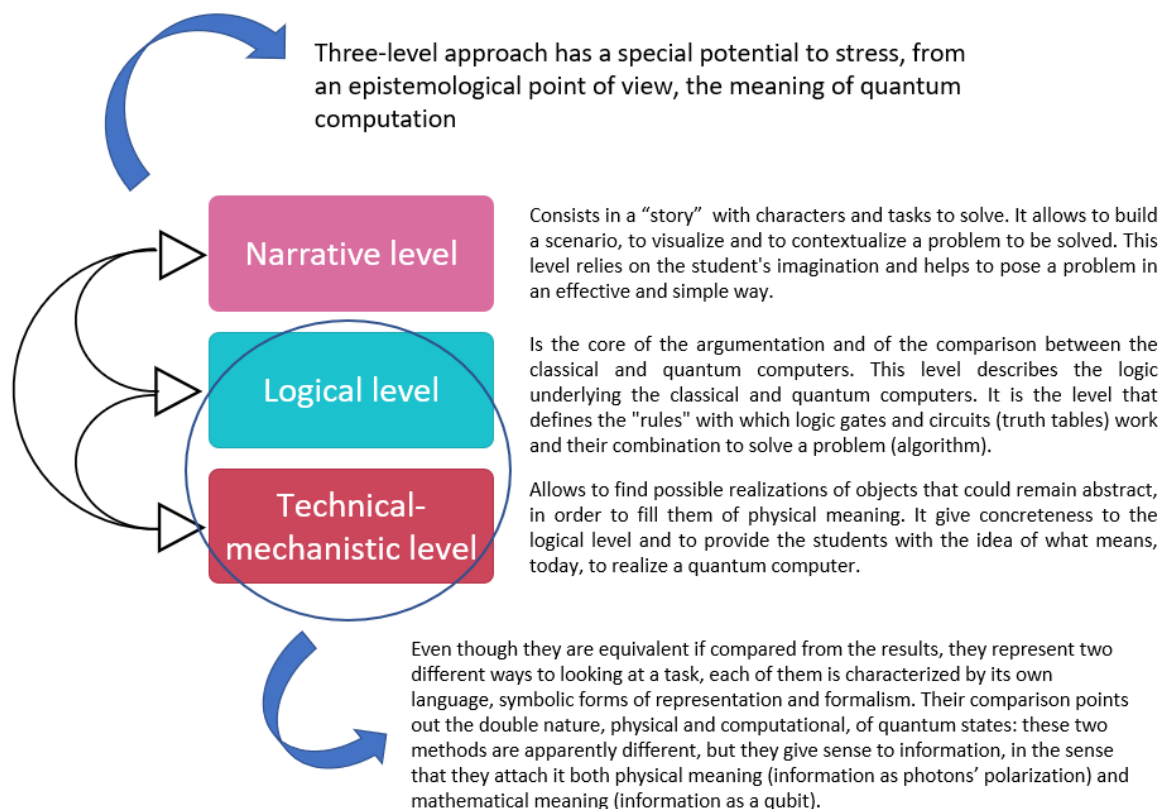

Figure 8: Synthetic image of the three-level approach

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