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Second quantum revolution: The progressive design of an approach to value its cultural and conceptual scope

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[This paper is part of the Focused Collection in Investigating and Improving Quantum Education through Research.] Quantum information science and technology is a growing field. Programs like Quantum Flagship in the EU and the National Quantum Initiative Act in the U.S. have called for science education and science education research to provide efforts and competencies for preparing the workforce and the next generations of quantum experts and promoting quantum literacy. The second quantum revolution is similar to the Newtonian one in that it has the potential to question worldviews in our society. We present our approach to design a teaching module for secondary school students that aims to value the cultural scope of the second quantum revolution. The model of educational reconstruction was used as a theoretical reference to reconstruct content for educational and cultural purposes. Renn's elaborated historical analysis of knowledge evolution provided the criteria for characterizing the cultural scope in content reconstruction. The module has been iteratively refined following a design-based approach involving back-and-forth dynamics between educational hypotheses and empirical results. The process started in 2018, and the module was refined through 5 rounds of implementation in extracurricular courses with secondary school students (for almost 130 students). The main finding underscores the importance of finding a balance between a process of simplification or elementarization of the content and its enrichment to foster learners to develop a deep understanding of quantum technologies, their conceptual intricacies, and their cultural scope.

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I. INTRODUCTION

Quantum technologies (QT) have rapidly grown in prominence. Their research and development have been at the center of strategic agendas in many countries, such as the Quantum Flagship in Europe, the National Quantum Initiative in the U.S., the 14th Five-Year Plan in China, and the National Quantum Technologies Program in the United Kingdom.

The principal domains of QT include quantum communication, which employs individual quantum entities for secure information exchange [1]; quantum sensors, which utilize phenomena such as the behavior of single quantum entities within magnetic fields to achieve high-precision measurements [2]; quantum computers, which poised to revolutionize problem-solving capabilities once they reach a critical threshold of logical qubits, allowing for vastly accelerated solutions to problems such as optimization [3,4], machine learning [5], and the factorization of large numbers [6]; and quantum simulators, which, in specialized aspects of computation, simulate complex molecular structures, advancing the field such as new materials and quantum chemistry [7]. The escalating interest in and growing relevance of QT across various industrial sectors have underlined their strategic importance [8].

The fields of education and educational research related to QT have primarily contributed to three key goals [9]. The first was to facilitate the creation of new ecosystems where universities, enterprises, and schools could engage in dialogue. The second aimed to respond to labor market needs by expanding the workforce through programs for both physics and nonphysics students. The third goal focused on attracting new generations of quantum experts and promoting quantum literacy.

At the European level, QTEdu, a Coordination and Support Action (CSA) project designed to support the European Quantum Flagship, played a key role in creating learning ecosystems essential for educating a quantum-ready society and fostering a quantum-ready workforce [10].

Thus far, considerable resources have been devoted at the institutional level to developing doctoral programs and master's or bachelor's courses for physics and nonphysics students and running training programs to expand the workforce [11]. The necessary skills and knowledge landscape has been mapped to establish standards and

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facilitate the design of education and training projects in QT [12,13].

Many global programs to raise public awareness of QT have also been launched, including establishing World Quantum Day and various events and initiatives celebrating it, such as the Italian Quantum Weeks.

A trend toward game-based learning has led to the development of interactive tools and quantum games, such as Hello Qiskit, Particle in a Box [14], QPlayLearn [15], Quantum Odyssey [16], and many others like Hello Quantum, Psi and Delta, ScienceAtHome, Virtual Lab by Quantum Flytrap, and The Virtual Quantum Optics Laboratory [17]. These tools were designed to introduce novices at different levels to the fundamental concepts of quantum mechanics and QT [17].

Physics education research has developed teaching and learning paths specifically tailored for secondary school students [18–21] and pre- and in-service teacher training courses [22–24]. To date, efforts have primarily focused on designing and developing teaching sequences accessible to these two target groups.

However, the scope and acceleration of technological developments have triggered profound changes, which Gisin [25] described as a revolution comparable to the Newtonian or Darwinian revolutions:

> We are living in an extraordinary age. […] Missing out on this revolution without giving it further attention would be as much a shame as remaining ignorant of the Newtonian revolution or the Darwinian revolution had we been their contemporaries. For the conceptual revolution taking place today is of no lesser importance. It completely overturns our previous pictures of nature and will doubtless give rise of new technologies that will simply look like magic. […] Had we lived at the time of the Newtonian revolution, would we have wished to understand what was going on? Today quantum physics gives us the opportunity to live through a conceptual revolution of similar importance. [25], (p. xi)

It is not by chance that many scholars, including Alain Aspect, refer to the development of QT as the "Second Quantum Revolution" [26]. The revolution we are witnessing today accelerates the production of fast and powerful technologies, reshapes our understanding of nature, and redefines the relationship between humans, science, technology, and society [25].

The questions that guided our research and we tried to contribute were

- What do these new technologies and what they embed reveal about our knowledge, nature, and the world we live in? What are the revolutionary conceptual, experimental, and technological aspects?
- How can we design a module that effectively introduces students to QT and conveys quantum physics concepts while emphasizing their cultural and social impact?

These questions guided us in designing the teaching approach and the module for secondary school students, which aimed to highlight the cultural and social dimensions of the second quantum revolution.

To unpack its cultural and social scope, we adopted the analysis of historical revolutions conducted by Renn and the Max Planck Institute for the History of Science research group. This analysis allowed us to place new technological artifacts within a broader sociocultural context. Unlike the normative approaches to scientific revolutions proposed by Kuhn and Lakatos [27,28], Renn's framework is explicitly non-normative, characterizing ongoing changes based on the historical transformations in knowledge systems. This framework and the model of educational reconstruction, which we used to analyze the content for educational purposes methodically, are detailed in Sec. II.

Section III outlines the design-based approach [29,30] we employed to develop and refine the module through five rounds of implementation with secondary school students (almost 130 students) in extracurricular courses.

In Sec. IV, we present the findings of the design process. Specifically, we introduce the design principles developed to emphasize the cultural and social dimensions of the second quantum revolution. We also describe how these principles were implemented across three versions of the module, as well as the students' reactions to the different iterations. The criterion we used to present and discuss the results is the tension between "making things easy but not too easy" [31]. The design and refinement of the module were driven by the search for a productive equilibrium between reducing unnecessary complexity and avoiding oversimplification, both of which could undermine the cultural and social dimensions of QT.

II. BACKGROUND AND THEORETICAL FRAMEWORK

The current revolution driven by QT follows the first quantum revolution, which began in the early 20th century when scientists sought to theoretically explain blackbody radiation phenomena. This period introduced the fundamental concepts of uncertainty and complementarity, the first mysteries of quantum mechanics [32]. This revolution established new principles governing physical reality and led to the development of key technologies, such as transistors and lasers, which form the foundation of modern society.

The second quantum revolution, as outlined by Dowling and Milburn [26], is characterized by applying established quantum principles to solve problems through the technical ability to isolate, control, and manipulate individual quantum objects (e.g., single photons, single atoms). It emerged from experiments that demonstrated the violation of Bell's inequalities and the nonlocal nature of entanglement, the second key mystery of quantum mechanics around which this revolution revolves. This phase has driven the development of a new era of QT, including quantum computers, simulators, sensors, and communication systems. Why do we refer to this transformation as a revolution?

Referring to Jürgen Renn's works [33,34], we describe a scientific revolution not in the Kuhnian sense but as a transformative process that gives rise to a new knowledge system. As Renn argues,

> Scientific systems of knowledge are indeed subject to persistent change in long-term processes of accumulation, loss, and transformation, which may occasionally give rise to far-reaching reorganisations of both the architecture of knowledge and the relevant epistemic communities. Some of these transformation processes are traditionally called "scientific revolutions." As I have argued above, however, they do not result from "paradigm shifts" but from transformative processes, such as the exploration of an existing system of knowledge to its limits, which may give rise to a "matrix" for the emergence of a new system. [31] p. 28

Renn's comprehensive framework, grounded in a deep and extensive study of the History of Science as the History of Knowledge, provides three criteria for characterizing transformative processes as revolutions.

A. Triggers of change

The first criterion is knowledge that undermines the foundations of the current knowledge system, which Renn refers to as "triggers of change." These triggers can be borderline problems or challenging objects.

Borderline problems span multiple knowledge systems, bringing them into contact and sometimes conflict, prompting integration and reorganization. Such issues are particularly important for understanding changes in well-established disciplinary sciences, as they often involve issues that overlap several knowledge domains. For example, the problem of heat radiation sparked the first quantum revolution at the beginning of the 20th century. It pertained to two distinct subdisciplines of contemporary physics: heat theory and radiation theory. Each had independent conceptual foundations, which were brought into contact through their application to this specific problem [31] p. 81.

Challenging objects are phenomena, artifacts, or elements of material culture that confront existing theoretical frameworks with explanatory tasks that cannot be resolved using available conceptual tools, thus prompting the further development and eventual transformation of these frameworks [31] p. 80. The theoretical frameworks applied to study these complex objects significantly shaped the range of possible questions and answers. The interaction between existing frameworks and new challenges revealed new insights and inconsistencies, leading to their evolution.

Exploring these triggers and knowledge systems can create internal tensions, leading to ambiguities, alternative solutions, paradoxes, and contradictions, which ultimately result in a loss of systematic coherence.

According to Aspect [35], this is the case with entanglement and the second quantum revolution. The discovery of this new quantum property led to the abandonment of the principle of local realism that had characterized physics up until that point. Thanks to Bell's contributions, Clauser, Aspect, and Zeilinger provided experimental evidence for the violation of Bell's inequalities, unlocking a new technological era and paving the way for the development of a new knowledge system: quantum information science. This transformation also marks the shift from binary and deterministic logical thinking to quantum logic.

B. Concreteness of the triggers of change

The second criterion Renn highlights [33] is the concreteness of the new knowledge system. The "triggers of change" are also materialized into artifacts—technological products that serve purposes beyond the original conceptual formulation of the basic scientific ideas. This materialization leads to the development of functional products that fulfill strategic purposes in society, economy, and politics. Both the first and second quantum revolutions led to the creation of transformative technologies. The technologies that emerged from the first revolution, such as transistors and lasers, form the foundation of modern society. The technologies emerging from the second quantum revolution are transforming research and affecting sectors such as politics, economics, society, energy, and health.

C. New knowledge transmission and dissemination

The third criterion concerns the mechanisms for transmitting, disseminating, and transforming knowledge and products (know-how and know-about), which allow for integrating, transforming, and applying new knowledge across different domains.

As discussed earlier, outreach and education are central to these processes. The primary contribution of science, technology, engineering, and mathematics (STEM) education research in this context has been strongly industry oriented, focusing on developing future quantum experts.

While these educational initiatives are essential for unlocking the full potential of QT and advancing its development, focusing solely on business and technological progress can lead to the temptation to devolve to technologies with the capacity to address and solve all the complex social, environmental, or educational problems (the so-called technological fix) [36–38]. This overreliance

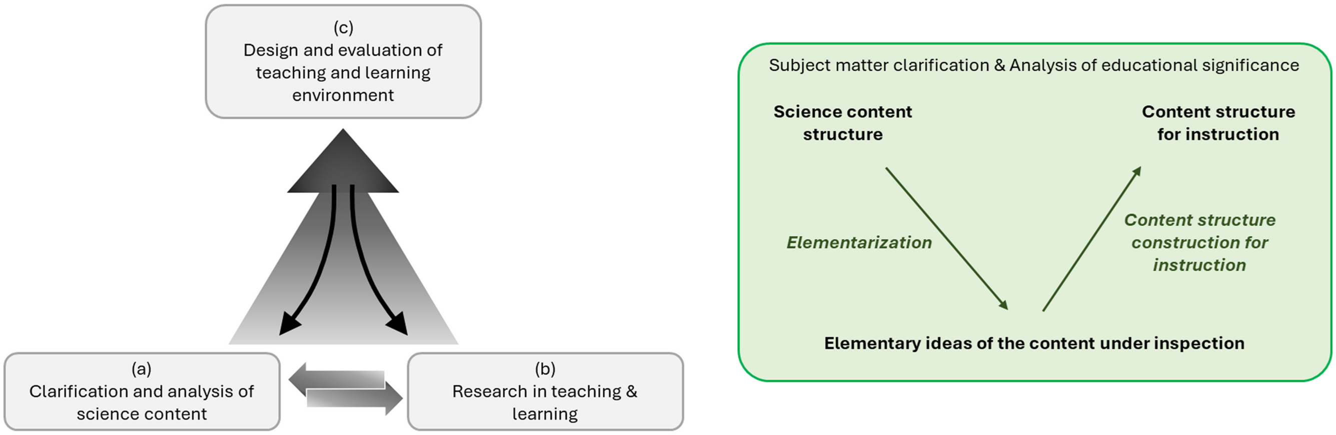


FIG. 1. The model of educational reconstruction, elaborated from Refs. [40,42].

can result in polarized attitudes toward technology, ranging from complete confidence in science and technology to intense fear and potential rejection [39].

Other possible roles for education research can be explored to highlight the educational and social potential of the second quantum revolution, even beyond technical training.

Particularly relevant for this purpose is the model of educational reconstruction developed by Duit and colleagues [40–42]. According to the researchers, the evolution of scientific knowledge and the learning processes are distinct, although they share some commonalities. Historically, scientific knowledge emerges from intentional and rigorous processes of abstraction and reduction within specific institutional contexts. Science seeks to produce knowledge with general significance, applicable across various contexts. For educational purposes, however, the process of abstraction and reduction has to be partially reversed. "Reconstruction" refers to the need to reshape scientific products by reintroducing elements that may have been overlooked during the formation of scientific knowledge, making the scientific perspective comprehensible and meaningful to learners.

The model consists of three interconnected phases (Fig. 1):

a. Clarifying and analyzing the educational significance of the science subject matter. This phase involves identifying key scientific concepts, principles, processes, and views on the nature of science and determining their relevance in various school and out-of-school contexts.
b. Investigating students' and teachers' perspectives on the subject matter. This includes examining preinstructional conceptions and affective factors such as interests, self-concepts, attitudes, and skills.
c. Designing and evaluating learning environments. This phase involves creating instructional materials, learning activities, and teaching sequences and investigating their impact on student learning.

These three phases are based on a two-step process that includes *elementarization* and the construction of the content structure for instruction.

Elementarization is a multidimensional process. First, it aims to identify the elementary features and fundamental components of a complex content domain—such as basic phenomena, principles, and general laws—to be taught, guided by the goal of ensuring student understanding [41]. Second, *elementarization* involves reducing the complexity of scientific content to make it more accessible to learners. This process does not merely simplify the content; rather, it finds ways to introduce key components while balancing scientific accuracy with accessibility. Third, *elementarization* requires planning students' learning processes as a sequence of instructional elements, guiding them from their initial conceptions toward the scientific concepts.

The content structure for instruction enriches content knowledge by incorporating empirical studies on various aspects of the learning environment. Research into students' perspectives explores their preinstructional conceptions, interests, self-concepts, attitudes, and studies on teaching and learning processes. As a result, the content structure for instruction must be sufficiently complex and enriched to meet learners' diverse needs [40].

Previous research has applied the model of educational reconstruction to make scientific knowledge accessible to secondary school students and highlight scientific content's cultural and educational dimensions [18,19,43,44].

In this contribution, content reconstruction is characterized by the decision to implement Renn's framework into the dynamics of *elementarization* and *enrichment*. During the *elementarization* phase, examples of quantum technological artifacts were selected and elementarized for secondary school students by incorporating insights from international research on quantum physics education [45–49]. We systematically watched over this process to avoid cutting vital joints to discuss the transformative elements of the technologies. These joints were the basis for the phase of *enrichment*, carried out to show the three transformative dimensions stressed by Renn: the conceptual novelty embodied by the artifacts, their practical or concrete applications for social purposes, and their social and cultural implications due to the knowledge dissemination and transmission.

Regarding knowledge transmission, we paid particular attention to several aspects:

First, we contextualized scientific and technological development within sociopolitical contexts, highlighting how QT research and development are reshaping the relationships among countries and between institutions like universities, schools, and industries.

Second, we examined models of progress and the role of technology in society, emphasizing how the second quantum revolution and technological advancements differ from traditional linear and incremental models of progress by embracing the complexity of contemporary scientific advancements. The quantum perspective is changing the nature of technologies and the nature of science and is redefining their societal roles. QT were presented as catalysts for transforming our understanding of and interactions with the world. For example, quantum entanglement and the principle of superposition fundamentally alter our concepts of classical information and communication —not just because they enable faster and more efficient problem solving, but because they reshape the foundational assumptions about how information can be processed and transmitted.

Third, we highlighted the value of quantum mechanics in fostering new forms of logical and argumentative reasoning, which are embedded in quantum technological artifacts and transcend classical binary thinking. Concepts such as entanglement, superposition, and true randomness require us to adopt probabilistic and nondeterministic approaches, which can significantly influence problem-solving and decision-making processes. These quantum concepts also promote more flexible and adaptive reasoning skills, equipping learners to address contemporary societal challenges and scientific advancements [33].

Finally, we emphasized the new interdisciplinary knowledge landscapes that QT create and the potential relationships between STEM and social sciences and humanities (SSH). These technologies were introduced as a STEM topic that demands an integrated approach to knowledge, breaking down traditional disciplinary barriers and fostering collaboration across various fields, including the social sciences and humanities, to fully appreciate and realize their potential.

III. METHODS

Starting in 2018, we have designed an approach to introduce the second quantum revolution that was conceptualized and refined within the framework of design-based research [29,30]. This approach emphasized two crucial elements: iterative dynamics and theoretical orientation. The approach and activities followed an iterative process of designing, testing, and revising, according to a back-and-forth, multiple rounds, dynamic process between theoretical hypotheses and empirical results. This methodological framework facilitated the progressive enhancement of instructional materials and enabled a rigorous, theoretically informed assessment of their impact on students' knowledge construction and skill acquisition.

Data were gathered from diverse sources, including classroom recordings and interviews, in each iteration and subsequently analyzed using qualitative methods. These methods were employed to investigate the specific dynamics within each teaching and learning scenario, providing insights into *why, when, and how* particular outcomes were achieved [50].

The process can be divided into three primary iterations, each aligned with key objectives arising from the ongoing discourse surrounding QT education. The first iteration aimed at an exploratory phase, establishing an initial pedagogical approach and leading to the formulation of foundational design principles—such as contrasting quantum and classical computing paradigms. The second iteration focused on "conceptual cleaning," prioritizing QT as a particularly direct and effective framework for introducing essential quantum concepts to nonphysics students. The third iteration sought to strike a balance between simplicity and complexity by addressing epistemological and ontological dimensions to enhance the cultural significance of the subject matter.

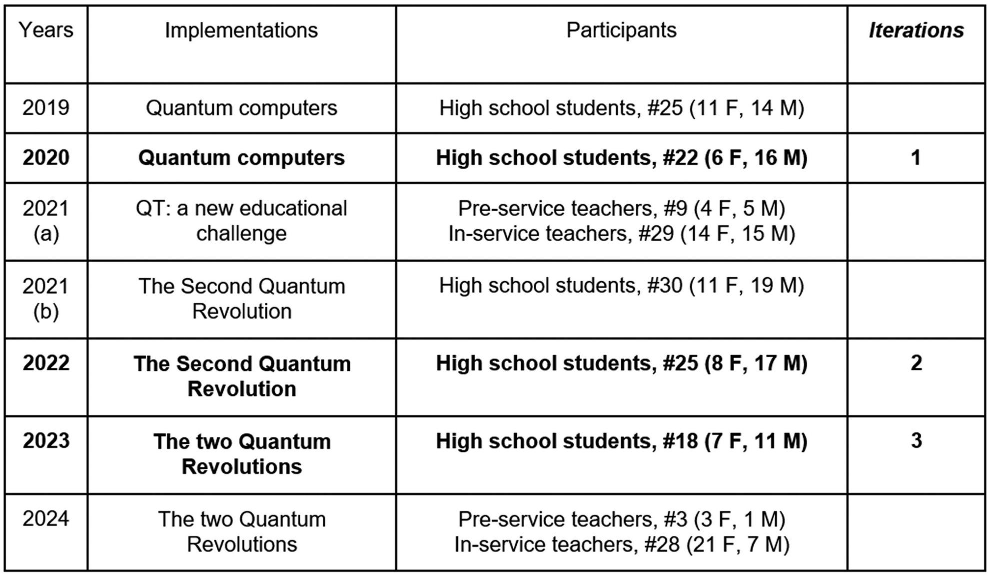
Each iteration was articulated through four interconnected microphases: (a) Identification of the educational objectives; (b) clarification and reconstruction of the content, involving the design of activities grounded in explicit design principles; (c) implementation of the modules, along with data collection and analysis to assess the achievement of the educational objectives; (d) a reflective debriefing on the entire iteration and subsequent refinement of the design principles.

In the following section, we present the process and report the main results of our design process.

IV. FINDINGS

The module for introducing the second quantum revolution was initially developed as part of the I SEE project, which aimed to create innovative approaches and teaching modules on STEM topics, such as artificial intelligence (AI), climate change, carbon sequestration, and QT. The project's primary goal was to foster students' capacities to envision the future and aspire to STEM careers by developing their professional skills and promoting their identities as capable individuals in a rapidly changing world.

Subsequently, the module was revised within the IDENTITIES project, which focused on creating modules aimed at innovating pre- and in-service teacher education. These modules explored curricular and STEM topics (such as parabolas and parabolic motion, climate change, and cryptography) through inter-, multi-, and transdisciplinary forms of knowledge organization.



Years	Implementations	Participants	***Iterations***
2019	Quantum computers	High school students, #25 (11 F, 14 M)	
2020	**Quantum computers**	**High school students, #22 (6 F, 16 M)**	**1**
2021 (a)	QT: a new educational challenge	Pre-service teachers, #9 (4 F, 5 M) In-service teachers, #29 (14 F, 15 M)	
2021 (b)	The Second Quantum Revolution	High school students, #30 (11 F, 19 M)	
2022	**The Second Quantum Revolution**	**High school students, #25 (8 F, 17 M)**	**2**
2023	**The two Quantum Revolutions**	**High school students, #18 (7 F, 11 M)**	**3**
2024	The two Quantum Revolutions	Pre-service teachers, #3 (3 F, 1 M) In-service teachers, #28 (21 F, 7 M)	

FIG. 2. Implementations of the module, participants, and reference iterations for the study.

The module was further refined under the FEDORA project, which emphasized the need to develop new narratives surrounding QT and the “quantum revolutions.”

The teaching module was implemented 5 times with upper-secondary students and pre- and in-service teachers. It was delivered as an 18-h extracurricular course or teaching training course, divided into six 3-h sessions. The participating students were in their final or penultimate year of high school, with the majority attending scientific schools. These students typically had a strong background in mathematics, including familiarity with algebraic transformations, matrices, vectors, complex numbers, and trigonometry.

This paper focuses on the results of three implementations with secondary school students. Figure 2 provides a timeline of the implementations and highlights, in bold, the three implementations that are the focus of this contribution.

A. Results from the first iteration: Exploring the approach and initial design principles

The first challenge met in dealing with QT for the first time was determining the educational goals. An entry point was required to address the confusion experienced by many regarding computers as physical objects. This confusion was also evident in the seminars and conferences attended to deepen understanding of the subject.

From the start, we noticed an asymmetry: popular seminars on classical computers rarely touched on the physical laws underlying hardware and logic gates. In contrast, seminars on quantum computers often began with explanations of quantum concepts, such as superposition and entanglement, and discussions of qubit manipulation [18].

Building on this asymmetry, we developed a design strategy aimed at highlighting the differences between classical and quantum computers. We revisited classical computing hardware, focusing on the “deterministic and linear logic” underpinning their operation. This approach provided a scaffold for comparing binary Boolean logic with quantum logic, introducing students to concepts such as quantum simulators, quantum computers, quantum gates, and circuits [18].

Our first design principle was to foster a close comparison between classical and quantum computers by analyzing the different logic behind their hardware [18]. This principle was grounded in the idea that computers can be perceived as experiments [51]. For example, apparatuses like the Mach-Zehnder or Stern-Gerlach devices can be conceptualized as instruments for manipulating information. As John Preskill observed [51],

> Information after all is something that is encoded in the state of a physical system a computation is something that can be carried out on an actual physically realizable device. So the study of information and computation should be linked to the study of the underlying physical process. (p. 7)

The second design principle, built on the physical nature of information, was to reconceptualize the foundational experiments in terms of computation [18]. This principle involved rethinking the three phases of the experiments—state preparation, manipulation/evolution, and measurement—as information input, processing, and output.

The third design principle was to keep quantum technicalities as simple and clear as possible to foster a deep understanding of the essential concepts [18]. Quantum experiments like teleportation or cryptography are inherently complex in terms of setup and formalism. Our aim was not to teach advanced technicalities but to help students grasp the core concepts, such as quantum states, superposition, state manipulation, measurement, and entanglement. Previous research has confirmed that these concepts are within the cognitive reach of secondary students [52–56].

Finally, the fourth design principle was to make the modules as inclusive as possible [18] by valuing QT as STEM topics, that is, as interdisciplinary topics. This principle was implemented by blending perspectives from physics, mathematics, and computer science to accommodate different intellectual approaches, aesthetics, and tastes. Operationally, we created a learning environment that comprised multiple representations, enabling students to compare, discuss, and integrate ideas from various domains.

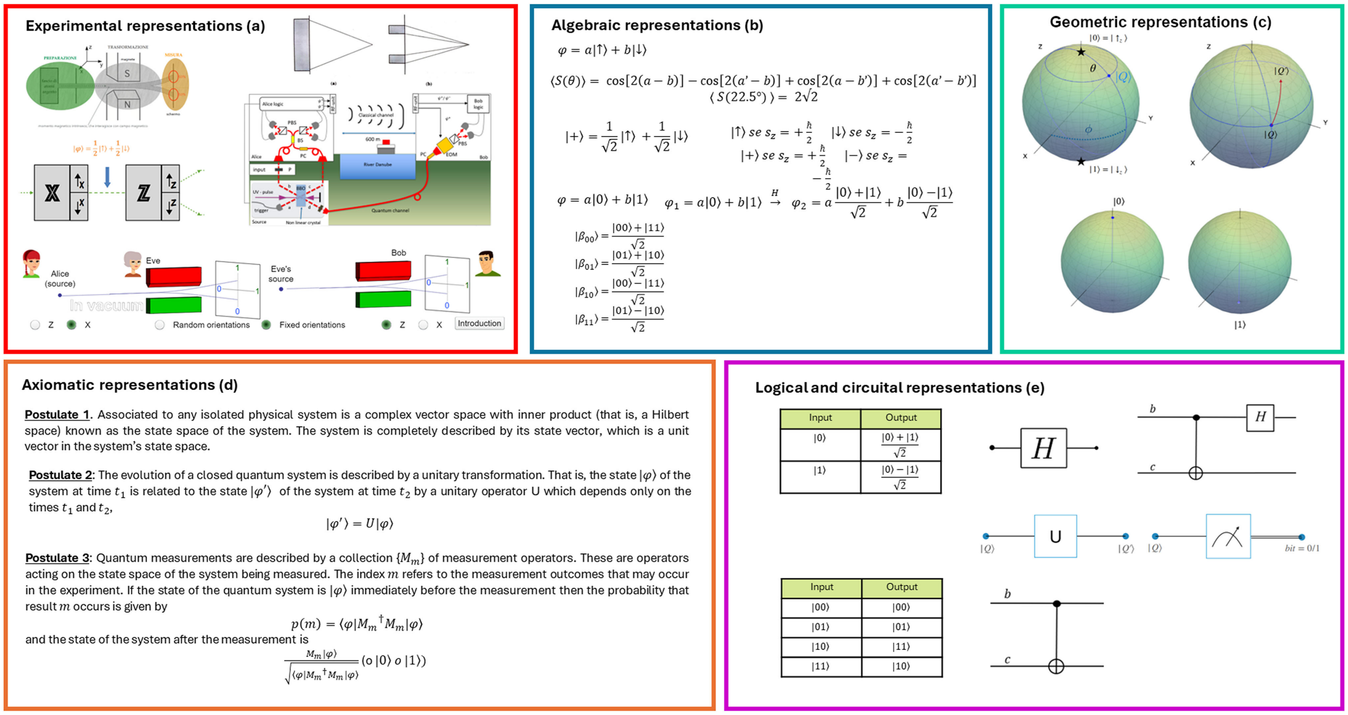
Figure 2 illustrates these representations, each serving different functions according to Ainsworth's taxonomy [57]. The experimental representations [Fig. 3(a)] refer to foundational experiments like Stern-Gerlach and teleportation. The mathematical representations include algebraic notation [Dirac notation, Fig. 3(b)] and geometric forms [the Bloch sphere, Fig. 3(c)]. The axiomatic representation [Fig. 3(d)] covers the postulates of quantum mechanics, while the logical and circuit representations [Fig. 3(e)] involve truth tables and circuits. These design principles guided the development of the module's activities [18,19,44].

Each session included two types of activities: (i) conceptual and epistemological, aimed at introducing key quantum concepts, and (ii) future-oriented and citizenship activities (see Fig. 4).

The conceptual and epistemological activities, the focus of this paper, aimed to introduce fundamental concepts to grasp what we mean today with QT (that is, the concepts of the quantum state, state manipulation, evolution, measurement, and entanglement) as well as key technologies like quantum cryptography, the teleportation protocol, the quantum internet, and the quantum random walk.

The future-oriented activities, meanwhile, aimed to guide students to explore the impact of the second quantum revolution on different dimensions such as research, politics, economy, society, ethics, education, and the future. For example, in group activity 1, ("QT &…"), students collaboratively explored the potential relationships between QT and fields like politics, society, communication, and economics. After reading selected articles, students discussed the possible connections between QT and areas like security, privacy, and transportation.

Another group activity, *Eve's City*, encouraged students to reflect on the potential impact of QT on future societies based on a text we provided. This text was designed to stimulate critical thinking regarding a hypothetical investment by the city's mayor in research and development initiatives aimed at expanding Eve's City and creating new opportunities. By examining the cyclical causality between such investments and local and global contexts, students were first tasked with stepping into the role of the mayor to decide whether to pursue the investment. Then, during future-oriented group activities 3 and 4, students were invited to explore the evolving relationship between



Algebraic representations (b)

$$\varphi = a|\uparrow\rangle + b|\downarrow\rangle$$

$$\langle S(\theta)\rangle = \cos[2(a-b)] - \cos[2(a'-b)] + \cos[2(a-b')] + \cos[2(a'-b')]$$
$$\langle S(22.5°)\rangle = 2\sqrt{2}$$

$$|+\rangle = \frac{1}{\sqrt{2}}|\uparrow\rangle + \frac{1}{\sqrt{2}}|\downarrow\rangle \qquad |\uparrow\rangle\ se\ s_z = +\frac{\hbar}{2} \quad |\downarrow\rangle\ se\ s_z = -\frac{\hbar}{2}$$
$$|+\rangle\ se\ s_z = +\frac{\hbar}{2} \quad |-\rangle\ se\ s_z = -\frac{\hbar}{2}$$

$$\varphi = a|0\rangle + b|1\rangle \qquad \varphi_1 = a|0\rangle + b|1\rangle \overset{H}{\rightarrow} \varphi_2 = a\frac{|0\rangle + |1\rangle}{\sqrt{2}} + b\frac{|0\rangle - |1\rangle}{\sqrt{2}}$$

$$|\beta_{00}\rangle = \frac{|00\rangle + |11\rangle}{\sqrt{2}}$$
$$|\beta_{01}\rangle = \frac{|01\rangle + |10\rangle}{\sqrt{2}}$$
$$|\beta_{10}\rangle = \frac{|00\rangle - |11\rangle}{\sqrt{2}}$$
$$|\beta_{11}\rangle = \frac{|01\rangle - |10\rangle}{\sqrt{2}}$$

Axiomatic representations (d)

Postulate 1. Associated to any isolated physical system is a complex vector space with inner product (that is, a Hilbert space) known as the state space of the system. The system is completely described by its state vector, which is a unit vector in the system's state space.

Postulate 2: The evolution of a closed quantum system is described by a unitary transformation. That is, the state $|\varphi\rangle$ of the system at time t_1 is related to the state $|\varphi'\rangle$ of the system at time t_2 by a unitary operator U which depends only on the times t_1 and t_2,

$$|\varphi'\rangle = U|\varphi\rangle$$

Postulate 3: Quantum measurements are described by a collection $\{M_m\}$ of measurement operators. These are operators acting on the state space of the system being measured. The index m refers to the measurement outcomes that may occur in the experiment. If the state of the quantum system is $|\varphi\rangle$ immediately before the measurement then the probability that result m occurs is given by

$$p(m) = \langle\varphi|M_m{}^{\dagger}M_m|\varphi\rangle$$

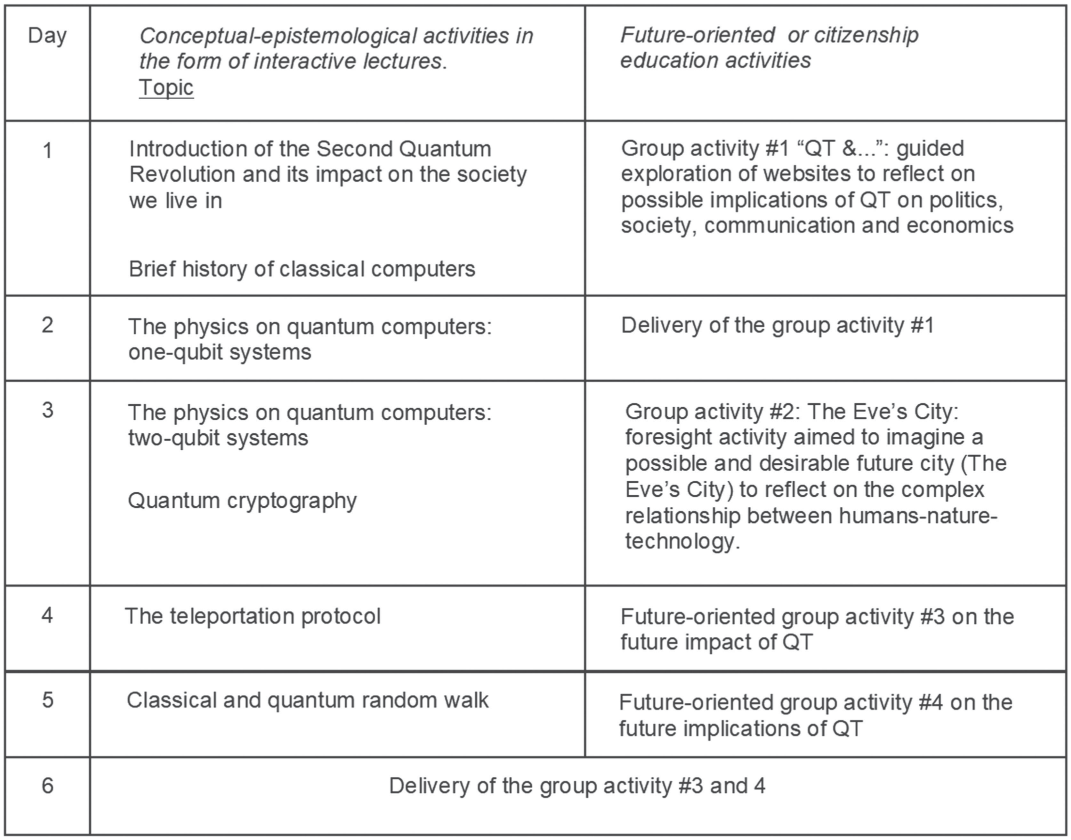
and the state of the system after the measurement is

$$\frac{M_m|\varphi\rangle}{\sqrt{\langle\varphi|M_m{}^{\dagger}M_m|\varphi\rangle}} (o\ |0\rangle\ o\ |1\rangle)$$

Input	Output
$\vert 0\rangle$	$\frac{\vert 0\rangle + \vert 1\rangle}{\sqrt{2}}$
$\vert 1\rangle$	$\frac{\vert 0\rangle - \vert 1\rangle}{\sqrt{2}}$

Input	Output
$\vert 00\rangle$	$\vert 00\rangle$
$\vert 01\rangle$	$\vert 01\rangle$
$\vert 10\rangle$	$\vert 11\rangle$
$\vert 11\rangle$	$\vert 10\rangle$

FIG. 3. External representations of the multiple representations learning environment.



Day	*Conceptual-epistemological activities in the form of interactive lectures.* Topic	*Future-oriented or citizenship education activities*
1	Introduction of the Second Quantum Revolution and its impact on the society we live in Brief history of classical computers	Group activity #1 “QT &...”: guided exploration of websites to reflect on possible implications of QT on politics, society, communication and economics
2	The physics on quantum computers: one-qubit systems	Delivery of the group activity #1
3	The physics on quantum computers: two-qubit systems Quantum cryptography	Group activity #2: The Eve’s City: foresight activity aimed to imagine a possible and desirable future city (The Eve’s City) to reflect on the complex relationship between humans-nature-technology.
4	The teleportation protocol	Future-oriented group activity #3 on the future impact of QT
5	Classical and quantum random walk	Future-oriented group activity #4 on the future implications of QT
6	Delivery of the group activity #3 and 4	

FIG. 4. First version of the module.

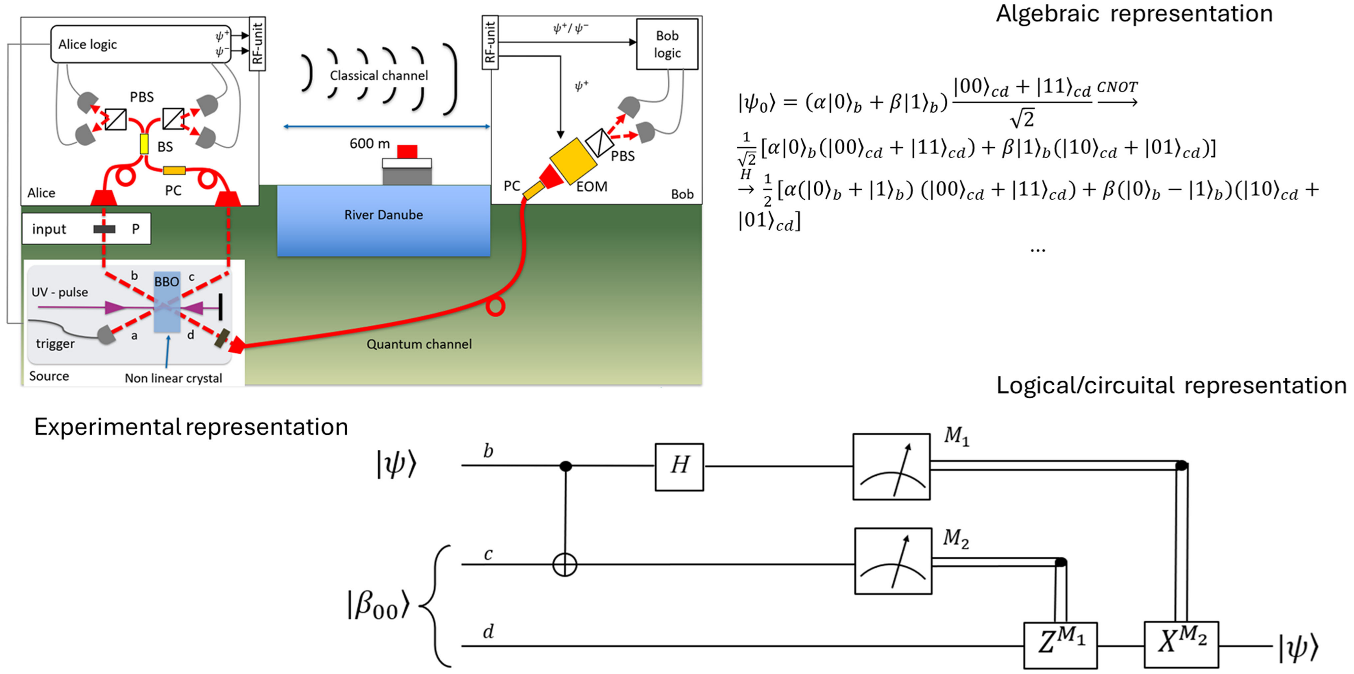
humans and society, science and technology, and nature, ultimately designing a future scenario incorporating QT.

From a pedagogical perspective, a variety of strategies were employed in class. These included lectures to introduce key concepts, teamwork to discuss conceptual questions, teamwork to analyze excerpts from official documents such as the Quantum Manifesto and reflect on QT’s societal implication, and collective epistemological discussions led by us to highlight the revolutionary aspects of quantum physics, such as uncertainty, ontological probability, quantum measurement, and entanglement.

We briefly present the teleportation case study [18] as an example of how the principles for activity design are implemented.

The comparison between experiment and circuit (design principle 2) was at the base of the educational reconstruction. Teleportation protocol does not have a classical counterpart, so design principle 1 was implemented by stressing the different logic and the basis of the circuit logic gates. We implemented design principle 3 by carefully choosing which experiment’s technicalities to prevent students from getting stuck in the details, enriching their knowledge, and consolidating the basic concepts. Design principle 4 was implemented by accurately articulating the interdisciplinary teaching discourse along four different levels that play various roles: the narrative, logical/circuital, algebraic, and experimental ones, represented by other representations. In Fig. 5, we report the algebraic, experimental, and logical circuital representations used explicitly for the teleportation activity.

More specifically, the narrative level was used to pose the problem and provide the scenario in which the problem can be solved. The content was conveyed through the story of two characters, Alice and Bob, who are tasked to solve the problem of teleporting the state of a photon from one location to another. This level aimed to stimulate students’ imaginations and assisted them in constructing a comprehensive storyboard that effectively situated the various steps of reasoning. The logical level served as the foundation of the argumentation, facilitating the comparison between classical and quantum computers. This level encompassed the fundamental logic underpinning classical and quantum computing, establishing the “rules” and truth tables on which logic gates were constructed and combined within circuits to solve problems (algorithms). The algebraic level involved the two-state Dirac formalism for quantum physics, which was employed to formalize the quantum state and its manipulation through the logic gates of the circuits. The experimental level pertained to the practical implementation and the experimental apparatus



$$|\psi_0\rangle = (\alpha|0\rangle_b + \beta|1\rangle_b)\frac{|00\rangle_{cd} + |11\rangle_{cd}}{\sqrt{2}} \xrightarrow{CNOT}$$
$$\frac{1}{\sqrt{2}}[\alpha|0\rangle_b(|00\rangle_{cd} + |11\rangle_{cd}) + \beta|1\rangle_b(|10\rangle_{cd} + |01\rangle_{cd})]$$
$$\overset{H}{\rightarrow} \frac{1}{2}[\alpha(|0\rangle_b + |1\rangle_b)\,(|00\rangle_{cd} + |11\rangle_{cd}) + \beta(|0\rangle_b - |1\rangle_b)(|10\rangle_{cd} + |01\rangle_{cd}]$$
$$\ldots$$

FIG. 5. The external representations of the multilayer discourse of the teleportation activity. The teleportation experiment selected was realized by Ursin *et al.* in 2004 [58].

used to realize the logic gates. From an educational standpoint, this level was intended to give concreteness to the logical level, providing students with a tangible understanding of what it currently entailed to create a quantum computer.

In February and March 2020, we conducted an analysis using an open-ended questionnaire to explore how students experienced the teleportation activity's multilayer and multirepresentations structure. Of 22 students, 14 completed the questionnaire. From the analysis [18], we observed that students were able to distinguish the different levels within the activity's structure. This ability to discern proved productive and effective, allowing smooth transitions between an overarching view of the teleportation phenomenon and detailed insights into how it occurs.

The data analysis further highlighted the importance of the narrative layer in helping students form a comprehensive understanding, enabling them to frame and address the problem effectively. The logical layer acted as the backbone of the discourse, emphasizing individual reasoning elements, establishing connections, and linking the experiment with the circuit. The experimental layer reinforced a sense of concreteness and feasibility that the phenomenon occurs. Finally, the mathematical layer guided students through the necessary calculations for logical progression.

One of the most significant outcomes of this investigation was an early sign that students started to adopt and integrate the multilayer and multirepresentation approach used in the teleportation activity. The different representations in the learning environment offered various entry points to the topic and different perspectives for conceptualizing the phenomenon. Students showed the ability to integrate these representations in a personal and meaningful way, using and coordinating them to (i) provide a systemic view of the phenomenon, (ii) describe how teleportation occurs, and (iii) give a sense of the phenomenon. This was evident when comparing students' descriptions of the phenomenon.

By examining how students began to describe the phenomenon, it emerged which representations provided them with the systemic view of what they were describing. We discuss the cases of Livia and Sergio (fictitious names).

The circuit provides a systemic view of the phenomenon of Livia. She started by describing an initial situation that consisted of three photons, two of which were prepared in an entangled state, and the other contained information to teleport from one point to another in space. In the student's words:

> There are three photons, b, c, and d. Alice has photon c already in entanglement with photon d belonging to Bob, while photon b contains the information Alice wants to transmit to Bob.

The experiment provides a systemic view of the phenomenon of Sergio. He described the parametric down-conversion and the production of two pairs of entangled photons. In his words:

> All this starts with the formation, through a light source that crosses a particular crystal, of two pairs of entangled photons, respectively a-b and c-d.

By looking at the narrative they used, the subject of the sentences, and how the two students described the temporal development of the phenomenon, it also emerged that different discourse layers and representations allowed them to find a personal way to discuss how teleportation occurs. In particular, Livia recalled the story of Alice and Bob while Sergio taped into the space-temporal structure of the experiment itself, focusing on the processes (“the formation of”) and the role played by Alice and Bob, who are experimenters (“operator”).

Finally, students used different layers and representations to make sense of the phenomenon. Livia interprets the systemic view provided by the circuit and the logical operations through physics as indicated by the presence of words and expressions like “photons,” “information to transmit,” “quantum state collapses,” and “through a mechanical channel.” Sergio instead uses the logical or circuital representation to interpret the experiment. This is particularly marked in the final part of the description, where he describes Bob’s transformations to recover Alice’s state in terms of applying “boolean operators.”

This analysis suggests, therefore, the educational potential of a multilayer and multirepresentations learning environment, showing that students can use and integrate different representations and develop personal descriptions of the phenomenon.

B. Results from the second iteration: Conceptual simplification/elementarization

In 2022, we re-implemented the module in a remote format due to the COVID-19 pandemic. The module’s structure was very similar to the 2020 implementation (as detailed in Fig. 2), but it was refined to suit the remote modality. Given the inherent challenges of remote learning, particularly in engaging students, we decided to emphasize the logical and circuital aspects to ensure clarity and focus primarily on the conceptual foundations.

To enhance student involvement, we incorporated additional collective discussions on the underlying logic of quantum computation and developed worksheets to familiarize them with truth tables, logic gates, and circuits. In the collective discussions, students were encouraged to solve algorithms by manipulating quantum states using logic gates. The worksheets were designed to guide students in dealing with algorithms, emphasizing operational and procedural ways of reasoning. They were developed with a progressive increase in complexity, considering the number of qubits and the types of reasoning required. Some exercises aimed to familiarize students with truth tables and state manipulations. In contrast, others encouraged reflection on equivalent circuits or involved inverse reasoning, wherein students were asked to design an algorithm based on given system states.

Even if many activities remained the same, this focus on the logical and circuital dimensions acted as a sort of cutting or cleaning tool, risking reducing the complexity to an oversimplified version of the content. As some studies argue, forms of simplification can be counterproductive [31]. For instance, forms of simplification can impede a deeper understanding. Moreover, rather than broadening students’ engagement, forms of simplification can make physics seem boring and meaningless or merely a method for problem solving.

To investigate if and how students dealt with the logical and circuital dimensions, we audio-recorded the teamwork activities to make students familiar with quantum computation. A shared *procedural* and *operational attitude* toward computing emerged from the qualitative analysis of the teamwork activities. Here, we report a short transcript of one of the groups that usually actively participate during the activities and solve correctly worksheets. The names of the students are fictitious.

Pietro: yes… there is the formula we saw the last time… on the slides…

Davide: yes, we pass $|0\rangle$ through the H gate… and re-write it as… as $\frac{|0\rangle+|1\rangle}{\sqrt{2}}$… and then you do the same with $|0\rangle$ and $|1\rangle$… then you can bring out… mmm… the square root of 2… yes… square root of two that stands under both and it comes… comes $\frac{|0\rangle+|1\rangle}{\sqrt{2}} + \frac{|0\rangle-|1\rangle}{\sqrt{2}}$… all multiplied by 1 to square root of 2… that is… what is inside the bracket can be rewritten as $|0\rangle + |1\rangle$ multiplied by 1 to square root of 2…. therefore…. therefore… the right answer is b… So it is all replacement…
[…]

Vera: in the second exercise… you have the H gate and then the Z gate… how do you reason?

Davide: It is the same thing, but you see the Z truth table… so $|0\rangle$ remains $|0\rangle$ and $|1\rangle$ becomes $-|1\rangle$… so you do the same thing…
[…]

Davide: Basically, it’s all replacement! You replace $|0\rangle$ with $\frac{|0\rangle+|1\rangle}{\sqrt{2}}$ and then you see if… in the Z truth table $|0\rangle$ remains $|0\rangle$ and $|1\rangle$ becomes $-|1\rangle$… so you reverse the sign…

Vera: I got it, thanks…
[…]

Pietro: I have a question… These $0\rangle$ and $|1\rangle$… we treat them as numbers… as if they can be added together? Because I treat them as letters… I mean, like it is 2a…

Vera: Yes, I do the same…

Pietro: But here I do not do $|1\rangle + |1\rangle = 2$, but I do 2 and 1 remains in the middle of the ket…

Vera: Yes, it is

Davide: Yes, it is exactly like this… But the 2 that is not in the middle of those brackets can be simplified!

Vera: Yes yes, it simplifies… Then the numerator becomes $|0\rangle + |1\rangle - |0\rangle - |1\rangle$…

Davide: In my opinion, it becomes $|0\rangle + |1\rangle - |0\rangle + |1\rangle$ because the minus is in front of the fraction line…
Vera: yes, exactly… it basically becomes $2|1\rangle$…
[silence]
Vera: Yes, yes, perfect! Let's move on.

As we can see from this excerpt, indicative of the other activities of the other teamwork, students frequently used expressions like "it is all a replacement," "re-write it as," and "the numerator becomes," suggesting that they approached computing as a procedural and calculus task that consisted of looking for the formula or the right truth table, substituting and then calculating.

Quite emblematic was the discussion opened by Vera: "These $|0\rangle$ and $|1\rangle$ … we treat them as numbers… as if they can be added together? Because I treat them as letters… I mean, like it is 2a…". The student argued that while students feel confident with the algebra that allows them to calculate and manipulate the quantum state, they fail to map the mathematical model into the physical one [59], showing difficulties in assimilating the physical model behind the Dirac formalism. In the rest of the discussion, the students simply applied a procedural approach of symbolic manipulation without questioning the meaning and by looking for the right answer.

The last comment was also emblematic: "Yes, yes, perfect! Let's move on?" remarking on students' attitudes toward computing as a mere procedural task. Once they have the right result, they can proceed to the following exercise.

The focus on computing resonated a lot with the conception of physics and with a type of reasoning often not only developed but also prioritized in school, acting as a way to reduce cognitive load. Students' attitudes were very positive. They proved to be very engaged and felt great satisfaction in the manipulation and control that computation allows.

Nevertheless, this approach to computation, influenced by our strong focus on the logical and circuital dimensions during the 2022 implementation, makes us reflect on the cultural scope of the second quantum revolution and leads us to refine our learning objectives.

C. Results from the third iteration: Make things easy but not easier: Epistemological and ontological complexification to impact at a cultural level

As discussed in the previous section, stressing the logical and circuital perspectives scaffolded a procedural attitude toward computation.

These results made us question the approach and the educational and cultural messages we aimed to convey. We, therefore, decided to take a step back and adopt a historical perspective, diving deeper into the key differences between the first and second quantum revolutions.

We added design principle 0: Compare and contrast the two quantum revolutions from a conceptual, epistemological, and experimental perspective to the four design principles mentioned in Sec. IV 1.

Referring to Renn's framework [33], this principle guided us to individuate the *challenging objects* [33] of the first and second quantum revolutions. Following Aspect [35], we focused on complementarity and entanglement—revolutionary concepts that first represented conceptual and epistemological challenges in the history of physics and later became experimental challenges.

The concept of complementarity we focused on was the noncommutative values of quantum observables. In particular, we focused on the noncommutative nature of quantum observables, specifically incompatible variables connected by uncertainty relations. These conjugate variables guided us to question the concepts of object and state of the object, time-evolution of a system, and measurement. As regards the quantum object and the state, we elaborated on the property of the quantum state that, unlike the classical one, encodes the information about a physical system without providing definite values for observables until a measurement is made. Regarding quantum manipulation or evolution, we focused on the time-evolution description that, contrary to the classical case, encodes the probabilities of finding a system in various states, marking a major shift from Newtonian determinism. Finally, we dug into quantum measurement's intrinsically probabilistic and destructive nature, which differs from classical measurement.

The second concept, entanglement, shattered the classical interaction model initially incorporated within the local realistic character of the physical theory. We valued a quantum state as one that can be described by superposition and exhibit instantaneous correlations, regardless of the distance between quantum objects. When one quantum object in an entangled system is measured, it instantly determines the state of the other, no matter how far apart.

The main feature of concreteness [33] of the second quantum revolution is the capacity to isolate, manipulate, and control the single quantum object encoded in a qubit of information. As the new basic information unit, the qubit represents a disruptive challenge to our logical and argumentative forms of reasoning, overcoming the binary way of thinking. In addition, the superposition principle and the entanglement materialize into experiments and are at the basis of the functioning of different kinds of technologies like quantum cryptography, teleportation, quantum machine learning, quantum sensing, and so on.

These protocols illustrate how QT blurs the disciplinary boundaries among the STEM disciplines and transgresses the boundaries between STEM and SSH. QT's interdisciplinarity highlights the need to *reorganize knowledge for transmission*, enlarging the social and cultural scope of the second quantum revolution.

The *compare-and-contrast* principle allowed us to create a renewed frame in which the first and second design principles could be relocated: the first consists of comparing and contrasting classical and quantum computation in terms of the logic behind computers' functioning and the second consists of comparing and contrasting the circuit and the experiment. This new frame has clarified the cultural scope of the two quantum revolutions, giving consistency to the entire module.

In light of these aspects and following the historical reconstruction inspired by Aspect [35], the new version of the module is reported in Fig. 6.

Operationally, applying the *compare-and-contrast principle involves* highlighting the commonalities and differences between the two quantum revolutions (Fig. 7).

At first, complementarity and entanglement were conceived and discussed through *gedankenexperiment* in two different Bohr-Einstein debates. The complementarity and the nature of the quantum object were the central issues addressed by scientists during the Solvay conference in 1927. In 1935, Einstein and Bohr, through scientific articles, argued about the completeness of quantum theory and its nonlocal character, bringing attention to the groundbreaking aspects that the entanglement raised. Both conceptual challenges later turned into experimental ones, and the theoretical hypotheses were reformulated for empirical validation. The two pivotal experiments are, on the one hand, the double-slit experiment with single electrons, awarded by the journal Physics World [60] as "the most beautiful experiment," was realized for the first time by Merli *et al.* [61] in 1974 and, on the other, Aspect's experiment, which demonstrated the violation of Bell's inequalities and pioneered quantum information science [62,63] in 1982.

In light of this, we dedicated the first and second meetings of the course to deepening the first and second quantum revolutions as conceptual, epistemological, and experimental challenges (Fig. 7).

The third meeting, similar to the first meeting in the other implementations (see Fig. 4), was refined to deeply reflect on the cultural scope, which resembles classical and quantum physics, of the physical nature of information [51,64], namely the encoding of the physical nature in

Day	*Conceptual-epistemological activities in the form of interactive lectures.* Topic	*Future-oriented or citizenship education activities*
1	The First Quantum Revolution: - the experimental challenge - the epistemological challenge - the conceptual challenge	
2	The Second Quantum Revolution: - the epistemological challenge - the experimental challenge - the conceptual challenge	
3	Introduction of the Second Quantum Revolution and its impact on the society we live in Brief history of classical computers The physics on quantum computers: one-qubit systems	Group activity #1: investigating the epistemological structure of classical and quantum physics through the Figure of the demon
4	The physics on quantum computers: two-qubit systems Quantum cryptography	Group activity #2: The Eve's City: The foresight activity aimed to imagine a possible and desirable future city (The Eve's City) to reflect on the complex relationship between humans and nature technology.
5	Teleportation protocol	Future-oriented group activity to imagine the future impact of QT
6	Future-oriented group activity to imagine the future impact of QT and delivery	

FIG. 6. Final version of the module.

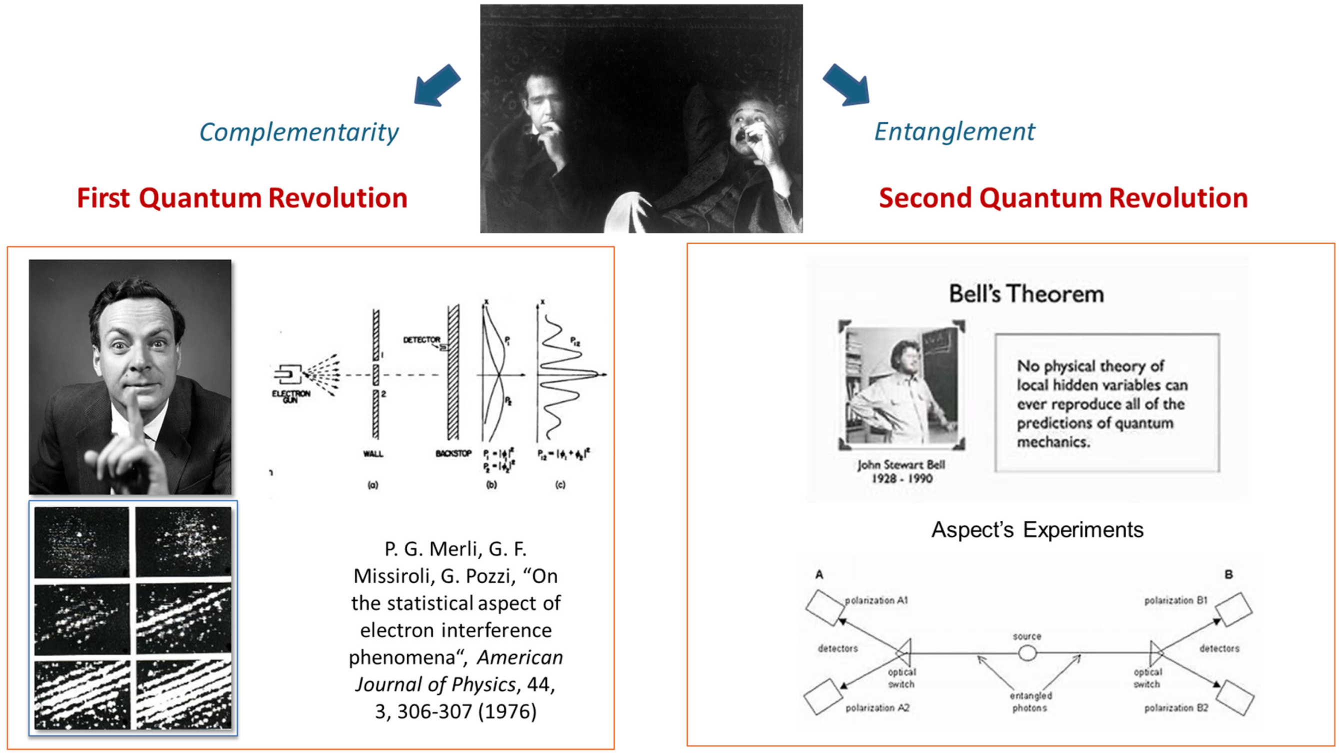


FIG. 7. Comparison between the first and second quantum revolutions.

terms of computational units, bits, and qubits. As the first and the second design principles aim to highlight, quantum computation and information are stressed for their deep implications on the logic of reasoning.

The choice of stressing the conceptual and epistemological leaps that emerge from the comparison between the first and the second quantum revolutions and between classical and quantum physics did not aim to complexify the content but rather to foster a reflection on the revolution in its making, grasp the interconnection between different knowledge systems, and deepen the relationship between scientific knowledge development and reorganization with societal, political, economic, and technological aspects.

During the activities, many data were collected and analyzed. We were particularly interested in investigating the potential of the multiple representations learning environment to promote students' learning. Therefore, at the end of the third implementation (see Fig. 2), we conducted a focus group with eight students, a heterogeneous group in terms of gender, kind of participation, and engagement during the different activities of the module.

The main phenomenon that emerged was what we called *personally inflected sensemaking*, which is a process in which students, by making sense of a new physics situation, actively engage personal resources such as individual intentions, meanings, and purposes [19,65]. This novel idea draws upon Bakhtin's notion of appropriation [66], where a learner adapts and transforms shared language, populating it with personal significance to align with their worldview. The personally inflected sensemaking involves a deep intertwining of individual experiences and rigorous academic content, leading to a unique and personalized understanding. It differs from other kinds of sensemaking since it underlies the role of personal inflexions in processing knowledge, thus just not focusing on unpacking the process of making sense of new information but on how students deal with that information through the lens of one's own experiences, intentions, and identity [65].

Hereafter, we report two case studies since the *personally inflected sensemaking* process is evident. At the beginning of the focus group, we asked students (the names are fictitious), to describe what it means to understand through representations.

From the beginning, Diana described a kind of understanding that has an operational flavor. In her words:

> I think I understood one thing when I answered all my questions because… I mean, I can retrace in my head the steps we have taken and … […] so I can retrace them…

As productive experiences, Diana referred immediately to the logical and circuital representations since they allowed her to "retrace the steps" she needed to solve the problem ("I can solve the problems we had… [and] I can also have the concept clearer"; "For example to me those of CNOT and Hadamard with below tables… that is to me enough to be able to retrace in my head…"). This suggested that Diana framed frames scientific knowledge as a problem to be solved.

Answering a question about what characteristics a representation must have to be productive, Diana argued that a representation has to be clear, linear, schematic, and useful representations, which could make complex concepts more accessible ("they [represenations] have to clear… […] not neglecting the fact of clarity … namely that aspect of clarity") as well as "useful" ("If we also want to also consider the usefulness"). This reflected her ways of understanding and her learning need to easily grasp "what replaces" to solve the problem.

Diana indicated as particularly productive both the logical or circuital representation ("if I have those tables, that… I know how the logic gates work through the representation… I can solve the problems we had and … however I can also have the concept clearer") and the algebraic one that is "practical…in the sense of the resolution [calculation] of… in mathematical resolution practice"). These representations, therefore, were particularly productive for Diana since they resonated with her way of understanding and with her purposes. She also emphasized the importance of having exhaustive and nondispersive representations, enabling her to easily extract and sequence information logically to solve problems efficiently.

These aspects revealed Diana's sense of intuition, triggered when she had immediate access to the knowledge she needed to solve a problem. Therefore, the cognitive load must be low to avoid too much effort.

Unlike Diana, Andrea described his ways of understanding as a process of internalization:

> [for me, understanding a concept is] internalize it we say and … not so much at the mnemonic level… but have it… assimilated … just to be able to… […] expose almost instinctively … that is in a sense without having a rigid scheme that takes me from A to B and then maybe gets to B… in the way… instinctively because I feel inside the concept…

His process of understanding consisted of the process that led him to "feeling the concept inside" and looking for and attributing personal meanings to the concept. To activate this process of meaning attribution, as Andrea discusses in answering the question about which characteristics a representation must have to be productive to him, representations needed to be compact, elegant, and able to convey information in a well-ordered and dense format (a representation must "have a squaring … that is, let's say… a being accomplished in itself and… […] in a sense basically exhaust all aspects… but in a synthetic way and say… maybe… […] also almost from an aesthetic point of view… in non-graphic representations… have a certain elegance"). He also described that a representation, to be productive, has to balance the density and the order of the information. Andrea referred to the geometric and the experimental representations as productive experiences since they are both "dense" and "ordered," facilitating deeper cognitive processing and allowing him to internalize concepts and trigger a deeper understanding.

The geometric representation (the Bloch sphere) was the most fruitful representation for Andrea since it balanced the density and the order and respected personal aesthetic:

> In my opinion, the sphere does not convey the idea of… simplicity in the sense that it is the sphere but the sphere as a locus of points… so in my opinion, the sphere is elegant in the sense that it is extremely compact that is it is perfectly tidy, has an order in the sense… It is the highest idea of order we have and at the same time has a very high density, in a sense… it transmits us a… basically a dimension of infinite probability, so… the sphere… […] has the greatest elegance…

The analysis shows that students were actively and naturally engaged in sensemaking processes through representations. Specifically, by leveraging their ability to compare, discuss, and critique representations, students discussed and clarified how they make sense of their understanding in navigating multiple representations learning environment.

The two cases illustrate a discussion on whether and how the multiple representations learning environment triggers different sensemaking processes through representations. Differences emerge in how students learn, conceive, and approach knowledge and in how they reason. Both cases describe highly personal cognitive processes, where the presence of individual expressions and references makes students' discussions particularly authentic and idiosyncratic.

To sum up, the multiple representations learning environment proved to be not only inclusive, providing different entry points and allowing room for different ways of reasoning, learning needs, and tastes, but also to have the potential to trigger very personalized learning processes.

V. CONCLUSIONS

This study contributed to two questions:

- What do these new technologies and what they embed reveal about our knowledge, nature, and the world we live in? What are the revolutionary conceptual, experimental, and technological aspects?
- How can we design a module that effectively introduces students to QT and conveys quantum physics concepts while emphasizing their cultural and social impact?

To address the first research question, we applied Renn's framework [33] to analyze the second quantum revolution in comparison with the first quantum revolution. By examining the three key aspects outlined by Renn, we characterized the ongoing transformative process as a revolution and highlighted its broader societal and cultural implications. First, we identify what could be the *triggers of change* that have questioned the validity of previous knowledge systems. In the context of the second quantum revolution, following Aspect [35], we reconceptualized entanglement and Bell's inequalities, which have been experimentally validated, as key triggers of change. Second, we discussed how these triggers materialize into technological artifacts, in particular, how quantum protocols, quantum computers, simulators, information, and sensors can be representative and emblematic examples of how research results convert into technological artifacts with profound societal and strategic implications. Third, we discussed the main initiatives of knowledge transmission and dissemination across different domains. Furthermore, we emphasized the interdisciplinary nature of QT, which not only blurs the boundaries within STEM fields but also fosters connections between STEM and the social sciences, broadening the educational and cultural scope of the revolution.

In addressing the second research question, we adopted a design-based approach, focusing on balancing *elementarizaion* and *enrichment*. This balance was achieved by iteratively refining the educational module, drawing on Renn's criteria to ensure that students grasp both the technical aspects of QT and their broader cultural significance. Initially, our module mainly focused on QT. Since the students proved to be familiar and confident in algebraically manipulating mathematical objects, we decided to increase the level of technical formalism and stressed computational thinking. During the second iteration, in fact, we mainly emphasized algebraic and computational reasoning, which proved to be effective in engaging students with the computing perspective. However, we found that this approach risked overshadowing the physical meaning as well as the cultural and societal dimensions of the revolution. In response, we decided to focus on QT as an emerging artifact of a revolution. We rebalanced the *elementarization* and *enrichment* process by incorporating the three Renn's criteria through a *compare and contrast* strategy between the first and second quantum revolutions, by providing insights about how the two quantum revolutions represented conceptual, epistemological, and experimental challenges, as well as guiding students to recognize the groundbreaking aspects and their implications on research, society, politics, economy, ethics and so on. The challenge was to prevent cultural aspects from inducing a bird's eye view that would not enable them to capture the conceptual peculiarities of QT.

The results of our iterations revealed that quantum revolutions have meaningful learning potential for students. The theme's interdisciplinary character and the plurality of external representations that can be used proved to provide different entry points to the topic and to trigger personalized learning processes.

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