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Quantum mechanics 2025 at the crossroads of science and humanities: Towards the epiphany of a new cultural world a century later

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Abstract

A century after its formulation, we discuss the multifaceted implications for education of the vast cultural connections that quantum mechanics (QM) has helped establish between physics and other disciplines. Drawing on the most recent research in QM education, we will address the epistemological paradigms that underpin our understanding of nature and the cultural significance of this theory for the intellectual development of students at various educational levels; always maintaining a careful focus on the fundamental educational challenge of teaching and learning about the nature of science through physics education.

Keywords: quantum mechanics, cultural understanding of physics, quantum education, nature of science, quantum teaching and learning

INTRODUCTION

The centenary of quantum mechanics (QM) provides an opportunity to reflect on one of the most profound intellectual revolutions in human history. Since its birth in 1925, QM has not only redefined the boundaries of physics going deeper and deeper into the structure of matter but has also challenged fundamental assumptions about nature, reality, and human knowledge.

It is now widely believed that QM should be taught in high school and also in degree courses other than those of the "hard" sciences, and most initiatives aimed at introducing significant aspects of QM into schools or university courses are currently and regularly organized and proposed. These activities are generally and primarily focused on technological applications, with the goal of training future quantum technicians (National Quantum Initiative, 2025; Quantum Flagship, 2025). While the importance of this end is beyond question, some perplexities arise spontaneously—in fact, the teaching objectives of classical physics traditionally go well beyond its applicative purposes. For this to be possible, it is important to outline a cultural framework within which to build the teaching proposal.

Philosophical and Cultural Perspectives on Quantum Physics: A Brief Overview

The need to approach QM not only as a technical formalism, but also as a cultural and philosophical turning point, has been widely recognized in the literature. Since the early historical and philosophical analyses of the interpretations of QM, the theory has been discussed as a privileged case for reflecting on the nature of scientific knowledge, the role of models, the status of physical reality, and the relationship between theory, experiment, measurement, and observation (Giliberti et al., 2025; Jammer, 1974). In this sense, QM is not merely one topic among others in modern physics: it

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Contribution to the literature

- This paper contributes to quantum physics education by framing QM as a major cultural, historical, philosophical, and epistemological transformation, fundamental also as a technological resource.
- It highlights the need to make explicit the conceptual bridges between history, experiment, formalism, interpretation, and ethical reflection when QM is introduced in educational contexts.
- By bringing together three complementary perspectives, this paper argues that a culturally rich approach to QM can support a deeper understanding of the nature of science and of the role of physics in contemporary society.

is a theory in which epistemological and ontological questions emerge from within the physical content itself.

Historical studies on the foundations of QM have also shown that foundational debates were never purely internal technical disputes. These debates were embedded in specific scientific cultures, institutional contexts, philosophical traditions, and, in some cases, political circumstances. The post-war history of quantum foundations, for instance, reveals how questions concerning interpretation, realism, causality, non-locality, and measurement were sometimes marginalized within mainstream physics and later re-emerged in connection with quantum information and the so-called Second Quantum Revolution (Freire, 2015). Similarly, studies of local scientific traditions, such as the Viennese context of "philosophysics", have shown that the boundary between physics and philosophy has often been more porous and productive than standard disciplinary narratives suggest (Del Santo & Schwarzhans, 2022). These works are particularly important for education because they challenge the idea that philosophical reflection is external to physics; rather, they show that it can be part of the development, understanding, and communication of physical knowledge. In this sense, an overview of the philosophical and cultural literature on QM provides the background for the central claim of this paper: quantum physics education should not be limited to formalism or applications but should also help students understand the conceptual and cultural transformation produced by quantum theory.

From the perspective of physics education research, this cultural and philosophical dimension is increasingly relevant (Liu et al., 2025; Tuero-O'Donnell et al., 2026). Research on teaching and learning quantum physics has emphasized that learners often encounter quantum concepts through isolated icons—such as wave-particle duality, the uncertainty principle, Schrödinger's cat, or entanglement—without the conceptual, experimental, and historical framework needed to make sense of them. Teacher education studies have also highlighted the importance of addressing "didactical knots" in quantum physics, including the meanings of quantum state, measurement, incompatible properties, stochastic outcomes, and entanglement (Bouchée et al., 2022; Donhauser et al., 2024; Greca & Freire, 2014). These knots are not only mathematical or cognitive difficulties; they also involve shifts in worldview, language, and epistemology.

The present paper is situated within this line of research, but it adopts a specific perspective. Its aim is not to provide a comprehensive account of the interpretations of QM, nor to reduce quantum physics education to philosophical discussion. Rather, it argues that the cultural, philosophical, historical, and ethical dimensions of QM should be made explicit when quantum theory is introduced in educational contexts. This is especially urgent today, when the Second Quantum Revolution tends to present QM mainly through its technological applications. While such applications are scientifically and socially important, they do not exhaust the educational meaning of quantum theory. A culturally rich teaching of QM should also help students understand why this theory transformed our concepts of reality, knowledge, causality, measurement, objectivity, and human agency within nature.

THE PROBLEM

QM emerged during a period of transformative shifts in both scientific and philosophical thought. Its revolutionary concepts—such as the uncertainty principle, wave-particle duality, and quantum entanglement—undermined deterministic frameworks that had dominated physics since Newton and challenged our *Weltanschauung*. In doing so, it revealed a world characterized by indeterminacy, interconnectedness, and probabilities. These characteristics, while forming the backbone of modern physics, also resonated deeply with philosophical inquiries into the nature of knowledge and existence. Indeed, these characteristics are often highlighted both at school level as well as in popular books, but they are frequently misunderstood or reduced to oversimplified popular discourse that borders on common sense.

Are these physical problems still significant for the personal development of a nowadays students? Or are they old historical vestiges that perhaps many of us are still fond of, but which do not attract interest among students? What remains of the questions about the world posed by the founding fathers of QM and of the answers they have generated within our educational system, both at the high school and university levels? (Jammer, 1974).

Contributions to the Symposium

This symposium, organized by the GIREP Thematic Group "Cultural Understanding of Physics", aims at discussing the multifaceted implications of QM for education, fostering an interdisciplinary dialogue that bridges science, philosophy, and humanities into a broader cultural framework (Giliberti et al., 2025). The three cornerstone presentations of this symposium delve into pivotal questions that QM raises about the nature of knowledge, the problem of the non-intuitiveness of quantum aspects and also some non-trivial ethical implications. They also seek to illuminate its profound cultural and spiritual dimensions, fostering a dialogue that transcends the boundaries of traditional scientific discourse.

More specifically, the symposium pursued three closely connected objectives. The first was to reconsider QM as a cultural event, not only as a technical achievement, by analyzing how its concepts transformed 20th century and 21st century views of nature, knowledge, causality, and objectivity. The second was to investigate how these transformations can become educationally meaningful, especially for students who do not necessarily aim to become quantum physicists or quantum engineers, but who need to develop a scientifically informed understanding of the contemporary world. The third was to identify teaching implications for quantum physics education, with particular attention to the role of history, philosophy, experiment, interpretation, and ethical reflection in building a deeper cultural understanding of physics.

For this reason, the symposium was structured around three complementary perspectives. The first contribution addressed the philosophical and ontological implications of quantum-relativistic physics and its consequences for our conception of nature. The second contribution examined students' and teachers' understanding of QM, showing how the absence of historical and experimental scaffolding can lead to fragmented or distorted conceptions. The third contribution focused on the continuing educational relevance of the epistemological and ontological questions raised by the founders of QM, arguing that such questions are essential for a reflective and culturally meaningful physics education. Taken together, these perspectives were intended to show that teaching QM today requires more than simplifying formalism or presenting applications: it requires the construction of conceptual bridges between physics, philosophy, history, technology, and society.

Indeed, while much of the recent discourse has centered on its technological applications, such as quantum computing and encryption, this paper tries to highlight the broader cultural significance of QM. It examines how this framework reshapes our worldview, influencing not only scientific education but also the broader societal and spiritual narratives that define human progress, showing how the historical journey of QM is not merely an account of scientific milestones but also a lens through which to understand its enduring impact on modern culture.

QUANTUM-RELATIVISTIC PHYSICS: A NEW PHILOSOPHY OF NATURE (BASED ON THE PRESENTATION BY ENRICO GIANNETTO AT THE SYMPOSIUM)

Introduction

Usually, we limit ourselves to teach physics as an experimental practice (pragmatical dimension), a mathematical practice (syntactical dimension), but not as an actual theoretical practice (semantical dimension). Semantical dimension implies a conceptual dimension, a philosophical content (ontological and epistemological content). Theoretical physics is a kind of philosophy of nature. Thus, physics must be considered as a particular kind of natural philosophy, related to a gnoseology of experimental actions and mathematical operations. Furthermore, when we are teaching physics, we are involved in a conception of science, a conception of nature, a conception of a relationship of mankind and nature (we deal with ethics, with existential implications).

Quantum Physics

Physics is inherently concerned with models, which are regarded as provisional and subject to revision when challenged by empirical or conceptual inconsistencies; this perspective should therefore be explicitly highlighted in physics education. However, over the decades—and contrary to what is often assumed—a gradual epistemological shift has taken place, leading to the recognition of the conceptual precedence of physics over mathematics.

Indeed, in 20th century, we had great scientific revolutions such as relativity, quantum physics and chaos physics. However, general relativity is not reducible to special relativity: indeed, special relativity and general relativity are distinct revolutions; special relativity was generalized and falsified by general relativity. In the same way, special relativity and QM were generalized and falsified by a new greater scientific revolution: quantum relativistic field physics.

Metaphysics of theology and mathematics, and metaphysics of epistemology were predominant for about two centuries and were undermined by Poincaré's (1880) work, getting back to Leibniz, who had already disputed Newton's conclusions both from theological and experimental point of views with reference to unobservability of absolute space and motion. The general relativity of motion, the relativity of space and time, the conventionality-relativity of mathematical-geometrical writing, the completely assumptive "conventionality" of nature's laws as physics' principles which can only be considered as inductive generalizations of experiments devoid of any grounding from a theoretical point of view, had to be experimentally acknowledged. Moreover, the end of matter as substance permanent in time, as noumenon whose physical phenomena are the manifestation. The natural phenomenon is the being of things, which is the symbol of nature's dynamic activity in its totality of realization, of electromagnetic field as visible and invisible light, under the form of active, physical principle of which the matter-substance is but an apparent, secondary manifestation: the natural phenomenon is non-hidden light self-manifesting in experiments. From hence, the new relativistic dynamics, later on achieved by Einstein, the new four-dimensional, spacetime chronogeometry introduced because electromagnetic waves are only definable as spacetime functions, the tracing back of matter to energy field and of being of things to sets of spacetime events tied to spacetime propagation of electromagnetic waves. Mathematics newly came to be determined, and indeed twisted from geometry into non-Euclidean chronogeometry, a posteriori with reference to experimental physics: Newton's metaphysics of theology and mathematics was therefore, at least partially, dissolved. However, the final deconstruction of metaphysics of theology and mathematics, that constituted the so-called "classical physics", was brought about only by quantum revolution.

Heisenberg (1925) paved the way to matrix mechanics, referring to the exclusion of all those concepts assumed for the comprehension of atomic and subatomic world that did not have an experimental-operating equivalent, as absolute space, time and motion concepts suppressed by relativity. Not only new Heisenberg's physics require to abandon geometry of trajectories, but also arithmetic and analysis, that is all mathematics of continuous for physical quantities to be replaced with matrix noncommutative algebra. Even the most famous Schrödinger's formulation involved a new noncommutative algebra of operators. If in relativity the hierarchy between geometry and physics was broken and four-dimensional non-Euclidean chronogeometry was determined a posteriori, in the new quantum perspective the hierarchy subordinating physics to arithmetic and standard algebra was broken as well, and noncommutative algebra was experimentally determined. Moreover, even classical logic was devoid of any basis in fact and so was it for any logical metaphysics derived from a metaphysics of theology based on pure ideas or pure thought of thought. Logic became experimental, determined by experimental physics.

By the adoption of non-Euclidean geometries in special and general relativity—whether non-Euclidean geometry is actually the true "geometry of nature" or just a more suitable language than Euclidean geometry's one for physical phenomena's representation—the hierarchy of scientific knowledge construction that put geometry as 'a priori' in relation to physics broke down: geometry is 'a posteriori' compared to physics. With the adoption of 'noncommutative' algebras and arithmetic in QM, equally and beyond any 'ontological' or epistemological value given to arithmetic and algebra, the hierarchy of scientific knowledge construction that sets arithmetic and algebra as 'a priori' in relation to physics broke down as well: arithmetic and algebra are 'a posteriori' compared to physics. Even geometry and analysis seem to lose meaning in microphysical processes, if they are not considered at a purely probabilistic level. Moreover, QM also implies the adoption of a non-classical (non-Aristotelian) logic, and a logic where the distributive property of conjunction is no more valid shall at least be chosen. Therefore, the hierarchy of scientific knowledge construction that sets logic as 'a priori' in relation to physics broke down likewise: even logic is 'a posteriori' compared to physics. The above-mentioned statements definitely imply that also epistemology cannot be 'a priori' anymore compared to physics: epistemology is not the ultimate basis of scientific knowledge, it is not the "first philosophy" that establishes what is real or accomplishable, but it is 'a posteriori' compared to physics and physical processes.

The gnoseology of experimental actions, actually, cannot be meant as an aprioristic theory of knowledge: the same experimental actions prove that nature is never determined in a complete and univocal way and that each knowledge is probabilistic, burdened with doubts and mistakes.

According to QM, a mechanical state of motion, identified by position and speed, cannot be defined either as, according to the "indeterminacy principle" formulated by Heisenberg (1927), they are not exactly definable and measurable together: nature is not representable according to mechanical models, it is not categorizable in terms of physical-mechanical variables.

Conceptually, QM shows many revolutionary implications. Arithmetic and algebra become a posteriori: we have to introduce new quantum numbers. We must recognize the impossibility of geometry and analysis. We have to change our logic, introducing a new a posteriori logic: a new quantum logic. The indeterminacy principle implies mathematical and experimental limits of gnoseology and ontology. The unpredictability of phenomena implies the non-existence of the laws of nature: it implies nature's freedom and contingency and a correlated probabilistic knowledge. Entanglement implies the informed connection of the universe, overcoming causality. There is a new understanding of nature and a new existential self-understanding of mankind as part of nature. A new ethics of respect for nature based on universal entanglement.

It is possible to write a differential equation only for probability amplitudes for measurements outcome: world's scientific knowledge is no more univocal or certain, but intrinsically probabilistic. Phenomena are unpredictable and only statistical regularities can be established. Quantum phenomena cannot be clustered in causal chains, nor in probabilistic chains: they are intrinsically acausal. The principle of causality breaks down. Similarly, the experimental method does not guarantee the reproducibility of measurements and experiments without conditions, nor it can provide the grounding of a 'mechanical-technical determinism', but on the contrary measurements are correlated to an intrinsic indeterminacy of physical processes and a knowledge of them that is never certain or univocal. The concept of science changes, losing its characterization of predictability, tied to the introduction of a certain and univocal knowledge. Mathematical "language", as well as experimental method, in fact cannot perform this function of access to a certain and univocal knowledge of reality. Hence, the methodological and epistemological basis characterizing modern science between seventeenth and eighteenth centuries, in opposition to the previous characterization of nature, science and epistemology, break down. However, QM shows many conceptual problems related to an ontology of corpuscular particles: wave features of particles were modified in probabilistic problems. Moreover, the historical continuity of physical theories does not allow us to understand that even QM has been falsified and replaced by quantum-relativistic field theory.

Quantum-relativistic physics overcomes QM problems introducing via relativity a new quantum field ontology. This new quantum field of ontology indeed is a temporal process ontology, an ontology of becoming. Quantum field can explain complementarity, by understanding corpuscular matter as a manifestation of an immaterial wave field. Quantum field can explain the emergence of an indeterministic, entangled nature as a whole universal process, which shows itself as a dynamically organized totality like ancient physics, in which mankind can understand itself in its existential and ethical dimension. Thus, I believe we have to teach this new quantum-relativistic conception of nature.

Quantum-Relativistic Conception of Nature

The relativistic quantum uncertainty principle implies new radical gnoseological and ontological limits. By the so-called second quantization, as Landau and Peierls understood since 1930-1931, quantum-relativistic field perspective entails new and more radical indeterminacies that deconstruct the concept of material corpuscle and as remarked by Preparata (2002), wave-corpuscle complementarity is to be understood in a new way. The concept of simultaneity used in the formulation of indeterminacy principle is relativistically an absolute to get rid of: spacetime, where measurements of both conjugate variables cannot be made, widens out to the so-called synchronicity zone of spacelike spacetime intervals. But due to the principle of indeterminacy, it is no more distinguishable from the causality zone of timelike intervals. Indeterminacy makes causality and synchronicity undistinguishable, resulting in the possibility to understand the phenomenon of entanglement. But that is not all: it is no more possible to get measurements related to momentum and energy in a moment or in a brief time, as their exactitude would take an infinite time (as for the momentum, the indeterminacy is about $\hbar/c$ per the inverse of time indeterminacy, $\Delta p\, \Delta t \sim \hbar/c$; the mistake on a particle position may come to coincide with de Broglie's wavelength, $\Delta x \sim \hbar/(mc)$ or $\hbar/p$, which implies that the photon is never localizable).

It follows that wave function of a certain quantity at a given moment is not definable, not corresponding to an observable, physically available information. Indeterminacies on momentum and energy correspond to those of creation-destruction of a particle-unparticle pair ($\Delta p \sim mc$ and $\Delta E \sim mc^2$), which means that the possibility to define a particle as an isolated material corpuscle breaks down: that is, indeterminacy corresponds to a real change (what is virtual has got a shorter time of existence), it is not a matter of mere ignorance on epistemological level; on the contrary, all this implies that the particle must be considered as a form of particular excitation of the field's vacuum state.

Quantum-relativistic field perspective reveals how the probability tied up to wave function cannot be interpreted in a subjective point of view and that this interpretation must be one with the fact that the particle constitutes the quantum of an effective physical field (Preparata, 2002): the field also propagates information on the particle's presence or absence in a spacetime zone which is always finite in its indeterminacy; which implies that the information is an objective physical quantity that constitutes the field materializability in a quantum-particle. Quanta-particles do not exist as separate, localizable and independent entities, but they are only tied up to local measurements in the field's spacetime. In this perspective, physical reality emerges through measurement processes in quantum fields, a point that standard QM education rarely makes explicit. The phenomenon of entanglement reveals that, as parts of fields, quanta/particles are always correlated with zero spacetime intervals and not spacelike or timelike, thus the information tied up to a quantum is not independent from the remaining quanta and from fields taken as a whole. A material particle is but a partial and incomplete field information; a system composed of two particles closely connected in some past or another is actually a field system, and this specific system is not factorizable as product of two separable fields. Standard quantum-relativistic field theory can define fields only within the limit of non-interaction of initial and final state (condition of fields' asymptotic freedom) of a transition process: this is the reason why only S-matrix (scattering matrix) can actually be measured, whose squared modulus allows the probability of process (Chew, 1961; Heisenberg, 1943; Wheeler, 1937). The dynamic reality of universe interaction is representable only by Majorana's, not factorizable, infinite components field (Giannetto, 1989).

The particle-corpuscular-material individuality appears then as a falsified, metaphysical assumption. We have the final breakdown of any possible materialist ontology and of any ontological mechanist materialism. The unity of universe is not substantial, but effective dynamic: thus, at a profound and not directly accomplishable level, it constitutes the equivalent of a living organized totality, nature as a physics of archaic and ancient presocratic pre-comprehension. Quantum physics does not represent anymore aprioristic human logos; rather a logos peculiar to physics, but knowable only a posteriori, never totally and deterministically.

Nature must be then newly thought about. Quantum-relativistic physics embodies an entirely indeterministic reality of a total, infinite, not factorizable components field, which goes beyond any form of speculative-theoretical-metaphysical realism. This physical radical indeterminacy and contingency is the condition of possibility of our freedom and so of our ethics: it is an objective ontological transcendental of our ethics. Even though indeterminacy cannot be considered in terms of freedom, it represents nonetheless the condition of its possibility of freedom in an existential sense: quantum-relativistic physics therefore overcomes the old problem of freedom's phenomenological-existential self-comprehension and of human, ethical responsibility within nature, excluded from ancient fatalism as well as from theology of predestination and previous deterministic physics. Thus, we can actually belong to nature. Science must be newly re-considered as a form of thinking which, by means of technical models, takes shape into action, thus as a particular form of practical philosophy that challenges the possibility of conceiving philosophy, in accordance with the ancient Greek paradigm, once more as a merely contemplative activity, defining it as a pure theoretical philosophy.

A COPERNICUS FOR QUANTUM MECHANICS DIDACTIC URGENTLY NEEDED (BASED ON THE PRESENTATION BY GRZEGORZ KARWASZ AT THE SYMPOSIUM)

Didactical Context to Quantum Mechanics

Textbooks on QM are countless, yet most of them adopt one of the three canonical formulations—Schrödinger's wave mechanics, Heisenberg's matrix mechanics or Dirac's formalism—without making explicit the bridges between them and their experimental roots. As our studies show, in Polish secondary and university education this easily leads to superficial or distorted reception of QM: it does not allow to predict behavior of physical objects and in general is much mysterious. A survey of about 100 leading theorists and experimentalists, asking whether a quantum state exists prior to measurement or is created by it, produced an even split (50/50); the report was aptly titled "Agree to disagree" (Schlosshauer, 2013).

We were firmly corrected by a leading theorist, Lev P. Pitaevskii: "Lev, an electron is a point-like particle, but a wave packet modelling it spreads in time even in free flight?" His answer was: "Completely wrong! It is not the electron that spreads—it is our knowledge of its position that does. When you make a measurement, you will always detect a point-like electron." If the author of "theoretical course" (Landau & Lifshitz, 1977) redirects us to the experiment, we should check the original thoughts of QM founders. In didactics we call such an approach "didactical reconstruction" (Duit et al., 2012). Our survey, conducted at the university where early applications of quantum chemistry were developed (Kołos & Wolniewicz, 1964), showed that students hardly link the theory, experiment, history and applications.

We analyzed 20 textbooks, including those by Sommerfeld, Bohm, Bohr, and Heisenberg: they usually offer a "personal" view—for example, even in Landau and Lifshitz (1977) the exposition centers on wave mechanics, while the density matrix is mentioned only marginally. Nor do we count the recent focus on quantum entanglement (Susskind & Friedman, 2015)—picturesque but giving physics a metaphysical tone (Margenau, 1941). As a consequence, non-physicists often encounter QM not through physics courses but through popular references—typically

(1) Heisenberg's principle,

(2) Schrödinger's cat,

(3) wave-particle duality and, more recently,

(4) teleportation.

These four "icons" of QM then float free, detached from the operational and mathematical framework that gives them meaning.

The mismatch between professional and lay receptions of QM is what motivates our study. On the one hand, the physics community debates fine-grained issues such as the status of the quantum state, nonlocal correlations (Blasiak et al., 2021), or relations between uncertainty and complementarity (Spegel-Lexne et al., 2024). On the other hand, future engineers, philosophers and theologians (groups being the object of our study) can complete their studies without encountering the basic notions of QM. Our aim is to document this gap and show that it is systematic: it follows directly from the way in which QM is (or is not) presented in school curricula and how it is introduced into non-physics discourse.

Research

To probe how basic notions of QM are understood by different groups of learners, we prepared two types of instruments:

(a) a basic-level test for university students who had not yet taken a course in QM,

(b) an advanced-level test for physics students and physics teachers who had completed such a course (usually more than one).

Basic-level test

The aim of the basic-level test was to assess recognition and intuitive interpretation of four "iconic" QM topics which we mentioned above. The test consisted of five items. The first four were content-related questions; each of them offered the option "never heard of it" followed by three alternative answers that were deliberately not mutually exclusive. The fifth item asked about the reception of the test ("did you like the test?") with the options "no", "yes, it triggered my interest in QM", and "yes, but it was too difficult."

The test was therefore not intended to check textbook knowledge, but to map what "sticks" from public discourse about QM. Because multiple answers were allowed, the test captured not only whether students had heard of a concept, but also which competing narratives they associated with it (e.g., "instant signaling" vs. "entanglement" for teleportation). In total, 48 first-year students (engineering, philosophy) at our university, graduates from collaborating secondary schools and students from a theology seminar completed the basic-level questionnaire. Answers did not show any significant correlation with the target group.

Advanced-level test

The aim of the advanced-level test was to examine whether respondents with formal exposure to quantum theory could reconstruct the historical and conceptual background of QM and recall the contributions of specific founders. For this purpose, we have prepared an open-ended questionnaire with the following items:

1. Who invented QM?
2. If you listed several names, what was the contribution of each of these scientists?
3. What were the reasons for the transition from the old quantum theory to the new one?
4. What were the components of the old quantum theory?
5. Which experimental data could not be explained by the old quantum theory?
6. On what basis did Heisenberg formulate his uncertainty principle?
7. What does the Pauli exclusion principle state?
8. What is a creation operator?
9. What were the experimental clues that led to the discovery of the electron?
10. In which equation do we encounter the term ½ $h\nu$?

This open format was chosen to reveal not only whether respondents remembered individual names or formulas, but also whether they could order them into a coherent historical-conceptual narrative. In total, twelve third-year students in physics and astronomy along with four active school physics teachers completed the test and gave their comments.

Results

Basic-level tests

For the first-year students (N = 48) with no prior instruction in QM, recognition of core QM notions was very low: about 77% had never heard of Heisenberg's uncertainty principle and about 67% did not know the meaning of wave-particle duality. Among those few who had heard of the uncertainty principle, most chose the physically correct option ("We cannot measure, with arbitrary precision, e.g., the position and the momentum of an electron"), so wherever there had been some exposure, their conceptual proficiency could be considered reasonably adequate. Among the roughly 33% of students who had heard of wave-particle duality, answers split between "the electron can be simultaneously a particle and a wave" and "depending on the experiment, either the wave-like or the particle-like aspect appears"; the latter is didactically preferable, because it points to the role of the experimental arrangement (Bohr's complementarity) rather than to a naive picture of a "two-nature" electron. The only topic with high visibility was Schrödinger's cat (only 17% had not heard of it), but here the dominant answers reproduced popular-science versions rather than the mathematical idea of a superposition: the cat is dead and alive simultaneously. Quantum teleportation split the group almost evenly between "never heard" and a mixture of correct (entanglement-based) and incorrect (instant-signaling) interpretations. Although 67% of the students found the test "not very clear," 33% declared that it triggered their interest in QM.

Advanced-level tests

Respondents with formal QM courses were able to list most key contributors—Planck, Einstein, de Broglie, Heisenberg, Schrödinger, Dirac, and Born. Interestingly, only active physics teachers—and not a single university student—mentioned Bohr, whose atomic model is still taught as a key transitional concept between classical physics and QM. Difficulties appeared once respondents were asked to assign specific contributions to individual scientists. Most of them correctly identified Heisenberg as the author of the uncertainty principle and Schrödinger as the author of the famous wave equation (although a few answers referred only to the "cat-in-the-box" thought experiment). Planck was also generally recognized as the originator of the idea of energy quantization. However, Einstein received only a small number of responses that explicitly pointed to the wave-particle duality of light; a considerable fraction associated Einstein primarily with the theory of relativity solely.

The following three questions, which concerned the transition from the old to the new quantum theory, were left unanswered by most participants (some even added the remark "What is the old quantum theory?"), or else they were clearly incorrect. In fact, only one respondent offered an approximately accurate account, noting that the old quantum theory was an attempt to "rescue" classical mechanics by introducing energy quantization in atoms and by adopting the wave-particle duality of light. At the same time, this early framework was unable to explain the emission spectra of multi-electron atoms, low-energy electron scattering (Ramsauer's effect), or spin-related effects.

In response to the question about the grounds on which Heisenberg formulated his uncertainty principle, almost all respondents pointed to the impossibility of measuring simultaneously the position and the momentum of a particle; two participants even mentioned non-commuting operators. None of them, however, referred to the actual, deeply experimental motivation behind Heisenberg's reasoning: that we do not observe "electron orbits" but only measurement outcomes such as emission spectra (see Giliberti & Lovisetti, 2025a), and that in practice we see not electrons themselves but their tracks, for example, in the Wilson cloud chamber.

Interestingly, most respondents had no difficulty answering the question about Pauli's exclusion principle or giving the formal definition of the creation operator. By contrast, apart from the active physics teachers (who actually teach Thomson's model), none of the third-year physics students were able to identify the experimental evidence that led to the discovery of the electron!

Finally, only about half of the respondents were able to identify the harmonic oscillator expression that contains the zero-point energy term $½\,h\nu$. The remaining respondents either left the question unanswered or pointed instead to the photon-energy formula. This outcome is surprising, given that the quantum harmonic oscillator is a central element of university-level courses in QM: nobody told students that this was a part of a seminal paper in QM (Giliberti & Lovisetti, 2025a).

Conclusions

A third-year physics student, having just completed two QM courses, answered only one question and remarked, *"We learned many mathematical formulae, but no historical background."* This remark, together with the questionnaire results, supports the central claim of our paper: when QM is taught primarily as a ready-made formalism, without its experimental and historical scaffolding, students can reproduce names and equations but lose the logic that generated them. The absence of Bohr, the vagueness about the "old quantum theory," and the purely instrumental reading of Heisenberg all point to the same didactical gap: the bridges between experiments, transitional models, and the final formalism are not made explicit. As a consequence, even advanced students can recall the Pauli principle or define the creation operator, but they cannot explain how the electron was actually discovered or why $(n + ½)h\nu$ is more than "just another formula with $h\nu$." The results of the basic-level test show that this gap opens much earlier, already at the stage of students who have never taken QM. Iconic notions of QM reach them mainly through popular culture: almost everyone has heard of Schrödinger's cat, whereas the genuinely foundational ideas—the uncertainty principle and wave-particle duality—are unknown to two thirds or more of the group. Moreover, where popular and scientific narratives coexist (as in quantum teleportation), students adopt both indiscriminately. This indicates that, in the absence of formal instruction, public discourse becomes the de facto curriculum.

Our survey therefore suggests that teaching QM should focus less on adding new topics and more on interactive *constructing* (Karwasz & Wyborska, 2023) the connective tissue between history, experiment and formalism, and that this restoration (Giliberti & Lovisetti, 2025a) should start already at the level of general science courses (for engineers, philosophy and theology students), before they import QM vocabulary from popular sources. Giliberti and Lovisetti (2024a) held a seminar on didactics of QM at Nicolaus Copernicus University. A retired professor of QM stated: "Sure, QM is still waiting for its Copernicus."

ARE THE EPISTEMOLOGICAL AND ONTOLOGICAL QUESTIONS POSED BY THE DEVELOPMENT OF QUANTUM MECHANICS TO THE FOUNDING FATHERS STILL RELEVANT IN TEACHING? (BASED ON THE PRESENTATION BY LUISA LOVISETTI AT THE SYMPOSIUM)

Physics as the "Science Par Excellence" and New Educational Challenges at the Turn of the Century

Since the early 20th century, physics has increasingly presented itself as the science *par excellence*, gradually adding to the unifications that had previously occurred (such as those of terrestrial and celestial physics, with Newton; or of optics with electromagnetism, with Maxwell) also those of chemistry with the physics of atoms, with QM (Giliberti & Lovisetti, 2024a).

Moreover, the importance of physics during World War II, along with the massive funding it received from many governments and a shift toward large-scale projects, led to a tremendous expansion of the discipline. This historical moment not only boosted physics itself but also extended its methods and tools to other disciplines. Just think of the discovery of DNA (Schrödinger, 1935a): it was made possible not only through biological insight but also through X-ray crystallography, a physical technique.

Yet, in recent decades, the spotlight has shifted. Life sciences and environmental studies now dominate the public imagination, raising urgent ethical and societal questions. In consequence, Physics no longer occupies the uncontested center of scientific attention. In light of these shifts—both in the role of physics within the scientific enterprise and in its societal relevance—it becomes necessary to reflect on how physics is taught and conceptualized, especially in relation to other disciplines and pressing global challenges.

This change compels us to ask a fundamental question: should physics education today be more explicitly connected with other scientific disciplines and with broader ethical and social concerns? Traditionally, especially in secondary and university curricula, physics has been taught as a self-contained body of knowledge—objective, rigorous, and largely devoid of ethical reflection. But is this still appropriate in today's interconnected and problem-driven world? QM, in particular, provides a unique opportunity to reopen these discussions. It is a domain where epistemological (how we know what we know) and ontological (what kind of reality exists) questions emerge in a natural and unavoidable way.

Core Questions in Quantum Mechanics and the Role of Quantum Field Theory

Historically, QM has been accompanied by deep interpretative debates, such as:

– What does it mean for a particle to be in a superposition? (Bell, 1990).

– Is the wave function a real entity or merely a mathematical tool?

– Does measurement (Bell, 1990) collapse reality into a single outcome—and what counts as a measurement? How should the measurement problem be interpreted? (Bohr et al., 1924).

– Do electrons in an atom have/follow definite trajectories—or is the very notion of a trajectory meaningless in the quantum realm? (Bohr, 1928; Giliberti & Lovisetti, 2025a; Schrödinger, 1935b).

– What is the true nature and meaning of entanglement? Does it imply a deep, non-local connection between particles, or simply a limitation in how we describe composite systems? (Mermin, 1989; Schrödinger, 1936) Although in many physics classrooms these questions have been dismissed under the pragmatic directive to "shut up and calculate" (Peskin & Schroeder, 1995), they inevitably resurface. Students do not just want and need to know how QM works—they want and need to understand what it means.

Quantum field theory as a conceptual completion of quantum mechanics

Let us focus, for example, on the concepts of trajectory and entanglement. In QM they are both conceptually challenging aspects, epistemologically more straightforward to tackle in quantum field theory. In this an important question which might be raised is: what significant things does quantum field theory have to say for education about the worldview that emerges from quantum physics? Quantum field theory (Heitler, 1953) provides a much clearer ontological framework than QM. According to quantum field theory, the world is made of fields that exist in three-dimensional space. In contrast, QM—whether in the Schrödinger or other formulations—tends to privilege the concept of the particle. The wave function, after all, describes the state of one, two, or more particles. Thus, QM offers a description of quantum properties that is inherently centered around the particle concept. Quantum field theory, by contrast, is structured around the notion of fields. From a teaching perspective, a field is naturally understood as an extended object, something that exists throughout space. With this framework, it becomes conceptually easier to make sense of certain quantum phenomena that are more challenging to grasp from a particle-based perspective. When we think of a particle, it is hard to imagine it without a trajectory; but when we think of a field, it is much easier. For instance, when we think in terms of particles, it becomes difficult to explain what it means for a system not to have a definite number of particles, or to understand the nature of entanglement in a physically intuitive way. But if we view particles as excitations of quantum fields, a number of conceptual hurdles begin to dissolve. In this picture, particles are excitations of normal modes of a field, and those modes occupy all available space. This framework helps us understand, for example, why identical particles obey specific statistical behaviors (Bose-Einstein or Fermi-Dirac statistics): they are excitations of the same field and therefore fundamentally indistinguishable.

Of course, quantum field theory introduces its own challenges. The concept of a quantum field cannot be directly equated with that of a classical field; it is not something we can visualize as a classical wave propagating through space. Still, we do have an object—something that "lives" in three-dimensional space—that can, in principle, evolve autonomously. Moreover, quantum field theory is essential for introducing the concept of the photon. Without it, our understanding of the emission and absorption of radiation remains incomplete. It is through quantum field theory that we gain a coherent description of electromagnetic interactions, making the photon a necessary entity to explain processes that standard QM alone cannot fully account for. Therefore, quantum field theory, when adopted as an interpretive and educational framework, provides a unified treatment of both particles and electromagnetic radiation. This is something that standard QM cannot fully offer. In QM, radiation is typically represented in an abstract way using state vectors (bras and kets), but the actual mechanisms of interaction—that is, what physically happens when radiation is emitted or absorbed—remain somewhat obscure or only indirectly described. Formalism tells us the probabilities of transitions, but it does not offer a concrete picture of the interaction processes themselves. By contrast, quantum field theory (Giliberti & Lovisetti, 2024b; Hooft, 2015) explicitly models interactions between matter and radiation as field interactions, allowing us to describe phenomena such as the emission or absorption of a photon in a way that is both physically meaningful and mathematically consistent, making it possible to model real processes like particle decay, scattering, and photon exchange with greater clarity. In this sense, quantum field theory does not simply extend QM to the relativistic regime—it "completes" QM from a conceptual point of view (Fetter & Walecka, 2003; Pais, 1986), and it encourages new interpretations and meanings and allows the understanding the dynamics of quantum fields and the reality of interactions in quantum electrodynamics and beyond.

These examples are not just curiosities; they are gateways into the philosophical heart of quantum theory. They compel students to confront fundamental questions about reality, knowledge, and observation. Suppressing these questions in education means reducing physics to a sterile collection of formulas—stripping it of its conceptual richness and its power to challenge our understanding of the world. Indeed, quantum physics is not only a technical tool—it is a profound intellectual revolution. And it deserves to be taught as such.

Teaching Quantum Theory in Depth and the Importance of Reflecting Also on Ethical Issues

In general, we argue that a meaningful understanding of physics, today, requires integrating philosophical (Del Santo & Schwarzhans, 2022), historical (Lovisetti, 2024; Lovisetti & Giliberti, 2025), technological (Ekert, 1991; Nobel Prize, 2022), cultural and ethical dimensions. This is not just an enrichment; it is essential to form a well-rounded scientific perspective.

There are already examples of successful educational strategies along these lines:

- Courses that combine physics with the history of science, showing how ideas evolved over time.
- Interdisciplinary modules where students explore also the impact of quantum technologies (like quantum computing or cryptography) on society, but in which the technological aspects are not the only nor the main focus of the discussion.
- Approaches that include reflections concerning the social and ethical impact of quantum physics, not only concerning, for example, the implications of quantum computing for cybersecurity and data privacy—with a discussion on whether should all advancements be pursued, regardless of their consequences—, but also (and especially) discussions concerning the production of knowledge and the freedom of research connected to these fields, along with the series of social and political decisions that are made regarding them.

In fact, ethical issues are not only those related to the good or bad use of resources by powerful groups or linked to conflicts and to warfare, but also those internal to the peer review process and editorial choices that disproportionately favor certain types of research at the expense of others.

This issue is not only retrospective. Indeed, as already observed, historical studies on the so-called "quantum dissidents" have shown that, around the 1960s and 1970s, foundational research on QM occupied an ambiguous and often marginalized position within the physics community. Questions concerning hidden variables, Bell's theorem, realism, and non-locality were not always treated as legitimate scientific problems but were often associated with philosophical speculation or professional risk (Freire, 2009). For example, in Clauser's words,

> any open inquiry into the wonders and peculiarities of quantum mechanics and quantum entanglement that went outside of a rigorous "party line" was then virtually prohibited by the existence of very religious stigmas and social pressures that, taken together, amounted to an evangelical crusade against such thinking. […] This stigma was very real and had more than just a mild social impact on the conduct of physics. For example, even as late as the early and mid-seventies, whenever a manuscript discussing the foundations of quantum mechanics […] was submitted to either the Physical Review or Physical Review Letters, editor Samuel Goudsmit would, in turn, enclose a one-page APS policy statement along with it to the manuscript's referee. That policy, in essence, urged the referee summarily to reject any paper on this subject unless the paper was both mathematically based and gave new quantitative experimental predictions. Bohr's response to EPR certainly could not have been published under Goudsmit's stated criteria. […] students were told simply that Bohr was right and Einstein was wrong. That was the end of the story and the end of the discussion (Clauser, 2022).

Noting how certain research, for example in the 1960s and 1970s was completely banned even in countries such as the United States, considered "democratic" and "liberal", raises ethical concerns about the freedom of research and the freedom to teach, and provides useful highlights related to the education to active citizenship, even from a modern perspective. This aspect is particularly relevant in a time like the present, where the Second Quantum Revolution is strongly shaping the direction of investments and the definition of what constitutes "optimal" research—favoring technological applications over interpretative, philosophical, foundational, or historical questions.

The Educational Importance of Discussing Some Quantum Historical Debates

Moreover, presenting students with historical debates (e.g., Einstein vs. Bohr) (Aspect et al., 1982; Bell, 1964; Bohm & Aharonov, 1957; Bohr, 1935; Einstein et al., 1935; Mermin, 1981; Reid et al., 2009; Schrödinger, 1935a) engages their critical thinking and helps them understand that science is a human endeavor, full of trial, error, and interpretation, giving a cultural framework for a deeper understanding of the nature of science. Recent research has also suggested that philosophical approaches to quantum physics education can support the development of students' critical thinking. This is particularly relevant because the conceptual difficulties of QM are not only mathematical: they concern the meanings of reality, objectivity, causality, observation, and knowledge (Tuero-O'Donnell et al., 2026).

In this perspective, QM can be a gateway to reforming how we teach physics more broadly. QM can thus serve as a starting point to reform physics education, emphasizing that scientific models are not absolute and definitive truths (Lovisetti & Giliberti, 2026) but evolving tools to describe and interpret reality (some examples from our educational approach to quantum phenomena are provided in Giliberti and Lovisetti (2025b) and Lovisetti (2024). This naturally opens up a discussion on how science describes reality—not just measures it.

To conclude, we believe that the epistemological and ontological questions posed by the founding fathers of QM are not only still relevant—they are essential to a physics education that seeks to be reflective, integrated, and responsive to the world we live in. Incorporating these questions into teaching (Giliberti & Lovisetti, 2025b; Lovisetti, 2024):

(a) makes physics more engaging and accessible,

(b) encourages interdisciplinary thinking,

(c) helps students connect scientific knowledge with the ethical and societal challenges of the 21st century.

Indeed, in a time of global crises—climate change, AI ethics, biotechnology—we need scientists and citizens who not only understand equations but also ask: "What kind of knowledge is this?", "What does it mean?", "And what should we do with it?" These are not questions with easy or final answers. But perhaps that is precisely the point: physics education should not only transmit answers—it should also cultivate the courage to ask new questions. Because the dialogue between science, philosophy, and society is still very much alive—and there are still many open questions waiting for the next generation to explore.

IMPLICATIONS FOR TEACHING QUANTUM PHYSICS

On the basis of the three contributions discussed in the symposium, several implications for teaching quantum physics can be identified. First, QM should not be introduced only as a set of counter-intuitive results or as a formal apparatus to be applied algorithmically. Students need to understand the experimental and conceptual difficulties from which the theory emerged: black-body radiation, atomic spectra, the stability of matter, the photoelectric effect, the Compton effect, the Franck-Hertz experiment (Giliberti & Lovisetti, 2025b). To these aspects, it is also important, in our view, to add a discussion of several interference experiments, which help place these difficulties in a different and complementary context (Giliberti & Lovisetti, 2025b; Lovisetti et al., 2023). These historical and experimental roots help students see QM not as an arbitrary collection of strange rules, but as a coherent response to the challenges associated with the interpretation and understanding of experimental results (Lovisetti, 2024).

Second, teaching should make explicit the conceptual changes introduced by quantum theory. Notions such as state, observable, measurement, probability, objectivity, causality, individuality, and separability cannot simply be transferred from classical physics to quantum physics without discussion (Giliberti et al., 2025). If these terms are used as if their meanings were unchanged, students may learn procedures without understanding the conceptual revolution involved. For this reason, philosophical reflection should not be treated as an optional addition, but as a way of clarifying the meaning of the physical concepts themselves.

Third, the historical development of QM should be used didactically, not merely anecdotally. Historical reconstruction can help students understand why different formulations of quantum theory were introduced, how theoretical concepts were shaped by experimental constraints, and why debates among Bohr, Einstein, Heisenberg, Schrödinger, Born, Pauli, Dirac, and others were scientifically productive. Such debates show that science is not a linear accumulation of facts, but a dynamic process of model building, conceptual clarification, criticism, and revision.

Fourth, the Second Quantum Revolution should be connected also to foundational questions rather than presented only through applications. Quantum technologies—such as quantum computing, quantum cryptography, quantum sensing, and quantum communication—are often introduced as the main reason for teaching quantum physics today. However, these technologies rely on concepts such as superposition, entanglement, measurement, indistinguishability, and information, whose meaning cannot be fully understood without foundational reflection. A culturally oriented teaching of quantum physics can therefore complement technical training by helping students understand what makes these technologies genuinely quantum.

Finally, quantum physics education should contribute to scientific citizenship. The history of quantum foundations shows that research agendas, editorial choices, institutional priorities, and cultural attitudes can influence which questions are considered legitimate within science. Discussing these aspects can help students reflect on the nature of science, the freedom of research, the ethical responsibilities of scientists, and the social consequences of scientific knowledge. In this sense, teaching QM can become a privileged context for educating not only future specialists, but also reflective citizens capable of understanding the cultural and ethical significance of contemporary science.

CONCLUSION

The centenary of QM is not only a scientific anniversary—it is a moment to rethink how this theory continues to transform our understanding of both nature and ourselves.

Throughout this symposium, we have seen that teaching QM today means more than transmitting a body of formulas or training future quantum engineers. It means restoring the cultural, historical, and philosophical scaffolding that once gave the theory its revolutionary meaning. From the historical reconstruction of its conceptual roots to the analysis of how students and teachers perceive it, from the discussion of quantum field theory as a more coherent ontological framework to the reflection on its ethical and social dimensions, a common thread emerges: QM remains a living laboratory for thinking about knowledge itself. To bring QM into classrooms in a truly meaningful way, we must connect its mathematical structure (Lovisetti et al., 2023) with its experimental origins, its philosophical implications, and its cultural resonance. Doing so can transform physics education into a space where students not only learn how nature behaves but also reflect on what it means to know nature. In this sense, the Second Quantum Revolution is not only technological—it is also educational and, first of all, cultural. QM, once again, invites us to question our assumptions about reality, causality, and human creativity. If, a century ago, it revolutionized physics, perhaps today it can help renew the dialogue between science and the humanities, guiding us toward a richer, more integrated understanding of the world we share.

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