

# 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 has helped establish between physics and other disciplines. Drawing on the most recent research in quantum mechanics education, we will address the epistemological paradigms that underpin our understanding of nature and the cultural significance of technological aspects 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.

## Introduction

The centenary of quantum mechanics provides an opportune moment to reflect on one of the most profound intellectual revolutions in human history. Since its inception in the 1920s, it 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 quantum mechanics should be taught in high school and also in degree courses other than those of the “hard” sciences.

Indeed, most initiatives aimed at introducing significant aspects of quantum mechanics into schools or university courses are primarily focused on technological applications, with the goal of training future quantum technicians [1-3]. 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.

## The problem

Quantum mechanics emerged during a period of transformative shifts in both scientific theory 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 quantum mechanics and of the answers they have generated within our educational system, both at the high school and university levels? [4]

This symposium, organized by the Cultural Understanding of Physics GIREP Thematic Group, aims at discussing the multifaceted implications of quantum mechanics for education, fostering an interdisciplinary dialogue that bridges science, philosophy, and humanities into a broader culture, will try to raise the questions presented above and discuss them together.

### **Contributions to the symposium**

The four cornerstone presentations of this symposium delve into pivotal questions that quantum mechanics raises about causality, determinism, the nature of knowledge, the problem of the non-intuitiveness of quantum aspects and also some non-trivial ethical implications. They also illuminate its profound cultural and spiritual dimensions, fostering a dialogue that transcends the boundaries of traditional scientific discourse.

The first contribution begins by examining the origins of modern science as a “practical philosophy”, tracing the influence of quantum-relativistic physics on the ontological and epistemological paradigms that underpin our understanding of nature. It argues that quantum mechanics, by challenging deterministic frameworks, necessitates a rethinking of ancient concepts such as physis—a dynamically organized totality.

The second contribution continues by celebrating the centenary of Heisenberg’s quantum mechanics, emphasizing its cultural significance. Moving beyond its technological impacts, the presentation explores how quantum mechanics reshaped societal and educational perspectives, enriching contemporary discourse on the human condition and the nature of knowledge.

The third contribution discusses several digital tools to support teaching quantum mechanics and machine learning applied to it. Indeed, using numerical experiments to teach non-intuitive quantum aspects is crucial for effective learning. These experiments illustrate key concepts, incorporating machine learning, and are developed with Jupyter Notebooks and Python, featuring a user-friendly interface. To compile these experiments, the  $\text{Ens}\Phi\text{Q} \rightarrow \text{QTechEdu}$  platform was created, providing universities and institutions with a valuable educational resource.

The fourth and last contribution concentrates the focus on the cultural and educational dimensions of quantum mechanics. While much of the recent discourse has centred on its technological applications, such as quantum computing and encryption, this paper highlights the broader cultural significance of quantum mechanics. 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. The historical journey of quantum mechanics is not merely an account of scientific milestones but also a lens through which to understand its enduring impact on modern culture.

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## Quantum-Relativistic Physis: a New Philosophy of Nature

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**Abstract.** Reality, as we understand it, is shaped by its representation through theoretical frameworks. Consequently, the mental representation essential for learning physics is inherently grounded in theoretical constructs. This work explores a potential foundational ontology rooted in the structure of quantum field theory, presented as a starting point for a broader cultural dialogue on the nature of physical reality, including its connections with other disciplines and discussing how deeper knowledge can help shape representations of the world.

### Introduction

Physics is considered as a particular kind of natural philosophy, related to a gnoseology of experimental actions. According to quantum physics, a mechanical state of motion, identified by position and speed, cannot be defined either as, according to the “indeterminacy principle” formulated by Heisenberg in 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.

Quantum-relativistic physics implies the emergence of an indeterministic, entangled Nature, which shows itself as a dynamically organized totality like ancient Physis, in which mankind can understand itself in its existential and ethical dimension.

### Quantum-Relativistic Conception of Nature

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 [1]: 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 greatness 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 measures in the field’s spacetime. 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 [2-4].

The dynamic reality of universe interaction is representable only by Majorana’s, not factorizable, infinite components field [5].

The particle-corpuseular-material individuality appears then as a falsified, metaphysical assumption. The unity of universe is not only and if necessary 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 Physis of archaic and ancient Presocratic pre-comprehension. Quantum physics does not represent anymore aprioristic human logos; rather a logos peculiar to physis, but knowable only a posteriori, never totally and deterministically.

Nature must be then newly thought about: Quantum-Relativistic Physis embodies an entirely indeterministic reality of a total, infinite, not factorizable components field, which goes beyond any form of speculative-theoretical-metaphysical realism.

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.

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# Towards One Hundred Years of Heisenberg's Uncertainty Principle: Cultural Impact on Physics, Philosophy and Theology

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**Abstract.** Heisenberg's uncertainty principle seems to have gained the most heard social resonance in the contemporary culture. Philosophers, scientists, theologians use it to solve problems like determinism, human free will, "God of gaps". In Polish schools quantum mechanics is poorly taught. We checked how young people—both secondary school and university students, from different faculties—interpret quantum mechanics and its fundamental questions.

## Open philosophical questions of quantum mechanics

The questions of causality, determinism, and human free will are essential from ever, in any culture and time. Greeks had Moiras (or Parks) determining human path of life. A too wide interpretation of Heisenberg's principle could undermine the concepts not only of determinism, but even of causality. A referee in a theology journal answered to a paper on determinism [1]: "author's concept is completely wrong. Already Basylius the Great showed that the world in indetermined." St. Thomas solved the problem introducing the primary and secondary causes, but leaving also a category of contingent events [2]. The question emerged even in a book of Max Planck [3] from 1937: for him the free will does not come from gaps in determinism, but from an action of human mind. We cannot see it, as the eye sees the whole world but not a proper pupil.

Nowadays, almost every second paper in theology dealing with ontology recalls the Heisenberg's principle, as the possibility of God to change the path of events: the concept is named "God of gaps" [4] and dates to some disciples of the very Newton.

## Current epistemic status

With the Nobel award to Alan Aspects [5] no doubts exist on the validity of Bell's inequalities. However, the physical interpretation of the EPR paradox is still not clear, quoting Robert Crease— "spookier than ever" [6]. Philosophical considerations, firmly based on physics, put at odds one of the fundamentals: the locality vs the free will, if one wants to preserve the very causality [7].

In particular, in the very field of Physics, the opinions on the meaning of Heisenberg's principle are evenly split. In a recent survey done among one hundred the most influential specialist in Quantum Mechanics, both experimentalist and theoreticians, the answer to the question if a quantum state is undetermined before the measurement (*i.e.*, the uncertainty belongs to the ontology) or is determined but simply unknown to the researcher (*i.e.*, the uncertainty is epistemic) the answers of experts were divided: The title of the reporting paper is "Agree to disagree" [8]. The most recent experiment shows more: Heisenberg's principle is a trade-off with the wave-particle duality [9].

## Research

We will report what is the perception of Heisenberg's principle (and quantum mechanics in general) among secondary-school teachers in Poland, and among university students. Four

questions of the scientific merit: on Heisenberg's principle, particle-wave dualism, Schrödinger's cat and teleportation were asked, with the first answer "never heard" and three non-exclusive alternative answers. The last question was: "did you like the test?" and the answers were "No", "Yes! It triggered my interest in quantum mechanics", "Yes! But it was too difficult", "Yes! But it was too easy."

The possible answers on purpose were not exclusively-or: (a) "Schrödinger cat" means that the wave function is a mathematical superposition [correct, rather theoretic], (b) it means that *after* opening the box, the cat is alive exclusively-or dead [correct, rather experimental].

The first run of tests was on a limited sample: 7 students of philosophy (2<sup>nd</sup> year of university), 5 in theology (2<sup>nd</sup> year), and 12 in physics and astronomy (1<sup>st</sup> and 2<sup>nd</sup> year); plus 1 high-school student (well-ranked) in 4<sup>th</sup> year, *i.e.*, before the maturity exam, of "technical profile".

## Preliminary results

Preliminary results, in all three groups, are rather surprising, not to say: disappointing. At the Philosophy course, 6 out of 7 students never heard about Heisenberg's principle. It means, that if later, in their philosophical carrier, they will recall this principle—their knowledge will be superficial (what we already observed as referee of some national papers). Similarly wrong answers were given on quantum teleportation: half of "philosophers" are convinced that this means the possibility of sending signals at zero-time delay—they are not aware of the limitations from Einstein's relativity. Tests done in Faculty of Theology gave similar results: only one answer correct on Heisenberg's principle, and two on the duality. The answers of students from Faculty of Physics were all (100%) correct on Heisenberg's principle, and on the duality (but it is interesting to note that, even if they have already attended a theoretical course of quantum mechanics, their answers were "It is a result derived *a posteriori* from the experiment" instead of "It is a mathematical superposition of wave functions") and more than 50% correct on the quantum teleportation ("this is just a poetic description of quantum entanglement"). The results from the secondary school were similar to "theologians" and "philosophers": 8 out of 11 never heard about Heisenberg, but as much as 7 out of 11 answered correctly about the duality.

The general perception of the test was good: the majority of students in all groups liked it, and half of them answered that the test triggered their interest in quantum physics. Resuming: results of Polish students are really urging not only to introduce seriously elements of modern physics to secondary school, but also for a broad dissemination action in the society. And concerning Heisenberg, apart from university students in physics, it seems that nobody never heard about him.

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# An Experience-Based Course of Quantum Mechanics: Numerical Experiments Ranging from Stepwise Potentials to Wave Packet Propagation and Machine Learning Applications

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**Abstract.** We developed several digital tools to support teaching quantum mechanics and machine learning applied to quantum mechanics. The idea behind that is main concepts of quantum are non-intuitive to an uninitiated student due to the lack of daily experience with quantum mechanics: the basis of intuition is experience. Therefore, teaching quantum mechanics with the support of numerical experiments for all main topics of quantum mechanics appears to be essential for an efficient and quick learning process. The numerical experiments demonstrate the core concepts of quantum mechanics and include the use of machine learning in quantum mechanics. They are prepared using Jupyter Notebooks and PYTHON computer code with a user-friendly graphical interface. Students and instructors can use this active learning environment to change the parameters of the suggested numerical experiments, or they can download, modify, and run the codes on their personal computers. Finally, a platform ([EnsΦQ](#) → [QTechEdu](#)), gathering overall numerical experiments (Jupyter Notebooks modules), was designed. It can be used by universities and institutions in their different educations.

## Reproduction

At the turn of the twentieth century, Max Planck introduced the concept of quantum energy to explain the origin of the thermal radiation emitted by a hot body (black body radiation). This is generally regarded as the first essential step of the rise of quantum theory, which has revolutionized our approach to describing the behavior of matter at the atomic scale. From Bohr's model of the hydrogen atom to the relativistic Dirac's equation, many scientists such as Albert Einstein, Louis de Broglie, Erwin Schrödinger or Werner Heisenberg evolved Planck's theory and made possible the development of this new discipline (see quantum mechanics textbooks [1,2]).

One of the most well-known applications of quantum mechanics is the scanning tunneling microscope (STM) [3], which is composed of a conductive tip brought very close to a surface to be examined. STM is based on the principle of quantum tunneling effect; it is used for imaging surfaces at the atomic level. Understanding how discrete energies come from, how atoms behave, and how they interact with each other is fundamental for designing such instruments. Nowadays, quantum mechanics is at the origin of many technological advances such as personal computers, Blu-ray players, or iPhones. In recent years, quantum computing [4,5] has been a rising domain at the interface with mathematics, computer science, and physics. The classic bit (or binary digit), the basis of traditional computer science, can take two values 0 or 1, while the qubit (or quantum bit) is built from a linear superposition of quantum states  $|0\rangle$  and  $|1\rangle$  (equivalent to spin states up and down of an electron). This basic unit of quantum information thus enables transmission of an infinity of information, contained in the development coefficients, and performs simultaneous operations on all these states, unlike the classical bit. Quantum computers are transforming many

sectors such as artificial intelligence [6], online security [7], and drug development [8]. Recently, artificial intelligence and its subdomain machine learning. In such applications, students and engineers who understand the fundamental concepts of quantum mechanics are needed.

## The problem

In this context, one of the main difficulties in teaching undergraduate quantum mechanics is the counter-intuitive nature of quantum laws. The counter-intuitive nature of any new knowledge usually means that one does not have any relevant previous experience, which can be used to analyze and predict the behavior of new phenomena. We do not observe quantum mechanical behavior in our daily life and, correspondingly, when students learn quantum mechanics, they encounter many difficulties in understanding the subject. This simply means that students need to perform experiments to get some experience and, later, an intuition about how the quantum world works. Designing labs for a course in quantum mechanics is expensive and not many colleagues can afford it. This is especially true for large universities (University of Central Florida about 65,000 students) and engineering schools (CentraleSupélec about 800 students/year).

## Contribution to the community

To support advances in quantum technologies, better training of future digital players in particular in quantum technologies and also technologies using machine learning techniques is needed. This work aims to take a major step in that transformation through the following achievements. We offer and deliver a series of Jupyter Notebooks modules with PYTHON numerical codes dealing with the main topics of quantum mechanics (postulates, time-dependent wave packets, atoms, angular momentum, nuclear decay, perturbation theory, etc.), and machine learning applications. These Notebooks will be made available to instructors and students and could be used as exiting course support and/or novel training programs in quantum technologies. Additionally, these modules will be made available to a broader education community in the form of a web-based learning environment [EnsΦQ](#) → [QTechEdu](#).

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# Are the Epistemological and Ontological Questions Posed by the Development of Quantum Mechanics to the Founding Fathers Still Relevant in Teaching?

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**Abstract.** Since the twentieth century, physics has been central to scientific unification, integrating fields like chemistry and atomic physics through quantum mechanics. Its prominence, amplified by wartime advancements and funding, has greatly influenced other sciences. However, in last decades, societal focus has shifted toward life sciences and environmental issues, challenging physics education to address broader interdisciplinary ethical and philosophical questions. Should physics teaching integrate ethical and social dimensions and connect with other sciences and other knowledge? Can quantum mechanics offer opportunities to rethink traditional physics education, emphasizing historical, philosophical, and operational contexts to enhance relevance and comprehension for today’s students?

## Introduction

Since the early twentieth 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 quantum mechanics. Moreover, the importance of physics during World War II, along with the massive funding it received from many governments [1], led to a tremendous expansion of the discipline, which has since partially entered into other branches of science as well [2]—it is hard not to think, for instance, of the importance of physical techniques in the discovery of DNA. In recent years, however, things have changed, and at least in the public imagination, the life sciences have gradually taken precedence, raising ethical, social, and even fundamental questions of a different nature from those typical of quantum mechanics. The issue of climate change and respect for nature is further shifting attention toward still different scientific fields.

## The problem

Shouldn’t the teaching of physics be increasingly connected to that of other scientific disciplines and explicitly pose ethical and social questions that also should find a place in our schools and university courses?

Many aspects of quantum mechanics can—and historically have—led to discussions that stray far from the scientific path and are placed within pseudoscientific interpretations of dubious value [3]. Yet, despite attempts to suppress them in school and university courses with prescriptions such as the well-known “shut up and calculate” [4], questions about the meaning of our answers concerning the structure of the world persistently resurface [1,5,6]. Should education not take it upon itself to address these questions?

Relativity is another cornerstone of current scientific thought. The consistent way to bring together relativity and quantum mechanics is to develop quantum field theory. What significant

things does field theory have to say for education about the worldview that emerges from quantum physics?

Indeed, it is increasingly argued that achieving a meaningful understanding of scientific concepts requires the synergetic appropriation of operational knowledge about the nature of science [6]. We believe it is essential to develop an educational framework in which physics is understood as evolving through significant questions connected to the structure of philosophical and historical thought, employing teaching strategies that make these topics relevant to the present.

We believe it is essential to develop an educational framework in which physics is understood as evolving through significant questions connected to the structure of philosophical and historical thought [7-9], employing teaching strategies [10] that make these topics relevant to the present [11-12].

Moreover, from a strictly teaching viewpoint, can quantum mechanics serve also as boost to propose an approach to physics that reframes the somewhat rigid tradition of the teaching classical mechanics with new key aspects and new viewpoints [5]?

In this presentation these and other issues and questions will be discussed.

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