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Cultural Understanding of Physics – Quantum Mechanics a Century Later

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Abstract: In a world where the second quantum revolution drives the study of physics orienting much research toward technological developments, physics courses often focus more on the applied aspects of quantum mechanics than on the epistemological ones. This technological shift of goals is quite widespread, and certainly not limited to quantum mechanics alone. Indeed, academic proposals to transform courses of mathematical analysis into calculus, to reduce the credits for analytical mechanics, or to diminish or abolish courses on relativity due to their limited practical applications are not uncommon. In many countries, one can even pursue a doctorate without a master's degree... This trend results in a widespread lack of cultural and historical awareness among students and young graduates in physics. This lack not only hinders a deeper and more meaningful understanding of quantum mechanics itself but also provides an inconsistent epistemological framework for physics in general, risking giving an incorrect image of the nature of science. This presentation will provide elements for discussion on the importance of contextualizing quantum mechanics within its cultural and historical environment as an emblematic example of a process aimed at cultivating physicists who are not only experts in a narrow field of research but also aware of the importance of a broader cultural context (at least to manage changes and innovations). In particular, we will discuss some examples of the initiatives by the physics education research group of the University of Milan aimed at fostering a cultural and historical understanding of quantum mechanics.

Keywords: Quantum Mechanics, History of Physics, Nature of Science

1. Introduction

> Hundred years have passed; hundred summers, with the length
> Of hundred long winters! and again I hear
> These waters, rolling from their mountain-springs
> With a sweet inland murmur[1] (Wordsworth & Coleridge, 1979, p. 254).

To echo William Wordsworth, it has been one hundred years since the extraordinary insight of young Werner Heisenberg first led to the formulation of the theory that became known as quantum mechanics. A century has passed, during which the physical motivations, conceptual foundations, epistemological drives, and revolutionary aspects have seemingly fallen into slumber, no longer stirring any impression among physics students. More than asleep, perhaps these roots are buried beneath the dazzling array of technological applications, ignored under the snow.

This is not the case for the general public, however. For them, these hidden roots remain active, fuelled by questionable popular approaches or fanciful interpretations, still capturing attention in bookstores or the media, often generating much confusion. The public asks questions, they are curious; the physics students, on the other hand, are silent and calculate - when they are able.

[1] In the original lines of this ballad, we changed the word "five" in "hundred" to adapt their meaning to the centenary of quantum mechanics.

For its part, quantum mechanics has aged remarkably well over its century-long lifespan. Alongside relativity, it remains one of the two fundamental pillars of theoretical physics, providing the framework upon which all our theories are built. In recent years, particularly with the advent of the so-called second quantum revolution, it has shown great promise in harnessing its principles and peculiarities to create an entirely new generation of technologies with potentially enormous impacts in various fields. Not that it has not already been practically useful in past decades; while initially "serving" mainly to clarify certain delicate physics issues, it soon revealed its immense potential for technological applications: transistors and lasers truly reshaped our world. Even today, it continues to demonstrate its incredible versatility and power in areas such as quantum cryptography and quantum computing.

It is therefore no surprise that much of the research is aimed at technological advancements, and that physics degree programs tend to emphasize the applied aspects of quantum mechanics over the epistemological ones. As a consequence of this approach, we increasingly encounter academic proposals to transform calculus into applied calculus courses, reduce university credits dedicated to analytical mechanics, or even diminish or eliminate relativity courses from undergraduate programs due to their limited practical applications.

This trend brings with it a widespread lack of cultural and historical awareness, as well as an epistemological deficiency, among students and young physics graduates. Such a deficiency not only hinders a deeper and more meaningful understanding of physics in general but also of the specific disciplinary content being taught. It also provides a conceptual framework that is largely incoherent and decontextualized. And without context, true understanding is impossible...

Science is now widely regarded as highly important for society, but its more human and profound aspects - the ones that, like art, can touch the deepest chords of the human soul - are still not truly taken into consideration. While science is often seen as more useful than the humanities, and perhaps more appreciated in this regard, it is valued primarily for its practical aspects. This is concerning, especially given the increasing, and entirely appropriate, focus on ethical issues and the dangers associated with the misuse of knowledge. As a result, scientific disciplines are often regarded with a certain degree of apprehension (Giliberti & Lovisetti, 2023).

In this situation, we believe that a proper understanding of the Nature of Science (NOS), its methods of knowledge, its values, and its convictions, is essential for an accurate grasp of scientific content. In fact, we believe that the NOS should be considered in teaching like a fundamental scientific topic itself, indispensable for understanding other concepts.

In this, attention to the cultural dimensions of physics can be of great help. One of the primary cultural aspects of physics lies in its drive to transcend conventional thinking, to break through the ordinary interpretation of reality, and to recognize that questions which seemed meaningful for centuries are, in fact, meaningless. Attention to the cultural aspects also helps to overcome simplistic *clichés* that breed mistrust and provoke emotional reactions.

So, we are encouraged to wonder whether the importance and utility of quantum mechanics or society is primarily limited to its technological applications, or whether there might also be an important cultural, and perhaps even moral, value of the theory.

This is not a rhetorical question. In fact, many physics graduates struggle to meaningfully articulate how physics contributes to culture beyond stating its importance for technological advancements and a generic statement about the knowledge it has provided about the world. However, they often fail to express any personal, social, moral, political, or artistic value that comes from this understanding.

Among over a hundred master's students in physics and about fifty doctoral students we surveyed, none could provide a meaningful answer beyond vague statements such as "it has changed our worldview"; how, why, and with what consequences remained largely inexpressible for most.

Research in physics education has yielded a very clear result: the traditional structure of disciplinary knowledge, as typically presented in textbooks, does not provide the most effective framework for learning. To motivate students and foster comprehension (including an understanding the NOS), a profound revision of the framework that shapes the knowledge we call physics is necessary, along with reflection on the role of teaching (Giliberti, 2021). In this revision and reconstruction of teaching, the history of the discipline can play a vital role.

2. Research on the knowledge of elements of history among physics students and graduate students at the University of Milan

The same physicists who struggle to express the cultural significance of physics often lack knowledge of its history. This ignorance is widespread, and found at all levels: among undergraduate students, master's students, PhD candidates, postdoctoral researchers, and even graduates who become teachers, as revealed by several open-ended questionnaires we conducted over the past three years at the University of Milan regarding the history of quantum mechanics.

But after a hundred years, we find ourselves returning to the roots of our knowledge, once again hearing the waters of culture, "rolling from their mountain-springs". These waters, once flowing underground, now surface "with a sweet inland murmur", reminding us anew of the role of universities and their traditions in sustaining and promoting culture in society. This murmur is the sound of students in the corridors, the increasingly fervent voices of dissatisfaction from our graduates who question the value of what they studied, despite their devotion to their field; it is the lesson of our teachers, growing ever more desperately hollow.

Especially in this moment of great social disparity, which has become untenable, focusing almost exclusively on tangible matters is a dangerous temptation. As it is written in Deuteronomy "He made you experience hunger... to help you understand that man does not live by bread alone, but that man lives by every word that comes from the mouth of the Lord" (*La Bibbia...*, 2005, p. 346). We live by the Logos, by words, by language - both mathematical, abstract language, and the language of the heart - which gives meaning and fills us with awareness. When symbols no longer speak to us and words are not understood, even the most moving poetry becomes the barren ground.

As a research group in physics education, we have been working for years on methods and strategies to meaningfully introduce quantum mechanics into high school curricula and non-STEM undergraduate programs. As part of this research, we posed the following questions to 184 undergraduate and 113 master's degree students in physics or mathematics, to 47 PhD students and early-career researchers, and 162 high-school teachers:

1. When was quantum mechanics first formulated as a theory?
2. Which scientists contributed the most to the birth and initial development of quantum mechanics?
3. How many different formulations of quantum mechanics exist?
4. When was the "bra-ket" notation introduced?

For question 1, only 5% of respondents answered "1925", which is the correct answer. The most frequent answers were "1900", "1905", and "1913", with only 16% providing a date from the 1920s. In our view, these responses do not simply (or only) indicate a lack of historical knowledge. In fact, they reveal a conceptual issue, highlighting how many physicists fail to differentiate between a series of models, such as Planck's blackbody model (1900), Einstein's explanation of the photoelectric effect (1905), or Bohr's hydrogen atom model (1913), and a fully developed theory.

This confusion is probably also due to the use of the term "old quantum theory" to refer to this earlier set of models: the old quantum theory, despite its name, is not properly a theory but rather a collection of *ad hoc* models proposed between 1900 and roughly 1924. Moreover, this "terminological" issue also persists in schools, where the term "quantum mechanics" is often used to refer to the old quantum theory or, more generally, to quantum physics, without making the necessary distinctions. Nevertheless, the responses we obtained clearly show a lack of awareness of these distinctions. This historical gap may also affect the conceptual understanding of the physics involved.

Regarding the answers to question 2, the most common responses were Planck, Einstein, Bohr, and Pauli, followed - though at a considerable distance - by Heisenberg and Schrödinger. Surprisingly, no one mentioned von Neumann, who provided the first rigorous mathematical foundation for quantum mechanics in his 1932 book *Mathematical Foundations of Quantum Mechanics* (von Neumann, 1932). This remarkable work formalized the principles of quantum mechanics using operator theory on Hilbert spaces, a mathematical framework that remains the standard way of presenting the theory more than ninety years later. Similarly, Born, despite his crucial contribution to the probabilistic interpretation of the wave function, was not mentioned even once. Dirac was mentioned by only 7 respondents, and only as a secondary figure, far behind others considered more important.

As for the third question, 39% of respondents believed there is only one formulation of quantum mechanics (some even explained that there is no distinction between Heisenberg's matrix mechanics and Schrödinger's wave mechanics "because they are equivalent"), which is somewhat akin to saying there is no distinction between the Lagrangian and Hamiltonian approaches in classical mechanics because they are physically equivalent. Another 53% chose two formulations (those of Heisenberg and Schrödinger). Only 5% recalled Feynman's path integral formulation. Wigner, Dirac, and Jordan, those evidently lesser-known figures, were never mentioned, nor was de Broglie-Bohm's pilot-wave formulation.

Regarding the responses to the fourth question, it is interesting to note that 86% of respondents believed Dirac introduced his bra-ket notation before the theoretical formulation of quantum mechanics, while in reality, it appeared only in 1939, fourteen years after Heisenberg's pioneering paper.

3. On the opportunity of history of physics in education

Is all of this just pure rote learning? From our perspective, no. On the contrary, the responses summarized above highlight significant gaps, not only from a historical point of view, but also conceptually, and culturally (in a broad sense), in the understanding of the NOS. Culture is what brings knowledge to life, and knowledge is what allows culture to develop, enabling each individual to establish the ethical foundation of their behaviour.

> With an eye made quiet by the power
> Of harmony, and the deep power of joy,
> We see into the life of things. (Wordsworth & Coleridge, 1979, p. 256)

A well-documented history of physics, accompanied by an accurate and rigorous treatment of scientific content and a teaching method that encourages active learning, should help bridge these gaps, playing a crucial role in improving our understanding of both physics and the NOS.

First, a critical study of the history of physics helps us recognize how certain key events are often presented incorrectly or imprecisely in textbooks. An example of this is the alleged Rutherford gold foil experiment which, although well-known to all physicists, did not occur as commonly described in texts (Leone, Robotti & Verna, 2018).

The knowledge of the formal structure of quantum mechanics, on the other hand, helps us understand that commonly used phrases like "electrons behave sometimes as particles and sometimes as waves" are not supported by the theory. From a theoretical/conceptual standpoint, the state of a system is always described by a vector in Hilbert space, regardless of which experiment is being described.

The combination of history and formal theory also helps us understand how and why questions of dualism are truly misplaced. The fact that a beam of matter (such as electrons (Merli, Missiroli & Pozzi, 1976; Tonomura *et al.* 1989) or fullerenes (Arndt *et al.* 1999) exhibits behaviours similar to those of waves or particles does not mean that it is necessarily "composed" of waves or particles; the implication is simply untrue. For instance, in single-quantum experiments, we do not "see" waves or particles, but rather interference fringes that gradually build up.

Studying history should also help us understand how scientific knowledge develops over time, showing the evolution of ideas, how they are tested, refuted, or refined, and how discoveries accumulate to form the body of knowledge that we now consider established theory. More specifically to our topic, Kuhn's concept of a "paradigm shift" can be effectively illustrated through the history of the old quantum theory and quantum mechanics, showing how scientific progress sometimes involves a radical reconsideration of fundamental concepts.

A historical approach would also allow us to see how science is influenced by the cultural, social, economic, and political context of its time. Understanding these influences helps us see science not as an isolated activity, but as an integral part of society, both shaped by, and shaping itself social and cultural changes. For example, it would allow us to understand why the majority of scientists studying blackbody radiation were German, and why this occurred at the end of the nineteenth century. Or why there was such a strong emphasis on observables, and how, starting in the 1930s, the United States became step by step the new centre of world physics, while Europe lost its prominence.

The history of quantum physics also offers an opportunity to reflect on the deep connection between science and technology, where each fuels and strengthens the other, creating a dynamic of continuous growth. Physicists rely on scientific instruments which, when placed within a theoretical framework, act as extensions of their senses, enabling science to progress; in turn, science stimulates technological advancement. Scientific discoveries generate new knowledge, which drives the development of advanced technologies designed to explore natural phenomena more deeply.

Equally important is the link between theory and experiment. It is crucial to examine how experiments such as those conducted by Lenard, Millikan, Stern-Gerlach, and Davisson-Germer were really carried out, describing in sufficient detail the apparatus used, the procedures followed, and the results obtained. These "details" are not mere technical aspects but are central to a deeper understanding of physics and its development.

Furthermore, the history of physics is rich in extraordinary successes, but also in errors and misunderstandings. Studying these failures teaches us the importance of experimentation, critical thinking, and continual revision in the scientific process. It shows us that the development of physics (and science in general) does not follow a linear path but is marked by setbacks, changes in direction, and reconsiderations. This is particularly evident when considering the numerous "pre-quantum" atomic models preceding Bohr's, such as those proposed by Kelvin, Perrin, Lenard, Thomson, Nagaoka, Jeans, and Rutherford.

The study of history also helps us understand the complex relationship between mathematical formalism and physical theory, showing how they often develop iteratively and reciprocally. Mathematical tools are sometimes adapted or created from scratch. In some cases, a scientific theory emerges intuitively or heuristically - through preliminary models that do not yet constitute a fully developed theory but represent initial attempts with both strengths and limitations. These limitations need to be analysed and discussed from a physical standpoint. Only later is the theory formalized mathematically into a broader, more coherent framework. In this context, analysing the various models of the old quantum theory and seeing how they gradually led to quantum mechanics offers us an extraordinary opportunity for understanding.

However, this does not mean we should avoid speaking of "wave-particle duality". The term "wave-particle duality" is clearly standard, well-established, and widely used in the literature; therefore, we certainly cannot think of discarding it. However, its meaning must be clarified to avoid misunderstandings. In fact, it does not accurately reflect the behaviour of matter, there is not a "true" duality but rather effects that appear in ways reminiscent of waves or particles. In this case, as well, a more precise and historically informed understanding is essential to avoid misconceptions and to fully appreciate the complexity of quantum physics. Indeed, "culture" also includes an awareness of a series of inaccuracies and terms that are not entirely adequate but are still in use for various, mostly historical reasons.

4. On the use of history of physics by the physics education research group of the University of Milan

As far as we are concerned, we believe that universities should be the driving force behind a transformation that helps to perceive (and not merely declare) physics as a form of culture, starting with how we present our courses to students. Indeed, we believe that there is still a need to discuss tools and methods that promote a specialized and disciplinary understanding of physics for physicists, in order to highlight its deep cultural aspects: ways to foster a cultural understanding of physics for future physics graduates and even for PhD students.

It is also important to create spaces that promote an understanding of the structural connection between physics and society. By "promoting", we do not primarily or necessarily mean focusing on the proper and effective communication of science. Instead, as James Clerk Maxwell once said, we mean, and aim for, cross-fertilization between disciplines:

> I suppose that when the bees crowd round the flowers it is for the sake of the honey that they do so, never thinking that it is the dust which they are carrying from flower to flower which is to render possible a more splendid array of flowers, and a busier crowd of bees, in the years to come. We cannot, therefore, do better than improve the shining hour in helping forward the cross-fertilization of the sciences. (Maxwell, 2011, pp. 743-744)

Many people who have studied physics in school have not encountered enough cultural elements to understand which aspects of it (and why) fascinate a physicist. There is something important missing in our teaching, and we struggle to realize it. This likely happens because we need to look at physics through different eyes - through a metacognitive lens. For this reason, it is also important to place disciplinary aspects within a broader human context.

> I have learned
> To look on nature, not as in the hour
> Of thoughtless youth, but hearing oftentimes
> The still, sad music of humanity. (Wordsworth & Coleridge, 1979, p. 258)

That is why, in recent years, our research group in Milan has undertaken various projects aimed at proposing this cultural view of quantum physics. We have conducted educational experimentations, involving students and teachers from secondary schools and universities, with the goal of presenting the content of physics rigorously, integrating historical aspects, and promoting critical reflection on the birth of the old quantum theory and the early developments of quantum mechanics.

For example, we conducted three trials (two in-person and one online) focused on the old quantum theory and on the construction of quantum mechanics, involving 210 high school students and 93 teachers. These trials were also reinterpreted for university-level courses, with 59 master's students in mathematics or physics.

During the lessons, we proposed a series of experimental activities (e.g., experiments with spectral lamps, determining the charge-to-mass ratio of the electron, or using thermal cameras), as well as guided readings of 24 excerpts from original scientific papers. We also organized numerous 10-minute group activities that required active reading and comprehension, using a conceptual inquiry approach to theoretical tasks.

The main goal was to present physics content rigorously and coherently while reflecting, through a multimodal approach, on the significant cultural impact of the gradual emergence of the old quantum theory and the early developments of quantum mechanics. The aim was to help create a framework that fosters critical thinking, while also providing a cultural and thoughtful perspective on quantum physics, highlighting key disciplinary and learning challenges specific to the subject.

Through various types of assessments, including all group work, individual in-progress tests, and a final exam with 10 open-ended questions that had not been previously addressed or discussed during the course, we evaluated students' average marks (using an evaluation grid traditionally employed at the school level), their ability to connect different ideas in a given context (Knowledge Integration Construct) (Liu *et al.* 2008), their level of critical thinking, and their understanding of the NOS. Comparing their results with those of control groups who followed a traditional approach, we found that the participants in the experimental groups showed a deeper and more well-rounded understanding of the topics covered, and also recognized the relevance of quantum physics for their cultural development.

At the heart of all these activities is a thorough and comprehensive historical reconstruction of the old quantum theory and early quantum mechanics, which gave birth to a book (Giliberti & Lovisetti, 2024). This reconstruction is the result of an in-depth research of approximately 800 primary sources, rigorously read in their original language and translated specifically for the reader, alongside around 300 secondary sources.

The historical account, which serves as the central thread of the entire book, has been enriched with comments, examples, and explanatory notes of a pedagogical nature, aimed specifically at "curious minds" at the university level - primarily, physics students and researchers in quantum physics. The inclusion of pedagogical and didactic insights within the historical narrative is intended to provide a broad cultural context that facilitates the understanding and contextualization of the physics discussed. This approach not only aims to deepen comprehension but also to stimulate natural curiosity and the desire to explore the various issues related to quantum physics. Additionally, at least in our view, it offers a concrete vision of the cultural significance of quantum mechanics.

The goal of this book is therefore to enable readers to gain a deeper understanding of the answers provided by the physics of the time - specifically, what they tell us from a physical standpoint, why those answers emerged, and from what experimental facts or theoretical aspects they were derived. However, we also hope to offer readers the opportunity to discover and grasp the questions physicists of that era were asking - questions that, in traditional quantum physics courses, are often overshadowed by a focus on the answers alone.

> [I am] well pleased to recognize
> In nature and the language of the sense,
> The anchor of my purest thoughts, the nurse,
> The guide, the guardian of my heart. (Wordsworth & Coleridge, 1979, p. 260)

Bibliography

Arndt, M., *et al.* (1999). "Wave-particle duality of C_{60} molecules", *Nature*, 401, pp. 680-682.

La Bibbia di Gerusalemme (2005). Bologna: Edizioni Dehoniane Bologna.

Giliberti, M. (2021). "Stories and Theatre for Teaching Physics at Primary School", *Education Sciences*, 11(11), pp. 696-709.

Giliberti, M. & Lovisetti, L. (2023). "Quousque tandem?", *Giornale di Fisica*, 64(3), pp. 191-211.

Giliberti, M. & Lovisetti, L. (2024). *Old Quantum Theory and Early Quantum Mechanics: a Historical Perspective for the Inquiring Reader*. Cham: Springer.

Leone, M., Robotti, N., & Verna, G. (2018). "'Rutherford's experiment' on alpha particles scattering: the experiment that never was", *Physics Education*, 53, 035003.

Liu, O.L., Lee, H.-S., Hofstetter, C., & Linn, M.C. (2008). "Assessing Knowledge Integration in Science: Construct, Measures, and Evidence", *Educational Assessment*, 13(1), pp. 33-55.

Maxwell, J.C. (2011). *The Scientific Papers of James Clerk Maxwell*, Cambridge: Cambridge University Press.

Merli, P.G., Missiroli, G.F. & Pozzi G. (1976). "On the statistical aspect of electron interference phenomena", *American Journal of Physics*, 44, pp. 306-307.

von Neumann, J. (1932). *Mathematische Grundlagen der Quantenmechanik*. Berlin: Springer.

Tonomura, A., *et al*. (1989). "Demonstration of single-electron buildup of an interference pattern", *American Journal of Physics*, 57, pp. 117-120.

Wordsworth, W. & Coleridge, S. (1979). *Ballate liriche*. Milan: Arnoldo Mondadori.