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Article

An Inclusive Approach to Teaching Quantum Mechanics in Secondary School

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Abstract: Quantum physics is not only a fundamental part of physics education per se but could offer an opportunity to develop cultural tools also relevant outside the boundaries of physics, for instance helping raise awareness about basic cognitive patterns or providing a model for how science works and grows. Given this kind of significance, when it comes to teaching quantum mechanics in secondary school, instructors should be as inclusive as possible; rather than working out its mathematical or technical aspects, which ultimately may turn out inadequate at this level, they should try to make sense of the subject, so that students not oriented toward a STEM-related career are also given the possibility of appreciating the cultural depths reached by physics. Therefore, based on my experience with numerous classes and by making broad reference to the philosophical discipline of hermeneutics, I argue that quantum mechanics represents an invaluable opportunity for each and every learner to broaden and enrich his or her set of cognitive tools with which to make sense of both the outer and inner world. An essential but decade-long qualitative survey clearly shows that by approaching quantum physics with this purpose, all physics and science itself acquire a new relevance in students' and society's eyes.

Keywords: inclusive physics teaching; teaching quantum mechanics; hermeneutics and science

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1. Introduction

Quantum mechanics (QM) stands as one of mankind's great intellectual achievements. It represents a way of calculating the properties of the natural world at the microscopic level, a domain where both classical mechanics and electromagnetism, otherwise strikingly successful for a range of ordinary experiences, have been proven inadequate. It also constitutes the paradigmatic basis for industrial applications, which contribute a considerable share of the gross domestic product of many industrialized countries [1]. Hence, QM may be considered an indispensable subject to be taught not only to STEM undergraduates but as a general background for all future citizens.

Having acknowledged this broad perspective and the fact that QM is already included in many secondary school syllabi across various countries [2], the question arises as to what and how QM should be taught. This problem has been tackled by several scholars over the recent decades, yielding a variety of proposals, rich but not lacking contradictions and incompleteness. For example, some studies [3] show a certain level of consensus about which aspects should be taught, but even this is not at all undisputed [4]. In terms of teaching strategies, proposals range from the historical perspective to the mathematical approach, to the computer-simulated and conceptual ones (for a review, see Ref [3]). Furthermore, the question actually concerns not only the secondary school level, e.g., Refs [5–13], but also the undergraduate university level, e.g., Refs [14–17]. It also cannot be overlooked that even when a carefully designed approach is used, it fails to make students understand the basic aspects of QM, thus prompting scholars to question whether QM should really be taught in high schools [10]. In conclusion, there is a need to investigate further and from different points of view [11].

My argument stems first of all from the recognition that all of the above studies implicitly set their horizon within the context of physics education rather than of education itself, namely assuming as an exclusive goal that of introducing each and every student to the quantitative description of the natural world, with the more or less explicit assumption that this would serve the sole purpose of developing future technologies (this is indeed the reason for the various warnings about the perspective of an insufficient number of scientists and engineers, as in Refs [18,19]). Hence, teaching physics (and thus also QM) would have as its only goal bringing out the talents of those young people destined to obtain a degree in a STEM field, while for all the others, it would have no particular role, except perhaps to give a basic scientific smattering doomed to remain unused.

In reverse, I will take here a more general point of view, that is, starting not from the objectives of physics teaching but from those of teaching tout court, thus addressing the problem of the effectiveness of teaching physics (and QM) not in those secondary schools that have a specific focus on science but at the high school level in general, thus including students who are not particularly interested in physics but still receive mandatory instruction in this discipline.

It is worth further grounding this distinction by referring to Roberts [20,21] who showed how there are basically two sources for the curricula with which science education is being pursued, two conflicting "visions". On the one hand, there is the scientific discipline itself, with its specific practices and products that constitute a complex of professional competences (Vision I); on the other hand, there is the complex of cultural, economic and social situations in which science takes part (Vision II). When one asks oneself what the knowledge and competences of a scientifically literate person consist of, one finds oneself choosing between these two visions. The approach described here is undoubtedly in line with Vision II, in that it does not pursue the acquisition of skills that can be used professionally (although it does not exclude this) but with the specification that it primarily emphasizes the area of personal culture, rather than that of scientifically informed "citizenship".

If we define "personal culture" as the acquisition of cognitive tools deployed to make sense of everyday life experiences, I argue that learning physics should be valued first and foremost as a way to contribute meaningfully to the construction of one's personal culture, i.e., as a peculiar opportunity to educate the student as a person rather than as a potential scientist. The possibility of teaching QM according to such a vision has been so far virtually unexplored, although there are many testimonies, even at a very intellectually high level, of how QM can give rise to deep cultural and human implications, that is, to borrow Kant's terms, not in a constitutive manner—i.e., not as a naive mumbo-jumbo equivocally at the disposal of those who would like to use science to provide foundations for truths or certainties that science cannot actually provide—but in a regulative manner, i.e., as an ideal direction of thought that can suggest new speculative horizons, as for example in psychology and theology [22–24], or provide unusual interpretive keys in other scholarly fields (e.g., Refs [25,26]).

To this end, I will first start with a premise by framing the typical secondary school's organization and by arguing about what the real outcomes of general education should be and how and to what extent physics teaching—and in particular QM—conforms or can conform to them. Then, I will suggest how to present QM as a framework rich in opportunities for the development of hermeneutic tools available to all students, i.e., broadly speaking, as a chance to stimulate production of meaning and cross-disciplinary critical thinking. I will provide a concrete item-by-item schedule of a QM class with explicit examples and hint at the results that can be achieved. Finally, the outcomes of such an approach will be assessed and the whole problem summarized.

2. The Actual Framework Situation

In order to elaborate a meaningful teaching proposal that could be effectively carried out in schools, one has to take into account as unambiguously as possible the "boundary conditions". To this end, I provide here a real-life school situation, which could easily be generalized and hence work as a paradigmatic example. This might appear perhaps too detailed, but it is really worth making it explicit once and for all.

The Italian secondary school system (grades 9th to 13th) consists of a variety of educational paths, which share a core of basic disciplines and allow subsequent enrollment in college. Other subjects are more specific to the line of study of each school (e.g., scientific, humanities, modern languages, etc.). As a consequence, all students are normally immersed in a large number of disciplines on a daily basis. For example, students such as those I used to teach (grades 11th to 13th of the humanities and modern languages lines of study) have 7 hours (each "hour" is $50'$) of classroom lessons a day, Monday to Friday, for a total amount of 35 hours a week, distributed among 12 different compulsory disciplines (plus one optional, Religion), with a weekly timetable that remains the same for all the 35 weeks comprised in a school year. Thus, students have to constantly split their minds and shift their focus from subject to subject. Moreover, sometimes, teachers divide their time slots into subdisciplines (such as English Literature and English Grammar), raising even further the total number of different syllabi a student should keep constantly in contact with. Each teacher assigns homework and periodically holds written and/or oral tests; therefore, once home, the student must again switch from one subject to another in order to be ready for the next day. In this clogged context, an average of two hours a week is allocated to physics (three hours if the line of study is scientific). This would result in an official total amount of 70 physics hours for every school year, if there were not also other compulsory activities that are not assigned a specific time slot in the timetable and must therefore be accommodated at the expense of the ordinary disciplines (week- or day-long field trips, conferences about health and behavioral issues, etc.). Eventually, the total amount available for teaching physics adds up statistically to about 50 hours of actual lectures per year. These lectures include experimental demonstrations, classwork and testing. Since electromagnetism is by far the main subject of the 13th grade physics syllabus, a goodwilled teacher may arrange things, so that it is compressed to about 40 hours, therefore with 10 hours left for modern physics. After having said something about cosmology and nuclear physics—it is unthinkable not to give future citizens a basic explanation of the great horizons opened up in these fields—that willing teacher would have a small treasure of 8 invaluable hours to teach QM, thus far from some proposals, as in Weissmann et al. [13] and Levrini and Fantini [27], of 25–30 hours, which are realistic only in scientifically oriented schools, not to mention projects consisting of as many as 80 lessons [28].

Furthermore, it is crucial to also pay attention to what real students are rather than what they are supposed to be (see "actual" vs. "implied" student in Refs [12,29]). Typically, Italian high school students approach physics from classical kinematics and the three laws of dynamics (between grades 9th and 11th, depending on the school's line of study) and then move on to energy and momenta and their respective laws of conservation, followed by thermodynamics, mechanical waves (grades 10th–12th) and ending with electromagnetism (grades 12th–13th). According to the Interministerial Decree n. 211 [30] containing the national indications, some modern physics, to be offered in the last grade of high school (13th), is at least "advisable", but it is traditionally often the case that teachers lack the time to teach it, especially in schools where physics does not represent one of the main subjects. To put it bluntly, from my long-term experience as an examiner in high school state exams, most teachers in schools where physics is not a mainstream subject end their 13th grade program with Faraday's law of induction or rarely make it up to electromagnetic waves.

One should also notice that 13th grade students have already extensively practiced basic algebra for years, but a good many of them still feel quite uncomfortable with it. There is an evident lack of transfer of knowledge; even solving a first-degree equation could be a daunting task if given in a context slightly different from that to which they had become accustomed. This should warn all those scholars who advocate a mathematics-based teaching of QM. For example, Pospiech [7] supports the idea that a minimum of mathematics is indispensable for teaching QM to high schoolers and that this could be kept at an elementary level (an approach I may even endorse); subsequently, however, the Pauli matrices would start to be introduced, which contain the imaginary unit i, i.e., something, which is not included in most high schools' mathematics syllabi. However simple it may appear to experts (especially those who have never taught in a high school), *i* does not sound simple at all to students. Many of them would be immediately scared by it, whereas the remaining ones would be content to be told how they must operate with these matrices just in order to pass the final test and then move on with their lives as if QM never existed.

For all these reasons, the concrete teaching of QM turns out to be heavily constrained in several respects. This basically implies that: (i) physics teachers must keep in mind that their students have much else in which they are required to invest their intellectual efforts; (ii) as a consequence, physics lectures must be as striking as possible, for example by containing a "take-home point" for each and every student; and (iii) since a large majority of students will not enroll in a physics course after high school, these physics lectures are the very last chance to convince them that physics nevertheless serves as a valuable contribution to their general education and personal culture.

Beyond the details, which, so as not to be vague, I have formulated with reference to a specific type of (Italian) high school, the essence of this description can easily be extended to a wide class of situations, whether in school or even university (I am thinking of physics classes in arts or humanities degree courses) or in the field of popularization: little time available, an audience with poor mathematical background, lack of emotional involvement toward science.

3. A Paradigm Shift: Teaching QM Culturally

Given the above constraints, teachers can still choose between several possibilities for approaching the teaching of QM. Their choice depends substantially on the answer they give to the question of what the goals of physics teaching are: to start training those who will pursue a science degree in college; to develop habits toward systematic study and memorization; to foster the acquisition of the value of observation and reasoning; to train consequential thinking and modeling; to develop problem solving and the usage of formulae; to be aware of the structure and functioning of the physical universe.

These might all be good and advisable reasons. On the one hand, each of them deserves respect and surely sooner or later plays an important role in education. On the other hand, intellectual honesty bears the objection that, for students not aiming toward a STEM-related career, most of the physics content and attitudes, if ever learned, are eventually quickly forgotten, and even in case they are retained, "students fail to see meaning in crucial scientific ideas, though they may be competent enough in first-order knowledge and technical manipulation" [31].

It has been shown how physics presented as a list of formulae and concepts without in-depth study has the effect of alienating students [32]. The students' minds must therefore be engaged, called into action. One limitation, however, is doing this by remaining within physics, when instead the step to be taken—at least when teaching at a general level—is to bring the topics to life in the imagination and in the daily life of the student across the board, as tools capable of revealing new aspects of our world, for example, even as conceptual metaphors.

Indeed, in order to achieve formative success, the meaning of what one learns has to be explicitly pursued and addressed. This is all the more true in the case of teenagers, who live in a stage of cognitive development well described by Egan as "of philosophical understanding" [33] (pp. 118–136), i.e., characterized by the search for connections, the construction of schemes that join facts concerning different domains. Learning works when it bestows meaning on things, that is, assigns to every thing its place and its interconnections in the ever-growing network, which is one person's life. In this sense, "Learning is a search of meaning" [5].

Let us look at what happens in high school teaching in this respect. Within the humanities, students are introduced to novels (such as Shirley Jackson's *The Lottery* or Anton Chekhov's *The Kiss*, just to name a few) not because they are propaedeutic for those who plan to graduate in literature and become professional literary critics but because they help readers—any reader—gain insights into their own life. As is well known, philosophers have made a distinction between sciences and letters by highlighting their diversity of approach, respectively, that of "understanding" and "explaining" [34]. Humanities would lead us into understanding because they provide references that have the power of conferring meaning on things, events, individuals and their mutual relations. Thanks to this power, subjects such as history, literature, art and philosophy are regarded as cultural assets because they provide the conceptual tools (materialism, idealism, objectivity, subjectivity, etc.) and categories (grief, hope, resilience, etc.), which a person or a society refers to in order to understand the world. When we understand something, it is as if we come into possession of a key that opens up a world that relates to our inner world.

What about physics? Notoriously [35], physics is almost never considered from this perspective, neither by the physicists, scientists and teachers themselves nor by the literates, citizens and, in particular, students. Within the dominant paradigm of physics teaching, physics is not expected to be something able to add meaning to one's own life. Physics is perceived as an "irrelevant" [36] subject, "sterile and impersonal" [37]. What do the students mean by this? Perhaps they are not aware that without physics there would be no new technologies? No, the irrelevance is that in relation to the world of their interests. In Schrödinger's words, science is "ghastly silent [. . .] and sundry" [38] (p. 93). There is no possibility of understanding because "we do not belong to this material world that science constructs for us. We are not in it, we are outside" [38] (p. 94). Physics concepts are confined to the realm of explaining, i.e., that of a causal connection between objects from which any reference to the subject who formulates it is excluded.

However, if these concepts are deemed unable to meet the longing for understanding, what will our students—future lawyers, clerks, artists, journalists, etc.—do with them but forget them as soon as possible? Because students do not feel engaged at the level of the self, physics concepts are lived passively and accompanied by a feeling of indifference, dislike or even hostility.

Things appear even worse if the teaching of QM would consist only of a mere "shut up and calculate". If this approach has been proved quite disappointing even for physics students at the university level [17], what should we expect from a generic high school audience? As had been remarked, even in the optimal case where they actually learn how to reproduce a standard procedure, repeating exercises over and over with this "plug-and-chug" philosophy would not lead to any deeper comprehension. "Once students learn how to do problems of a particular type, many will learn nothing more from doing more of them: new problems are done automatically without thinking" [39].

It is necessary, then, to ask whether it is possible to teach physics in a way that engages the level of understanding and reveals physics as a field with some cultural propulsion of its own.

To begin with, as has been shown (e.g., Ref [40]), the understanding-based approach cannot be considered for the exclusive use of the humanities. For instance, if the subject of a physics lecture changes from the calculation of a wheel's angular momentum to cosmological themes, the class's level of attention increases, and the disdain drops. This is because the latter argument implies a higher level of connection with one's own self. However, with a little creativity and proper attention to the language and general structure of physics concepts, this operation of approaching physics from the standpoint of understanding and meaning can also be accomplished with many other topics in the syllabus. Arguments that, at their face value, seem to have nothing to do with the great themes of human existence can indeed be accessed through different perspectives, so that they become keys capable of opening new mental horizons.

Thus, what should be done to make school-taught physics an opportunity for cultural enrichment for all? Its great imaginative power must be delivered in such a way, so as to bring out its hermeneutic value, that is, trying to strip it of its technical aspects in order to export it to other fields, closer to the inner life. To give an example, if a teacher talks about interactions between molecules, showing the formula and the graph highlighting their characteristics, s/he can deliver the lesson through consideration of the concept of interaction in general, e.g., that between humans, and how this may or may not depend on distance or any other factors. In the students' eyes, those molecules now have something to say, making us reflect on ourselves and our being in the world. This is where the concepts of physics become hermeneutic tools, i.e., mental schemes capable of shedding new light on our experiences and of organizing knowledge in a meaningful way.

Furthermore, this paradigmatic change in approaching physics is also necessary from the perspective of efficiency and inclusion. Physics too is called upon to contribute to an education for all, not just a few, also considering the goals of the United Nations' 2030 Agenda [41]. Then, such an approach would also be a matter of social justice and of using the investments in physics education to the maximum. Teaching physics with a one-dimensional attitude, which is directed only at STEM-oriented students, is indeed a highly inefficient process, a waste of resources and a restriction of citizens' right to receive instruction that values their talents and concurs with all their different disciplines for their human and intellectual development. This can be achieved if we consider that it comprises concepts and cognitive tools that possess adaptability and evocative power, which may work as compelling metaphors and generative schemes. More than the contents of physics, it is indeed its language that is formative, in the sense that it shapes the way we think (e.g., Ref [42]). Language is not just a means by which we describe an independent reality, but it possesses a constitutive force through its intrinsic ability to structure perceptions and thoughts. Words are loaded with meaning; they evoke certain states of things; they bring allusions. This is exemplarily shown by physicists themselves, who happen to appeal to references such as "asymptotic behavior" or "first-order approximation", to name but a few, also outside their professional life. Such use is not just jargon employed for fun but an effective way of conferring meaning to things and facts. When physics-educated persons say "approximation" in ordinary life, it is because they see things differently to persons who have not been instructed in physics. The meaning they associate with this word differs significantly in power and effectiveness from what a non-physics-educated person could do. Concepts such as "asymptotic behavior" or "first-order approximation" are powerful images; they imply the opening of new possibilities of thinking (*Denkmöglichkeiten*). Including the words of physics and their underlying concepts in one's vocabulary increases the complexity of one's grip of the world and does so in a way, which is not that of law or art.

Returning to the issue of what and how to teach physics, since the language of adults is influenced by the educational path they followed as students, the point is precisely that physics should be taught, so that it may count among the subjects that have left their imprint. Even if these adults never refer in their professional life to the physics' contents they learned back in high school, nonetheless, we may consider their physics education successful and efficient if some schemas of physics persist like a shadow in their everyday cultural state of mind.

Therefore, I strongly support the idea that physics education at the overall pre-university level should be regarded as a learning path whose main goal is helping young people come into contact with a multiplicity of cognitive tools and to test their effectiveness in creative ways—for example, by making parallelisms between disciplines or transporting the patterns of physics into the literary or artistic world and vice versa [43,44].

Science teachers should, therefore, reconsider the very core of their discipline as a framework that not only constitutes a solid basis for the explanation of nature and the development of technologies but that also adds value to the cultural competences of the person. When faced with a class of students representing a wide spectrum of interests and talents, they should make the effort to articulate physics from multiple points of view. In this sense, all teaching should not just be about saying things while an audience listens; this presupposes both disciplinary competence and the establishment of a human relationship. Teachers should try to reach as many "gray areas" as possible [39], so that physics becomes a more inclusive subject for students who have no interest in sciences. This implies the effort of finding common ground with students and the ability to devise the most appropriate analogies in order to extrapolate a core message from every subject, making it exportable and linkable to other areas. Since physics concepts possess a force that goes beyond their area of application, physics teaching should aim at building structures that turn out to be useful for students' future life and learning, regardless of whether they will become physicists or not. This way, teachers would stand as interpreters and originators of culture, more as renaissance polymaths and less as dispensers of formulae and technical details, which are useless to most.

Having made this elucidation on education and physics teaching in general, what does it imply in terms of the teaching of QM specifically?

QM may be precisely the driving force for this paradigmatic change in physics teaching. Indeed, QM's concepts explicitly call into question the analysis of topics (such as measurement, observation, the status of reality and its relationship with theory . . .) more strongly than other branches of physics do. By doing so, QM invokes precisely the plane of understanding. Hence, QM's concepts possess an intellectual design and an analogical value, which make them appealing outside their proper scientific use. Because of this, in the eyes of non-specialists, QM has the potential to redeem all other topics of a physics syllabus.

Therefore, the instructional model I propose for teaching QM is based on the principle that teachers must bear in mind that the content of the lesson reaches the student if the potentiality of a meaning is stuck to it. This occurs if they are able to explore a multiplicity of words, metaphors, mental models, references. QM becomes an exceptional endeavor, which tests the cultural depth of science educators, challenges them to develop their language and to build bridges with other topics.

4. Examples of QM's Hermeneutic Potential

Let us now see explicitly how quantum mechanical concepts can trigger reflections that elude from the technical side of physics and become meaningful at the overall cultural level. The following examples (each step corresponds to about a one-hour lesson) are taken from my own practice and are just a subset of those aspects that arise more frequently or that I find more appealing. Of course, depending on the feedback and the various interests of a class, emphasis could be put on one aspect rather than another. In all cases, an approach that may be broadly defined as "narrative" should characterize the unfolding of the arguments. Among the well-defined features of narration (for narration in science teaching, see, for example, Refs [45,46]), I stress here its transformative power; students should enter the classroom with a certain set of cognitions and values of any kind and degree and should leave with these altered, affected or at least challenged. This occurs more effectively when the great themes of humanity (i.e., the understanding approach) are kept as the background of the narrative.

- Step 1: "Merry skies with clouds". Introduce the situation of physics at the end of the XIX century, when practically all of nature was considered explained by mechanics and electromagnetism but "two clouds", i.e., a satisfactory explanation of the photoelectric effect and black body radiation. Apart from these, it was thought that only better measurements and a more precise determination of the constants remained to be carried out. The qualitative description of the two phenomena can be given to the class with no formula required but by using simple wording and drawings. Comment on how the most brilliant intellectuals may also have a vision constrained by the canons of an era. Describe Karl Popper's idea of the working of science as falsification attempts [47]. Unsolved problems are not an adversity; they are rather an opportunity to test a theory and to develop it further. This lesson should not be left as an allusion but must be made explicit and translated into a suggestion for ordinary life. One should not be afraid of criticism (by teachers, parents and friends) because it may represent a precious opportunity for growth.
- Step 2: "Conjecture and corroboration". Contrarily to expectations, the solution of the two anomalies forced the introduction of an idea that had revolutionary consequences: the quantum of light. Some overarching aspects can be presented here. At that time, electromagnetism had just completed wonderful development; after Maxwell's

brilliant work on synthesis, Hertz proved it right. Technological advancements that were unimaginable a few years earlier started pouring into society. Nevertheless, there were these two little problems. Perhaps anyone would have just thought, “Who cares? Enjoy what is working!”. However, scientists are not like that. They are stubborn in the right way because it is only in the details that a theory may show its failures and present a new solution. Moreover, Planck himself was a kind of conservative man and strongly believed in the broad, coherent, explanatory power of classical electromagnetism. However, against all his convictions, he was forced by intellectual honesty to recognize its failure and hence to work out an alternative solution. It is very important to emphasize the idea of science as an ever-growing knowledge precisely because of its positive attitude toward the possibility for correction. A second reflection can be carried out by developing a metaphor out of the rationale of the photoelectric effect, which essentially consists of the archetype of something that comes in and causes something to go out. What matters is to understand which of the cause’s parameters are crucial and which are not. Not only in physics, it is important to take the time to check which variables are the fundamental ones. For example, when a new piece of knowledge comes to our attention, which of its characteristics allow it to be effective on us? Is it “the more time you study, the better it is”, or is it “the better you study, the better it is”?
The third aspect concerns the discretization of a physical quantity. Let the class reflect on the variation of quantities, of various kinds, so as to develop awareness of the two instinctive categories of continuity and discontinuity, which we apply ubiquitously almost without being aware of them. Can you identify events in your life that represent discontinuities?

- Step 3: “Wavy ideas”. The thought-provoking idea by de Broglie: particles show a wave-like behavior. Stress again the experimental corroboration, which should follow any scientific conjecture. Review wave diffraction and explain the work contributed by Davisson, Germer and Thomson. Tell the anecdote of how the two Thomsons, father and son, were both awarded the Nobel Prize, 31 years apart, by giving contradictory remarks on the electron—a particle for J.J., a wave for G.P. This could stimulate a reflection on the relationship between generations, which may all have valuable ideas at the time, even if these appear in contradiction with each other. Some scholars [7] argue that it would be better to avoid using classical references, such as “wave” and “particles”. This suggestion contrasts with cognitive studies, which show that students inevitably already have mental models [48], and learning should not ignore them but rather build on them by successive accommodation. Avoiding these terms would also make it impossible to show how QM emerged from the refutation of classical physics, thus preventing de facto the illustration of the growth of science.
  Mutually exclusive and yet complementary accounts, such as the particle-like and wave-like descriptions of QM, are an archetype, which is not limited to physics. For example, literature also sometimes offers examples of facts described by complementary points of view. In each chapter of William Faulkner’s *The Sound and the Fury*, the narrator changes, and the narrative is irremediably linked to the narrator’s own features and role in society. Analogously, the same quantum object possesses characteristics, which are strictly dependent on the experimental apparatus used to detect it.
- Step 4: “Adopt and adapt”. Describe Bohr’s atom and its characteristics and explain how de Broglie’s hypothesis provided a justification for the quantization of electronic orbits. Why is understanding the atom so important? Report Feynman’s statement about the “atomic constitution of the world” being the most powerful scientific idea in the fewest words [49]. Highlight the use of analogy in investigating things. For Bohr and Rutherford, the solar system represented a convenient structure to be adopted and adapted to the organization of matter at the microscopic level. Encourage students to see the analogies around them and to try to develop some, perhaps between ordinary life and physics models (e.g., not only the electric current and car traffic, but one’s

life goals and the obstacles that stand in the way as resistance). Solicit students to be creative, to also refer to an "adopt and adapt" strategy, each in the area of their preference, to think of examples of this strategy and discuss them together.

- Step 5: "To Ψ or not to Ψ". Quote Schrödinger's attitude toward theorizing and describe pictorially the wave function. Explain the concept of superposition and apply it to the wave function. Describe Born's interpretation of $|\Psi|^2$. Emphasize the problem of measurement in QM and the idea of the collapse of the wavepacket. Illustrate the apparent contradiction between unobserved and observed reality, which are thought of as radically different realms. Ask students what they mean by "reality". Quantum objects do not (or may not, if you like to leave the interpretation of QM open) possess positions and momenta, but rather, they have a potentiality. Recall (or explain) Aristotle's ideas of act and potency at the heart of Western thought. Provide some examples, e.g., the potentiality of every morning when we get up and do not know what the future holds. A wide histogram of possibilities is ideally assigned to each of us by statistics, but which one will be realized and which one will not? Only time will tell, only passing through the day, only experiencing it. The concrete experience of every day—namely, what happens to us, our choices, our life—transforms this potency into reality. The passing of time comes as an uninterrupted "collapse" of potentialities into facts.
- Step 6: "Looks like it or is it?". Introduce Heisenberg's uncertainty principle on position and momentum. Together with the superposition of states of the wave function, it allows a general discussion about two interesting polarities of thought, which are closely related to each other.

  The first polarity is that of the epistemological vs. the ontological level of description. According to Heisenberg's own pictorial description (a measurement necessarily involves an interference with the system being measured), the uncertainty principle seems to concern epistemological limits, that is, the way we know something. Yet, it later acquired an ontological status; it is the particle itself, which has no exact position and momentum. Highlight the subtle, yet enormous difference between the epistemological and ontological content of any information, e.g., in the case of fake news.

  The second polarity concerns instrumentalism vs. realism. Reflect on the nature of science. Is it enough for knowledge to work, or should it also aim to be true, that is, to trace the true state of things? Mention the difference between Galileo's and Jesuits' approaches to Copernicanism [50]; they both used the same kind of calculations, but while the former believed they reflected the real state of things, the latter simply considered them as useful artifacts. Analogously, mention the debate between Einstein and Bohr about the nature of QM. Is it true that a particle is in a superposition of states, or is it just a statistical approximation that we use to overcome our ignorance? In any case, stress that physics is based on quantities, which always imply an experimental counterpart (QM expressly deals with the "observables"). Exemplify by noticing that, according to this attitude, the orbits in Bohr's atom must be considered philosophical prejudices, so that they had to eventually be excluded from the theory. Mention operationalism, that is, the idea that the concepts used in physics must be defined through the operations one puts into action. Consider this stance in comparison with concepts of ordinary life. What is love? What is beauty? Would it make sense to define them operationally too? Would it be possible?
- Step 7: "Electron in a box". De Broglie's thought experiment about an electron in a box [51] (pp. 28–29) may be simpler than the classic Schrödinger's cat to illustrate the contradiction of QM with classical physics (perhaps students will mention the cat anyway; in that case, this further example enlarges a little bit the visual). The description is straightforward (use simple drawings as well): as long as we do not measure it (i.e., open one of the two halves in which the box has been split), the electron is in a superposition of states, described by the wave function Ψ, which

stretches over several thousand miles (i.e., with non-zero peaks in Paris and in Tokyo). The orthodox interpretation of QM argues that this is the actual state of things of nature and not just a statistical, epistemological approximation of it. Thus, when one opens the half-box in Paris, the wave function suddenly collapses, and the electron appears either in Paris or in Tokyo and instantaneously disappears from the other city. This puts some peculiarities (of QM or of nature itself) in evidence, such as non-locality and togetherness in separation, which seem very interesting to explore, even on a metaphorical level. For example, quantum objects appear to follow separate rules for when we are looking at them and when we are not. What about each of us? Suggest a reflection on the difference between our inner life with its fundamental opacity and the outer, measurable life. Interestingly, some scholars (e.g., Ref [52], p. 301) have interpreted the psychological insights gained by the main character in R. Musil's *The Man Without Qualities* as examples of uncertainty manifested in life.

- Step 8: "More contradiction". Explain the double-slit photon experiment [6] by focusing on the evidence that considering quantum particles as having well-defined positions leads to contradictions. Make the class aware of the fact that we always implicitly assign a well-defined position to any object in the world, even if we do not know it. For example, where is your mom? Perhaps you do not know precisely, but you guess she could be 10% at home, 85% at work, 5% shopping, etc. This statistic reflects our ignorance, not that mom is really spread over a multiplicity of positions; it concerns the epistemological level and not the ontological one. On the contrary, for quantum particles, it indeed concerns the ontological level, so that what we unconsciously considered a universal property of things—having a position—turns out instead not to be truly universal. Lesson learned: categories are needed to bestow meaning on things, but it is also important to remember that they may have limits, and one should not forget this when using them. Lead the students into an extrapolation of a universal message from this exemplification—for instance, by letting the class reflect on the use of categories when judging facts and people. Everyday intuitions do not hold indefinitely; even if they work perfectly in our "dimensions", it is not guaranteed that they can be extended indefinitely. This ultimately concerns all our ideas. Even very well established concepts may fail or show limits (e.g., what is a "mother"? We all think we know, until the moment we consider the case of a person born of a woman but raised by another. Which one is the mother, then?).

In each of these examples, I have highlighted only the aspect that I consider innovative and which is the subject of this article. The explanation of each topic is in fact and necessarily composed of further contributions, which have already been the subject of numerous other papers on the teaching of QM (see the references in the Introduction) and which range from the use of computer simulations to the projection of informative videos to conceptual modeling (with formalism always kept to a minimum).

From the point of view of didactic strategy, these lessons are, all in all, traditional, with the teacher holding the lecture and the students following from their desks. At a time when it seems that this type of lesson no longer meets the expectations of the currently prevailing pedagogical paradigm, which prefers more participative forms of educational interventions (group work, flipped classes, etc.), I quietly argue that, in some cases, the traditional lesson form retains its benefits. The first reason is the limited time available; a less traditional type of intervention (from an organizational point of view) would certainly require more time. However, the really essential thing about this approach is that teachers be able to say interesting things, that they get in touch with the intellectual intimacy of their students. If this occurs, even the traditional lecture becomes a moment of active learning, just as reading a book or watching a film that are engaging (and which we can in no way consider as passive activities if they are able to stir mental processes). Active participation is, in any case, stimulated by questions that the teacher will frequently have to ask the audience. Pupils can be left to think about a certain issue, individually or in small groups, for example, in the case of solicitation to provide further arguments for the heuristic application of an idea just presented. As in the case of the uncertainty principle, where an increase in knowledge of one quantity necessarily occurs at the expense of a decrease in knowledge of another quantity, the class can be asked to provide examples where this principle also seems applicable in everyday life and whether it is possible in those cases to find a solution that cannot be found among the quantities of QM instead. If time is really too short, one can leave such reflection as homework. Finally, in what may seem from an organizational point of view to be a traditional approach, it must be emphasized that the physics teacher, as he or she approaches the boundaries of physics and enters the world of life—an area that belongs to everyone and is not exclusive to the teacher's professional training—becomes a little less of a teacher and a little more of a research companion. Then, an atmosphere of shared reflection arises in the classroom.

5. Outcomes and Discussion

School must produce awareness. If it does not, it does nothing. For what use are literature, art and science if not to help the students mature their awareness of the world and of themselves? A critic of the above assumption may stress the fact that there is a great lack of precision and coherence in presenting QM this way. My reply is that a school teacher should not always worry about inexactness, incoherence or incompleteness of his/her teaching. These are not necessarily flaws; ultimately, that is the very nature of knowledge, and when it comes to school education, all that is taught must be reasonably inaccurate in the sense that it is a compromise between detailed and complex academic knowledge and the need to distribute this knowledge in an acceptable and understandable way. Concerning the teaching of QM to high school students, surely, precision is less of a value and more of an impediment to good and inspiring learning. Of course, it should be obvious to both the teacher and students that what is offered in high school is just an introduction to the subject and that once students have become acquainted with the rudiments, those interested will have all the time to refine, sharpen and deepen the subject during their university studies. This is all the more appropriate the less science-oriented the high school is. However, to avoid misunderstandings, it is important for the teacher to point out, repeatedly, that those topics presented are, at the professional level, rigorously accompanied by very careful experiments and mathematical formalism, which makes them precise and controllable. It is also good for the teacher to emphasize the difference between his/her proposal, which is characterized by a critical approach, and certain situations where QM is uncritically and simplistically set up as a foundation for pseudoscientific opinions passed off as scientific.

The approach described here should therefore not be confused with that of oversimplification. It is, in fact, a matter of working out the right "productive forms of complexity" [27], which, taking into account the varied interests of students (of a non-science-oriented high school), need not be evaluated only at the level of conceptual or formal precision. In a generalist school, "complex" would mean being able to offer meaningful intellectual stimuli. The success of such an approach will then be measured not in how correctly students have learned QM but in how much it will have left important cultural traces in them.

A further objection could be that such kind of approach makes it difficult to monitor whether students have acquired new skills or not. Surely, this is rendered much easier if they are taught how to calculate Pauli matrices. My reply is that we need to be careful not to succumb to the paradigm of measurement at any cost, especially when it comes to education. In some cases—and teaching QM falls among these—successful high school teaching is that, which inspires the students, even though it is arduous or plainly impossible to measure the effects of such inspiration. Even when the teacher offers a very thoughtful, coherent path into some subject, this coherence and completeness is rarely appreciated by the student, who is often more impressed by a single thing or concept simply because he or she has their own way of approaching it. Therefore, it may be worth spending more time stimulating the students' own creativity rather than passing them over some predigested knowledge they are never going to digest by themselves. Even surveys such as that of Ref [6], though certainly showing and measuring how to improve the effectiveness of the teaching of QM, are not able to assess how much of this knowledge turned out to have a real impact on the culture and life of students. What would we obtain from a test on QM given to these same students five, ten, twenty years after they had been so well instructed on the double-slit experiment?

The humanistic approach to QM proposed above excludes, in principle, the feasibility of objective, quantitative testing of the contents acquired by the learners. Setting QM as a framework for the development of hermeneutic tools, namely as a topic whose knowledge increases the meaning of what the learners experience around them, is only evaluable on the subjective level and on the long-term scale. Of course, a teacher could still evaluate the results provided by multiple-choice tests, open questions, etc., concerning the specific topics of QM, but what matters for once is the qualitative, emotional feedback by the students. This could be effectively evaluated simply by observing the attention and the sense of discovery that students show during the lectures and the eagerness with which they ask questions. Nevertheless, for more than a decade, between 2009 and 2020, a questionnaire was administered to 8 classes in grade 13, with a total of 114 students, with questions relating partly to the specific topics (which changed from year to year, as mentioned) and partly to the approach. It is precisely these latter questions, despite slight changes in wording, which, nonetheless, allow a small but effective assessment of the impact produced by this hermeneutic approach. They are the following:

(1) "Do you find physics more interesting if it is explained with cultural references?" (on a Likert scale);

(2) "Which part of the whole physics syllabus did you enjoy the most? Why?" (the syllabus refers to the physics course, which lasts three years, from grade 11 to grade 13);

(3) "Did your interest in physics change after you encountered QM? Why?".

Putting all the answers together, even if they refer to slightly differently formulated questions, the following is obtained:

(1) A total of 113 students (99.1%) answered "yes" or "very much" or "more yes than no", while 1 student (0.9%) answered "not at all";

(2) A total of 80 (73.7%) students answered "quantum mechanics" or "quantum physics" (or other equivalent expressions) or "the last part" (i.e., QM); 19 (16.7%) students chose "astrophysics"; 7 (6.1%) students chose "electromagnetism"; 4 (3.5%) students chose "thermodynamics"; 3 (3.5%) students chose "mechanics"; 1 student (0.9%) answered "none". Concerning the motivations, students who answered "quantum mechanics" used words such as "fascination", "interest" and similar ones, and they referred, with different nuances and expressions, basically to the problematization of the concept of reality and to having identified mental schemes capable of stimulating their imagination;

(3) A total of 102 (89%) students answered "yes", while 12 answered "no".

In particular, more than anything else, the expressions used by the students to justify their answers effectively render the type of objective achieved. The comments received over the years indeed have a common denominator, which can be summarized by the expression: "I did not know that physics could be so deep and interesting" (S., class of 2017). Other comments, taken almost at random among dozens of others, attest unequivocally the level of engagement with which the students approached the subject: "I discovered that physics viewed with a little philosophy really becomes a very interesting subject" (M., 2015); "I never thought that something called QM could have anything to do with me!" (L., 2020); "You won't believe it, but I found myself Saturday night asking my friends if they think everything in the universe has a precise position at any given time" (B., 2019); "I thought I only liked art. And I do. But I discovered that you can also have great artistic ideas by studying other things, such as physics, with the right spirit. Thank you!" (C., 2019). All of this demonstrates an unequivocal increase in their involvement with physics and a reassessment of their judgment of physics. In an authoritative study highlighting the poor learning outcome of quantum mechanics [10], the author concludes that students in particular fail to grasp the discontinuity between classical and quantum mechanics, i.e., they do not show the expected “state of shock” due to the discovery of an “alternative worldview, which challenges some of the fundamental assumptions underlying classical physics”. On the contrary, this sense of wonder and surprise is exactly what appears to be an unambiguous result of the approach described here. During the lectures, it seems that they feel like protagonists for the first time in their scientific education, that they understand that physics is a fascinating enterprise and also that behind the most common things there is a profound mystery, which can set the human intellect in motion, leading to a series of results and reflections of considerable scope and significance for all and not only at the technical and technological level.

At this point, a teacher might fear that students might misunderstand and be led to believe that this way of proceeding is actually doing physics. In this case, the instructor must be explicit and state again what his or her goals are and the limits with which the subject has been approached. Most of the time, however, the concern is undue, as students show that they clearly understand the difference between doing physics and being involved in some aspects of it.

Again, a legitimate objection might be that the only evaluation presented here is a series of testimonies, which do not concern what the students have learnt, other than that physics might be interesting. Yet, if this were the case, it would nevertheless represent success, given the sources [53–55] that show how, on the one hand, interest in science (and particularly in physics) declines drastically in the years from primary school to high school, precluding in advance the possibility for students to even be tempted by the idea of pursuing studies in science. On the other hand, other studies [56,57] clearly show that knowing how to arouse interest, especially when it is an intrinsic interest (and therefore not an interest motivated by things external to science, such as the need to pass an exam), is a fundamental factor both in the appreciation of science and as a statistical indicator of the likelihood that students will pursue science in their future education. Compared to the above literature, the value of this paper is significant simply with regard to the attitude of physics teachers, which is most effective in arousing students’ attention and interest. Teachers’ enthusiasm, their ability to connect with students and their world is probably the most decisive factor in making students appreciate physics. In this sense, this article explicitly offers some such cues (i.e., a multi- and person-centered approach grounded in everyday life), which teachers can make use of in the case of QM.

Secondly, if we really want to address the issue of assessment, the point of observation would need to be reversed. Normally, when talking about the quality of a certain approach, one focuses on how well students aligned with the content the teacher wanted them to acquire. Now, this should at the very least be considered as only half of the investigation. In fact, the reverse direction, that is, how well a teacher was or was not able to align physics with his or her students’ backgrounds (“mental models” in Ref [39]), should also be investigated.

As a by-product of this approach, the role—and also the social consideration—of school teachers emerges as reappraised; they are no longer arid mathematical operators but true intellectuals who establish original bridges between our everyday life experiences and the experiences and images provided by science. As a further side effect, different styles and approaches of doing physics would also be good for physics itself, since they give birth to new nuances and perspectives, and physics would further unfold as an inexhaustible source of pleasant intellectual discovery also for an experienced teacher.

Finally, how adaptable is this approach to other classrooms and teachers? With respect to my experience, as far as the involvement of experienced teachers in this new type of approach is concerned, one is usually confronted, on the one hand, with a lack of training in these humanistic aspects (some physics teachers feel uncomfortable dealing with discourses lacking in formalization and quantification) and, on the other hand, with a certain “subject cultural” type of resistance (well described in the literature, for example in Refs [58,59]), whereby teachers tend to always follow the same syllabus, consolidated by years of experience (and perhaps indifferent to the concrete results obtained). This is not an opposition in principle, far from it, but rather a certain, understandable inertia in repeating teaching syllabuses that give security and stability to the teacher's work.

On the other hand, from some newly trained teachers (and to whose training I myself contributed precisely through a short course on the cultural elements of physics—in particular historical and philosophical, but also literary and artistic—held at the University of Trento, Italy, during the special PAS ministerial initiative of 2013 and 2015 to qualify physics graduates to teach), I obtained enthusiastic feedback on the specific training they received and, subsequently, on the spill-over of this training into their classroom activities. However, we have never researched this on a quantitative level, satisfied, on a practical level, with the largely qualitative feedback received from students, which is, in the case of these newly trained teachers, quite similar to my own (although they did not conduct a written survey). Still, this type of investigation could be an excellent research target for the near future.

6. Conclusions

QM is a great human intellectual achievement whose results are highly technical but, at the same time, "rife with anthropic concepts" [60], so that even before being a scientific subject, it is a cultural context. This should be the main rationale for its inclusion in high school physics curricula. In this paper, I argued that this could be done in an inclusive way, that is, by reaching out to the cultural background of students and without fearing the necessary simplifications. Within this approach, teachers become interpreters of QM, so that it may help unlocking critical and creative thinking. In doing so, they should not be afraid of treating even physics topics with an abundance of words rather than formulae and by proposing metaphors and cognitive links of any kind because students who will not pursue STEM studies should also leave the class with some cultural gain. Even if this gain turns out to be confused, partial and approximative, it may add more to the development of cultural insights than a bunch of mathematical formulae, which come out of nowhere and are not related to the student's experience. In this essay, I provided explicit examples and qualitative outcomes to prove how QM may become an inspiring opportunity for exploring themes, such as the working of the scientific method, the limits of our cognitive categories and the connections between QM and history, psychology and literature.

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