DOI: 10.6093/978-88-6887-307-3

# Old Quantum Physics for Cultural Education

Marco Giliberti[1], Luisa Lovisetti[2]

[1] Department of Physics "Aldo Pontremoli", University of Milan - marco.giliberti@unimi.it

[2] Department of Physics "Aldo Pontremoli", University of Milan - luisa.lovisetti@unimi.it

*Abstract*: Personal culture can be considered as that rich knowledge that makes people able of a broad vision, new ideas, and personal reflections about reality. With social culture, instead, we mean those habits, values and behaviours adopted by a given society. But we can also consider disciplinary culture, *i.e.*, the one "identified" by a disciplinarily differentiated group, like physicists. It is from this last point of view that often scientists complain of a lack of diffuse scientific culture. This fact comes from the observation that, indeed, few people think physics is able to touch, besides people's minds, also people's hearts. However, even scientists themselves rarely wonder why, and in what sense, science should really be a cultural part of the whole society. The Physics Education Research Group of the University of Milan strongly believes that awareness of the importance of cultural aspects of physics should be highlighted, and placed at the base of physics education. In this talk, we will mainly focus on our work on the historical-philosophical-educational aspects related to the birth of quantum physics, the challenges it generates and the perspectives it opens up for a general overview of the problem. We will discuss motivations, proposed methods, and tools to manifest physics as culturally strongly intertwined with the vision of the world and of life of each of us.

*Keywords*: Physics education, History of physics, Cultural understanding

## 1. Introduction

The indicator number 1 of the success of the initiatives implemented by the Italian PNLS – Piano Nazionale Lauree Scientifiche (National Plan for Scientific Degrees) 2023-2025 is given by the percentage of students enrolling in the second year of physics having acquired at least 40 CFU (Crediti Formativi Universitari – University Course Credits). In this way, the university is encouraged to increase the number of students keeping up with the courses - and this encouragement is certainly positive: in fact, we know that today, in Milan, the percentage of students who drop out of the bachelor's degree is as much as 50%. But how can we do it? And how will it be done? Will we simplify the content of the courses, or will we increase student evaluations in exams? Or will we, as teachers, find a way to be more effective and higher in our objectives without the need to lower the bar? Will we make it?

However, perhaps the problem is not that of lowering the bar. Perhaps the problem is that what we want and what we could do depends on the profiles we hope students will have upon graduation. From this point of view, there are many possible dimensions of action:

- we could propose a profile that emphasizes knowledge in various fields of physics or one that is highly specialized in a single sector;
- we could propose a profile where the ability to create connections and parallels between different areas of knowledge is important;
- we might focus on a highly cultural profile of the outgoing student in its most concrete manifestations, for example, with its connections to technology;
- we could work for a high cultural profile on historical, philosophical, and epistemological aspects;

- we could work for a high capacity of judgment, since independent thinking might appear more important;
- we might choose a profile for our students with non-trivial collaborative abilities in group work;
- we may also look for specific communicative skills in our students, given the society we live in;
- we might propose a curriculum aimed at developing metacognitive reflection skills, fundamental, for example, for teaching.

The crucial point is: will we be able to propose various profiles so that each student can choose the one that suits them best? And how is it possible that teaching methods have changed so slowly over the years despite, on the one hand, school demands in terms of national guidelines and, on the other hand, university demands, essentially if all fronts have evolved a lot in recent decades? In this regard, what can research in physics education say?

## 2. Science without art (nor part)

In the XXI century, the relationship between physics and the arts, as well as the humanities in general, has become increasingly intense and fruitful. However, in major theatres, it is still challenging to see scientific performances on the bill; they are often presented in *matinees* for schools and expressly have a (pseudo) educational value, serving as essentially informative communication tools rather than works of art.

Moreover, in the world's leading art galleries, there are no beautiful and important paintings inspired by physics on display; and as far as we know, no poet has received the Nobel Prize for poems related to physics. In reality, few people believe that science is capable of touching the hearts (as well as the minds) of people, containing fundamentally non-rational, emotional aspects, as one expects art to do.

Returning to the earlier examples, "The Potato Eaters" and not "Physicists in the Laboratory" is a painting by Van Gogh. On the other hand, "Broken Symmetries" is a famous physics paper by Goldstone, Salam, and Weinberg (Goldstone, Salam & Weinberg 1962), even though it could be the title of a bestseller about the relationship between men and women; it could, but it is not. Do any of us know a poem or a show titled "Invariant Lagrangians"? Probably not.[1]

Indeed, scientific theatre, as well as scientific painting or scientific music, struggle to emerge from an artistic perspective. Scientific theatre shows generally attract a considerable audience and, perhaps not always, but very often, they are indeed interesting. However, it is difficult to consider them artistically beautiful.

As we are accustomed, the almost total absence of science in major artworks appears unreasonable. In fact, science is a cultural product of humanity and the society in which she lives, constituting an important part of the social framework, significantly contributing to changing our worldview and our perception of our place in the world we live in. As Feynman said, "Why do the poets of the present not speak of it?" (Feynman, Leighton & Sands 1963, p. 3-6).

Moreover, the situation is completely symmetrical in the scientific field as well. We find very little theatre,[2] very little painting (indeed, we could say no painting at all) and no poetry in university physics courses. In fact, it is even difficult to imagine that things could be different and that a true interdisciplinary construction of knowledge could be useful and productive not only for the formation of a mature person but also for the understanding of the disciplinary aspect itself. Yet, the offering of so-called scientific exhibitions, events that combine art and science, is extensive. Still, how many of these

[1] But in case you do, please let us immediately know!

[2] The only example known to us, is the use of theatre to enhance the understanding of physics in the course of Didactic Experimentation Preparation for the master's degree in mathematics, at the University of Milan, held by one of the authors (M.G.) with the collaboration of the other one (L.L).

events truly manage to combine art and science in a way that enhances both and does not impoverish them in operations that are merely trendy?

**3. It is a question of culture**

It is thus all a matter of culture, and what is meant by this word.

Culture can manifest itself in many aspects; for example, there is rich personal culture, the one that enables individuals to have a broad vision, new ideas, personal reflections on reality, to open new perspectives, and find new paths.

However, there is also social culture, the set of habits, values, and behaviours adopted within a specific society, in its relations with other societies, with other values and also with other cultures. Then there is, perhaps most importantly, disciplinary culture, the one identified by a distinct disciplinary group, such as physicists or chemists, or scholars of literature or musicians. From this perspective, it is often lamented, especially by scientists, that there is a lack of sufficiently widespread scientific culture within society, within schools, within institutions, and within cultural events.

Yet, when the topics discussed are meaningful to people – for example, because they are perceived as useful, beautiful, fascinating, or because they contribute to well-being, or because they create conditions of greater productivity and effectiveness –, well, in those cases, interest, attention, the desire to understand, the willingness to listen, and sometimes even the pleasure to get involved are generally much greater.

However, culture is often discussed in a different sense, almost as if it were a citizen's obligation, spoken of as a civic duty. Sometimes, culture is discussed as a social elevator. But what, in our opinion, is the most important and defining element of culture is often left aside: culture speaks to what is deep within us; that's why it touches our soul, modifies our worldview, our vision of life, gives us the opportunity to experience the pleasure of exploration and the significant, yet often overlooked, pleasure of understanding.

Perhaps we could say this: culture is the pleasure of an endless exploration, a tool for understanding, and, therefore, often also for action.

**4. Physics as culture**

Indeed, one of the main cultural aspects inherent to physics lies in its significant push to transcend common thought, to transgress the usual interpretation of reality, and to understand that questions that have seemed important and meaningful for centuries are, in fact, devoid of meaning. It is the culture of physics that proposes entirely new questions, so different that they wouldn't have made sense before. It's a matter of perceiving the sense. Prototypical in this regard is the question of whether the Earth is stationary or in motion. It took at least two millennia to understand that the notions of motion and rest are equivalent; an extensive effort was required, ultimately leading to the principle of inertia formulated by philosophers, scholars, physicists, and finally by Newton, before grasping the depth and importance of this concept. The same thing happened to the inertia principle as what Weinberg wrote about the cultural significance of quantum mechanics,

> The historical importance of quantum mechanics lies not so much in the fact that it provided answers to a number of old questions about the nature of matter – much more important is that it changed our idea of the questions that we are allowed to ask (Weinberg 1993, p. 51).

It is often said that the important thing is to ask questions, while the aspect of what questions are appropriate is sometimes overlooked. Not every question is a sign of understanding; a first step toward understanding precisely consists in being able to ask meaningful questions and understanding that some questions simply do not have answers. Posing them is like carrying burdens that are historically heavy and do not take us far. Understanding what new questions are permissible to ask, even without necessarily obtaining answers, is perhaps the most important thing that school could teach.

In fact, the knowledge we have acquired in recent centuries far surpasses that obtained in all previous millennia. Therefore, each student's knowledge will inevitably be a very small set, almost negligible, compared to the total, even if she/he focuses on a specific field of study. However, her/his education will not necessarily be vain – despite her/his small amount of knowledge – if it is not primarily based on knowledge but, as is rightly fashionable to say, based on actual skills. If the student understands what she/he can do with such a new knowledge, where it comes from, how it was obtained, who obtained it and why, how these new insights can truly change our lives and theirs, and why these pieces of knowledge are genuinely important for us, for each of us, for everyone.

## 5. Cultural Pedagogical Content Knowledge

So, again, let us ask ourselves: can research in physics education be useful? It is from educational research that we know the traditional structure of disciplinary knowledge is not the most effective framework for learning. To motivate study and facilitate understanding, a profound revision of the structures shaping our knowledge of the world is necessary – and the world of physics is our main focus here. Alongside this deep revision, it is crucial to reflect profoundly on the mediating role that the teacher must play; the teacher who works with students, as it happened in the art workshops of the Renaissance when education was imparted by peers and gradually, through imitation, followed the Master's school, eventually reaching maturity.

This is why educational proposals should unequivocally highlight the model-like nature of knowledge, the humanistic nature of modelling, and help students gradually develop new scientific ways of looking at the world, systematically comparing the complexity of abstract concepts with the complexity of real facts.

The context from which physical ideas and descriptions emerge must be meaningful, both for the student and evidently for the teacher proposing it. It must be rich enough, not devoid of context and meaning – contrary to what often happens. Indeed, the younger or less experienced the student, the more the presentation is usually simplified, whereas it is advisable for it to be richer and less simplified, placed in a broad context.

When we think about common knowledge – or rather, what we awkwardly term "common knowledge" (awkward in the sense that we would not even be able to define it broadly) – and disciplinary knowledge and we consider them as two mountains, we should not view education as a path leading from one summit to another, leaving us so much time in the valley between them. Instead, we should see it as a Tibetan bridge connecting the two peaks without passing through the valley of minimal knowledge, otherwise we no longer know how to use "good" common sense nor even structured disciplinary knowledge, as often happens (just think of the senseless statements heard in physics orals or the nonsensical notions about wave-particle duality). We must address human development by combining common knowledge with disciplinary knowledge. Our action must be both-and, not either-or. Teaching is often sterile, with cultural aspects left entirely to physics communication and popularization. This is why cultural aspects should be intrinsically present in disciplinary teaching in synergy with what happens and with the disciplinary aspects of other subjects.

Not only should teachers pedagogically understand disciplinary constructs, i.e., possess the so-called Pedagogical Content Knowledge (PCK), but they should also be able to integrate this knowledge into a broader cultural environment. The vastness of the cultural environment, in synergy with the aspects related to methodologies handed down by decades of research in education, constitutes the driving force of both disciplinary and cultural education for teachers. That is why we consider it crucial for teachers training to adopt a perspective of Cultural PCK.

In the past, physics education has mainly focused on the most effective methods to achieve an appropriate understanding of disciplinary knowledge. Only recently the question has arisen of how this knowledge can be integrated in a global perspective that is culturally meaningful for students. For instance, it is widely known that the first principle of dynamics is particularly challenging for everyone, including students. In the past, physics education research has studied and now knows methods and tools that are useful and effective in improving the learning of dynamics principles; methods that allow students a deeper appropriation of dynamic concepts. The result of all this is that students following educational paths based on research that has led to these results respond much better, for example, to the force concept inventory (Hestenes, Wells & Swackhamer 1992). In a sense, we could say that they understand dynamics better than those who have not followed these paths and, therefore, may respond with fewer errors to this inventory.

However, these methods that aid understanding are not generally capable of improving the cultural comprehension of dynamics principles and allowing students to frame them both historically and philosophically in a context that fills them with wonder and changes at least part of their worldview. In short, what will these fundamental dynamics concepts mean to them? What values will they have for them, and in what ways will they change their lives?

From this perspective, even active learning (crucial to ensure teaching), is not a "mere" strategy to improve understanding but a didactical tool for that active appropriation of skills that we call culture. Indeed, for active learning to lead to personal cultural appropriation, it must be placed in a network of relationships that confront it with other perspectives: historical, philosophical, epistemological, technological, and emotional.

## 6. The central role of university in educational improvement

So, have we to start in order that, in addition to pedagogical and disciplinary knowledge, besides active learning knowledge, we can also discuss a way of learning able to incorporate disciplinary aspects into a broad cultural framework? Our idea is that we must start from the university and university cultural education; we must start from the university because, otherwise, we will have physics graduates who, as well-prepared as they may be in their discipline, will not know how and why physics truly fits into the culture of a country and of a society.

Phenomena, whether physical or social, are all like the tip of an iceberg (Ludwig & Thurler 2007, p. 4) and culture is the set of connections we make to hypothesize the underwater shape of the iceberg. From this perspective, history and philosophy of science are fundamental for teaching. The approach to teaching must be epistemologically well-founded and give great consideration to what is called the Nature of Science. Indeed, knowledge, typically scientific knowledge, results from a very complex process that allows us to identify both how ideas evolve and their current state. Knowledge of the evolution of these ideas helps identify the epistemological and ontological barriers that must be overcome to understand.

A cultural structure of this kind allows the construction of teaching approaches that help avoid paths based on imprecise, blurry, or overly simplistic perspectives. From a concrete standpoint, there also needs to be significant synergy with non-formal and informal tools for approaching culture: the student certainly does not live only at school, and we must learn to manage, convey, and exploit the information and cultural aspects that come from every direction and every hour of the day.

The university must be the pivot and at the same time the engine of this revolution in the teaching approach.

## 7. Educational research as support for history and knowledge

The idea that history can help education is a well-known fact (although perhaps not widely utilized in teaching). However, what we would like to highlight is a less known aspect, namely that education can also assist history in focusing on interpretative problems. In fact, along with history, education, by its nature of studying ways of understanding and learning, can aid in constructing and exploring paths and conceptual syntheses that benefit all branches of physics. It can lead to considering problems from perspectives different from those of specialists and help historians ask questions they might not be accustomed to. In general, education can help physics become culture for people, facilitating an understanding of past comprehension problems and, therefore, promoting historical interpretation from a different perspective. In any case, it can foster the appropriation of physics as culture in various sectors.

It is from this perspective, the research work initiated about three decades ago by the Physics Education Research Group of the University of Milan, focusing on the teaching of quantum mechanics, takes shape. This research involves conceptual aspects, learning nodes, deepening certain aspects of the foundations of quantum physics, proposing experiments, teacher training within the national scientific degree plan, as well as non-formal or informal aspects like scientific theatre. The aim is always to overcome the dichotomy sometimes present between history and logical-didactic reconstruction.

Lately, this work has consciously structured itself as research on the cultural presentation of quantum mechanics. In this context, "cultural" is understood as the opposite of chatty, discursive, confused, or purely explanatory. But "cultural" is also understood as the "right" level, a level that can speak to people according to who they are; not placing itself in the valley of minima, not halfway between disciplinary culture and common thinking, but in a reconstruction of knowledge that considers both these mountains. This reconstruction seeks to think about teaching quantum mechanics with the perspective of being concretely useful, starting from concrete facts such as how it is currently taught in schools, how it is taught in Italy, how it is taught in Europe, how it is taught worldwide with the various diversity of approaches found.

The epistemological and historical aspects are always kept in mind. Studying Thomson's atomic model or matrix mechanics, or discovering the difference between Schrödinger's waves and de Broglie's ones will serve to reflect on the physical meaning of what we are dealing with and will not be a mere historical erudition. Discussions conducted on these bases with expert colleagues, teachers, secondary school students, and university and doctoral students help us greatly to place this meaning in a network of knowledge and relationships that changes our way of seeing ourselves in the world with personal, social, and ethical consequences. But for this, one must not stay in the valley of minima: not in between and not on the hills.

## 8. Quantum physics for cultural education

Therefore, in our work, it is crucial to rely mainly on primary sources because secondary sources are more useful for obtaining interpretation, a general overview. However, primary sources highlight the personal aspects or style and focal points of the author, allowing for a more detailed interpretation of what is being read. Knowledge of primary sources enables a broader and more detailed view; however, secondary sources help form an overall picture that depends on the secondary source itself: without them, it would be difficult to have frames of reference and far-reaching interpretations.

In addition to use both primary and secondary sources (more than 800), the study derived from research on learning is fundamental. This allows an understanding of conceptual nodes, disciplinary nodes, learning nodes, epistemological difficulties, the social framing of quantum mechanics in the current view, and the perspectives presented in books, documentaries, or popular science lectures.

It is also important to develop detours on another level: the pedagogical one. This involves offering clarifications that emerge only with today's perspective and start from current issues. These clarifications should mix pedagogical considerations and push towards personal views, so that the cultural proposal does not exhaust itself in purely disciplinary learning but opens up to a network of meaningful connections. If not explored explicitly, these connections may fall prey to some popular science presentations with excessively imaginative and dubious cultural interpretations. To achieve this, we must free ourselves from decades of rigid science education based solely on rationality, so that personal observations and comments, proximal to the purely scientific area of interest, become possible. To clarify, if we do not observe and comment that $\hbar$ is (more or less) the symbol of Saturn, we should not be surprised if extremely extravagant books fill the need to bring together different aspects of knowledge, with cultural operations that we may not agree upon.

With these four points together – the use of primary sources, the use of secondary sources, the development of pedagogical aspects starting from nowadays, and the promotion and explicit discussion of personal opinions and the attribution of meaning, all framed within the results obtained and the still-open questions from educational research on learning –we allow the construction of an approach to quantum mechanics that follows the model of educational reconstruction and leads to continuous refinements based on research and proposed as Cultural Pedagogical Content Knowledge.

This approach, briefly outlined here, allows ample freedom to proceed within its structure, much like the metric structure of the sonnet has seen in the history of poetry the writing of very different verses. Freedom of proposals, methods, and approaches can emerge almost limitlessly. Moreover, it allows for the introduction of usually neglected issues, such as the changing meaning of symbols and words in history: today's electron is certainly not the electron of the late XIX century; today's quantum mechanics is certainly not that of Heisenberg, not only because it has enriched with discoveries but because it identifies different aspects of knowledge.

For the study of a discipline to be useful to personal development, it needs to help the effective construction of personal meaning attribution tools based on structured knowledge from the discipline. In particular, for our research on the teaching of quantum physics, this way of thinking and practicing educational research helps quantum mechanics become culture, which is precisely what we need in schools. However, as mentioned earlier, this way of understanding practices and research starts from the university. Cultural presentations of physics must find more and more space at the university. This is why, for example, with the friend and colleague Nicola Ludwig, we conducted a 30-hour doctoral course entitled "Tools and methods for a cultural presentation of physics" within the PhD courses at the University of Milan. But starting from the PhD is certainly not the main way; it is necessary to start much earlier. Starting from the first year of university is necessary to educate people and, therefore, future teachers. For this, we should also have the courage to seek the help of professionals from other disciplines, something we have already experimented with when we enlisted the help of Flavio Albanese, an actor, who helps us read poems, literary passages, and develop connections in the activities of the PNLS, student orientation, and teacher training in the second-level Master's Degree IDIFO. But this requires a lot of work: every hour of joint intervention of the authors of this paper and Albanese needed from 20 to 30 hours of preparation.

It is no longer possible to remain halfway, in a neutral middle ground; "in medio stat virtus" does not mean a trivial departure from both common thinking and scientific thinking but active work, an "et, et" approach. In light of these considerations, we have concretely proposed an orientation didactic workshop entitled "Old (but Gold) Quantum Theory – Discovering the early quantum physics through the original papers of its protagonists". The activity was developed through face-to-face meetings with 9 teachers and 36 students of the last two years of high school, by means of 5 afternoon sessions of 3 hours each. During the course, the cultural impact generated by the gradual and troubled birth of quantum theory was discussed in a multidisciplinary view, in order to frame the conceptual proposals of the old quantum theory in a culturally resonant context, for today's students, for today's society. This involved the use of transversal tools useful for a critical assessment of what was proposed in a strategy of active and participatory learning. Working in small groups, students read and commented original texts, even in the original language, and discussed their meaning, observing the difference in questions posed a century ago. This allowed them to frame today's issues in a less absolutist and more prejudice-free perspective.

In October 2023, a broader online course has started, consisting in 11 meetings of 2 hours each. The path begins from the old quantum theory and leads, step by step, to the construction of the axiomatic structure of quantum mechanics (Lovisetti, Organtini & Giliberti 2023) and their use for understanding some aspects of the real physical world. The activity is attended by 144 high school students and 84 teachers. At the end of each meeting, students are given a Google Form with several questions and exercises related to their learning, allowing us for an assessment of their learning problems, their cataloguing and overcoming. The meetings are extremely participatory, with numerous and continuous questions even well beyond the scheduled end time. All questions are noted, catalogued, and monitored in a research effort on the effectiveness of the course.

Always within this cultural dimension, within the international Physics Education Research Group GIREP, the thematic group "Cultural Understanding of Physics" (CUP) was created by us.

## 9. Conclusions

It is essential that the approach to physics becomes much more cultural than what is normally done. For this reason, it is important to bring together disciplinary, epistemological, and historical aspects, in an active learning approach and in a broad cultural perspective, which connect physics to other disciplines.

It is precisely in this way that both the cultural and disciplinary aspects can be strengthened, without remaining at a level of superficial understanding that makes the disciplines "unsavoury". Here, therefore, is our attempt based on such an approach which aims to arrive at a culturally significant presentation of quantum mechanics in a much more in-depth manner than is usually done. The results obtained so far (Lovisetti, Organtini & Giliberti 2023) are extremely encouraging, and push us to insist in this direction.

Finally, we believe that it is essential – as well as we hope – that approaches of this type are also pursued at university, starting from the early years; otherwise, it will be difficult for physics graduates to have perceived the cultural depth and importance for life and society of what they have studied.

## Bibliography

CUP (2023). *Cultural Understanding of Physics: instruments and methods*. GIREP thematic group. Available at: https://www.girep.org/thematic-groups/cultural-understanding-of-physics-instruments-and-methods/ (Accessed: 30 June 2024)

Feynman, R., Leighton, R.B. & Sands, M. (1963). *The Feynman Lectures on Physics.* Vol. 1. Boston: Addison-Wesley Publishing Company.

Giliberti, M. & Lovisetti, L. (2023). "Quousque tandem?", *Giornale di Fisica,* 64(3), pp. 191-211. doi: 10.1393/gdf/i2023-10527-2

Goldstone, J., Salam, A. & Weinberg S. (1962). "Broken Symmetries", *Physical Review*, 127(3), pp. 965-970. doi: 10.1103/PhysRev.127.965

Hestenes, D., Wells, M. & Swackhamer, G. (1992). "Force Concept Inventory", *The Physics Teacher*, 30(3), pp. 141-151. doi: 10.1119/1.2343497

Lovisetti, L., Organtini, G. & Giliberti, M. (2023). "Inducing the construction of formal axioms of Quantum Mechanics and fostering their comprehension by high school students: The effectiveness of a conceptual approach", *Il Nuovo Cimento C,* 46(6), 200. doi: 10.1393/ncc/i2023-23200-1

Ludwig, G. & Thurler, G. (2007). *A New Foundation of Physical Theories*. Berlin Heidelberg: Springer-Verlag.

Weinberg, S. (1993). *Dreams of a Final Theory*. London: Vintage.