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History as a tool for clarity: Enhancing quantum mechanics understanding through key historical insights

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Abstract
Quantum mechanics (QM) is often taught without sufficient attention to its historical context. This lack of historical perspective affects learners at all levels, from high-school teachers to young researchers. As Physics Education Research Group in Milan, we conducted a study with high-school teachers and prospective teachers to investigate whether and how selected historical aspects can be useful for fostering a better understanding of the nature of science and the conceptual structure of QM. We will present the results of our research, which overall strongly support the inclusion of historical aspects in the teaching of QM.

Keywords: quantum mechanics, history of quantum physics, cultural understanding of physics, nature of science, quantum physics education

INTRODUCTION: BACKGROUND, STARTING POINT, AND RATIONALE

A century has passed since quantum mechanics (QM) was born, with Heisenberg's (1925) seminal paper of 1925 (Giliberti & Lovisetti, 2025a). However, despite the renewed attention to QM brought by the Second Quantum Revolution (National Quantum Initiative, 2025; Quantum Flagship, 2025), many physicists—including those working on quantum-related topics—still show limited knowledge of its historical development. This occurs at all educational levels, from high-school teachers with a degree in physics to early-career researchers, as highlighted by open-ended questionnaires administered over the past four years to a sample of 506 participants (high-school teachers, Bachelor's and master's students, PhDs, and young researchers).

For instance, in response to the question "When was the theory of QM born?," the most frequent answers were "1900," "1905," and "1913," with only 5% identifying the correct year, 1925 (**Figure 1**). This is not merely a matter of historical accuracy. Rather, it reflects a conceptual issue, namely the tendency to conflate early models of the old quantum theory (such as Planck's model for blackbody radiation, Einstein's explanation of the photoelectric effect, or Bohr's atomic model) with the emergence of a coherent physical theory: QM (Giliberti & Lovisetti, 2024a). Similarly, when asked which scientists contributed most significantly to the theoretical foundations of QM, respondents most frequently cited Planck, Einstein, Bohr, and Pauli, followed by Heisenberg and Schrödinger. No participant mentioned von Neumann (1932) or Born (1926a, 1926b), and Dirac appeared only marginally (**Figure 1**).

This limited historical awareness also emerged clearly in relation to Dirac's bra-ket notation. 83% of respondents believed it had been introduced—or necessarily had to be introduced—before the formulation of QM (**Figure 1**). In fact, it was proposed only in 1939 (Dirac, 1939), fourteen years after Heisenberg's paper. This misconception reveals a broader confusion between mathematical notation and the formal axiomatic structure of a physical theory.

Taken together, these results point to significant gaps not only in historical knowledge but also in conceptual understanding and in awareness of the nature of science

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Contribution to the literature

- This paper contributes to quantum physics education by investigating how selected historical insights can support conceptual clarity, NOS awareness, and pedagogical reflection in teaching and learning of QM.
- It provides empirical evidence from in-service and pre-service teacher education, showing that historically informed approaches are associated with higher recognition of the interplay between theory and experiment, the role of historical experiments, and the ethical and cultural dimensions of science.
- By using history not merely as background information but as a structured educational tool, this study contributes to the literature on HPS-informed science education and offers a framework for integrating historical, epistemological, and ethical perspectives into QM teaching.

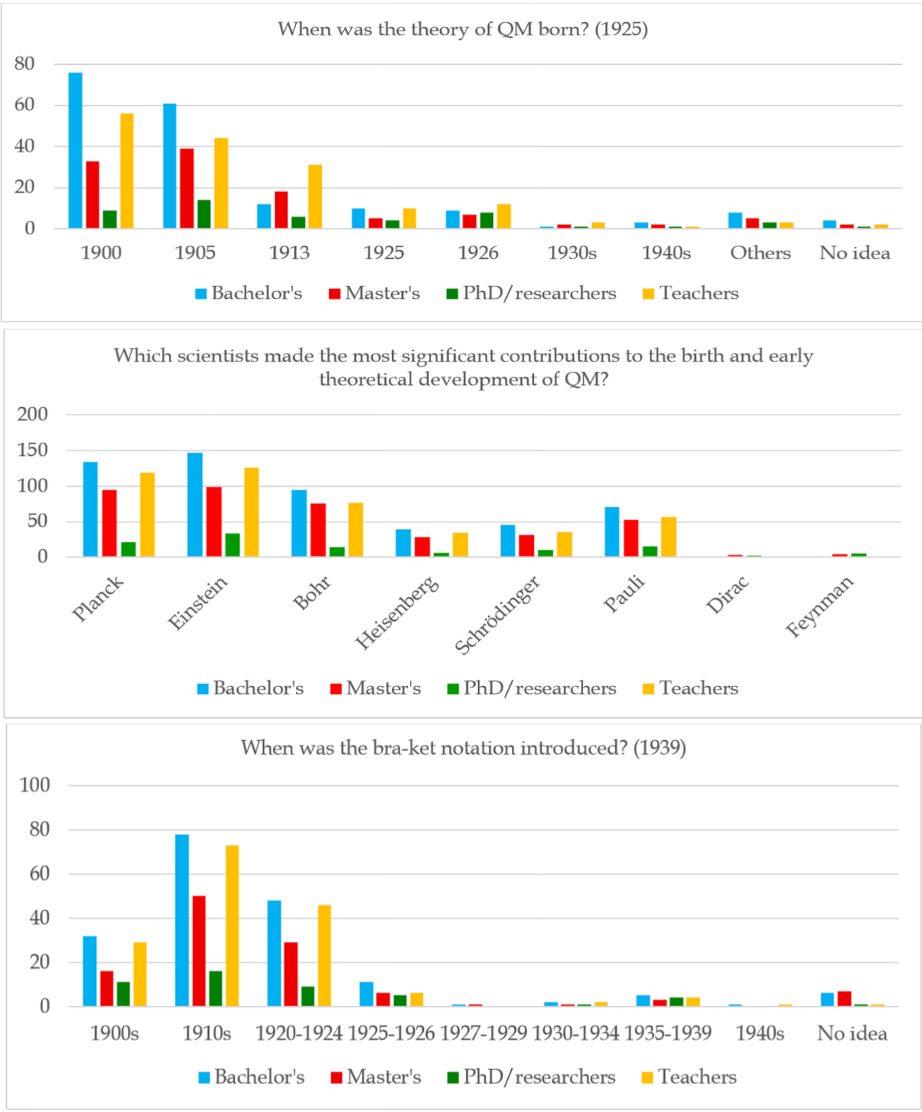

Figure 1. Diagrams illustrating the responses to three of the questions collected in the questionnaire (the authors' own elaboration)

(NOS), understood as a dynamic, tentative, and culturally embedded enterprise. From this perspective, as a Physics Education Research Group at the University of Milan, we argue that historical perspectives play a crucial role in supporting both conceptual clarity in QM and a more informed understanding of the NOS (Giliberti & Lovisetti, 2025b; Stadermann & Goedhart, 2021).

Historical Perspectives in Quantum Physics Education

Over the past decades, research in physics education has consistently shown that quantum physics is often perceived by both students and teachers as abstract, counterintuitive, and disconnected from experience (Bouchée et al., 2021). The strong emphasis on formalism tends to overshadow the historical and epistemological processes through which the theory developed. As a result, learners may acquire computational proficiency without developing a coherent conceptual understanding of QM.

This issue extends beyond students. Studies have documented that even in-service teachers and researchers frequently display fragmented views of quantum theory, treating early models as isolated facts rather than as steps in a complex theoretical transition (Greca & Freire, 2014; Krijtenburg-Lewerissa et al., 2017; Matthews, 2014).

Recent research on quantum physics education has increasingly emphasized the role of teacher education, not only as a means of transmitting quantum concepts, but also as a space in which teachers can develop epistemological and pedagogical awareness (Borish & Lewandowski, 2024; Donhauser et al., 2024; Hennig et al., 2024; McAfee et al., 2025; Merzel et al., 2024; Stadermann & Goedhart, 2021).

Within the GIREP community, the Teaching and Learning Quantum Physics Thematic Group has explicitly addressed quantum physics education at secondary-school level and in teacher education, identifying the preparation of teachers as a crucial condition for meaningful and sustainable innovation in quantum education. In particular, the discussions developed within GIREP workshops and symposia have highlighted the need to support teachers in connecting conceptual, formal, experimental, and epistemological dimensions of quantum physics, rather than reducing quantum instruction to a set of isolated phenomena or mathematical procedures (Michelini et al., 2021; Stadermann & Goedhart, 2021).

This perspective is also consistent with studies on the integration of NOS perspectives into quantum physics teaching, which suggest that quantum physics can provide a particularly fruitful context for discussing scientific modelling, theory-experiment relations, uncertainty, and the development of scientific knowledge (Giliberti & Lovisetti, 2025b; Stadermann & Goedhart, 2021). However, much of the existing literature has focused either on students' conceptual difficulties, on curriculum design for secondary-school quantum physics, or on teachers' use of NOS-oriented materials (Buzzell et al., 2025; Krijtenburg-Lewerissa et al., 2017). The present study contributes to this field by focusing specifically on in-service and pre-service teacher education and by investigating how historically selected case studies in the development of QM may foster conceptual clarification, NOS awareness, and ethical-cultural reflection.

Building on this body of work, our study differs from previous history and philosophy of science (HPS) and NOS-based interventions (Abd-El-Khalick 2013; Allchin, 2011; Erduran & Dagher, 2014; Matthews, 2024) by focusing specifically on in-service and pre-service teachers, by explicitly integrating historical development, NOS reflection, and ethical dimensions, and by adopting an empirical mixed-methods research design. Rather than using history as illustrative background, we employ selected historical case studies as structured learning tools to support conceptual understanding and reflective awareness (Giliberti et al., 2025; Lovisetti, 2024; Lovisetti & Giliberti, 2025a, 2025b; Lovisetti et al., 2023, 2024). While prior research has highlighted the educational value of historical and philosophical approaches in science education, our work aims to investigate how such integration operates in the specific context of QM teacher education, and how it influences participants' understanding of scientific knowledge, experimental practices, and broader societal dimensions of science.

THEORETICAL FRAMEWORK AND RESEARCH QUESTIONS

In this paper, we use the term "quantum mechanics" in a historically and conceptually specified sense. Strictly speaking, we refer to QM as the theoretical framework that emerged from 1925 onward, beginning with Heisenberg's matrix mechanics and subsequently developed through wave mechanics, transformation theory, and probabilistic interpretation. Earlier developments, such as Planck's quantization, Einstein's light quantum hypothesis, and Bohr's atomic model, are therefore not treated as QM in the strict sense, but as part of the old quantum theory and as historically essential precursors to the emergence of QM. This distinction is central to our educational approach, since one of the conceptual difficulties addressed in the intervention concerns precisely the tendency to conflate early quantum models with the formulation of a coherent quantum theory.

The theoretical foundation of this study draws on the intersection between HPS and physics education research. A growing body of literature supports the idea that historical and epistemological reflection can play a crucial role in improving conceptual understanding and fostering a more authentic image of science (Allchin, 2011; Clough, 2018; Erduran & Dagher, 2014; Holton, 1978; Irwin, 2000; Justi & Gilbert, 2000; Lovisetti, 2024; Matthews, 2024). In this study, we adopt HPS-informed reflection on the NOS as our primary analytical lens. Historical case studies constitute the main educational tool, while ethical and cultural considerations serve to broaden participants' reflection on the societal embeddedness of scientific knowledge.

History and the Nature of Science

An "informed" view of the NOS (Lederman, 2007) includes awareness of specific epistemological features of science, namely that:

(a) scientific knowledge is tentative but durable,

(b) science involves creativity and imagination,

(c) theory and observation are interdependent,

(d) social and cultural factors can influence scientific development.

In this study, NOS awareness is operationalized as participants' explicit reference to these features in questionnaires, discussions, and interviews.

As Clough (2018) and Erduran and Dagher (2014) argue, explicitly addressing NOS through historical and philosophical reflection helps teachers and learners connect epistemological ideas with real scientific practices, making the abstract features of science more tangible. Integrating selected elements of the history of quantum physics into teaching practice provides a fertile ground to explore these aspects (Giliberti & Lovisetti, 2025b; Lovisetti, 2024; Lovisetti & Giliberti, 2025a). The evolution from Planck's quantization to Heisenberg's matrix mechanics exemplifies the non-linear and collective nature of scientific progress. Discussing such transitions helps learners perceive science not as a sequence of final truths but as an evolving human endeavor. Indeed, as many historians of physics have shown, the emergence of QM was not a single event, but a complex and multilayered process influenced by social, institutional, and philosophical dynamics. In this sense, historical development is used not merely for contextualization but as a means to explicitly address NOS features.

Historical-Epistemological Approaches in Science Education

Studies within science education (Niaz et al., 2010; Pronskikh & Sorina, 2022) have shown that historical case studies can:

- enhance conceptual understanding by providing meaningful contexts for abstract ideas,
- help students and teachers connect formalism with its conceptual origins,
- promote reflection on the social, ethical, and cultural implications of scientific practice.

In the present study, "ethical dimensions" refer to issues related to scientific responsibility, freedom of research, and the societal use and suppression of knowledge, while "cultural dimensions" denote the influence of historical, institutional, and ideological contexts on the development and acceptance of scientific theories.

Within the framework of QM, historical inquiry can also illuminate epistemological issues such as indeterminacy, complementarity, and the probabilistic interpretation of nature.

Research Questions

Building on this framework, our study aimed to explore how integrating selected historical and philosophical elements into QM teaching influences teachers' and prospective teachers' understanding of the NOS and their pedagogical awareness. Here, pedagogical awareness is understood as participants' ability to recognize the educational value of historical-epistemological perspectives and to explicitly refer to their integration into lesson planning, instructional strategies, or didactic pathways. This construct was operationalized through coded indicators in questionnaire responses and interviews.

From the research we have conducted in recent years (Giliberti & Lovisetti, 2025b; Lovisetti, 2024; Lovisetti & Giliberti, 2025a), it has emerged that teachers and students (both at the high school and university levels) who participated in the trials we carried out demonstrated a better understanding of physics concepts when quantum physics content was presented alongside a selection of historical aspects. We therefore formulated the following research questions:

1. In what ways, and to what extent, does the history of QM aid in designing approaches and pathways that foster a greater awareness of the NOS?
2. In what ways, and to what extent, does the discussion of key historical experiments contribute, educationally, to a deeper understanding of quantum aspects?
3. In what ways, and to what extent, does the history of QM help in understanding the philosophical, ethical, and cultural dimensions associated with a physical theory?

TRIALS, METHODOLOGY, AND ANALYSIS OF DATA OBTAINED

This research employed a mixed-methods approach, combining qualitative content analysis and quantitative comparison. Data were collected through questionnaires, group discussions, and semi-structured interviews. The qualitative component focused on participants' reflections during and after the educational activities, while the quantitative component categorized explicit indicators related to NOS and historical or ethical understanding.

The study involved 311 in-service teachers in three online trials (between the academic years 2023/24 and 2025/26) and 69 graduate students in mathematics or physics, all enrolled in the in-presence course "Preparation of didactic experiences 2" at the University of Milan. Participation was voluntary, with no financial incentives provided. None of the participants had previously attended formal courses focused on HPS or NOS. Within the Italian teacher education context, in-service teachers typically engage in continuing

Table 1. Summary of results obtained and comparison between participants on the course and people of the control group

Aspect evaluated	In-service teachers (trial)	Pre-service teachers (trial)	In-service teachers (control group)	Pre-service teachers (control group)
1. Awareness of the NOS	85%	91%	37%	38%
2. Recognition of the interplay between theory and experiment (iterative feedback loop)	81%	88%	39%	36%
3. Recognition of the importance of historical experiments	73%	85%	36%	32%
4. Awareness of ethical, ideological, and social aspects of science	79%	82%	25%	31%
5. Recognition of the importance of historical reflections into teaching or didactic planning	93%	94%	42%	39%

professional development courses organized by universities, while pre-service teachers follow discipline-based didactic training alongside subject-matter studies.

Each trial lasted approximately 30 hours over ten weeks, with weekly synchronous online sessions (about 3 hours each) complemented by asynchronous group work and readings. Online interaction was supported through videoconferencing platforms and shared digital workspaces allowing participants to discuss historical sources and collaboratively answer guided questions.

Participants read and discussed original papers, worked in groups, and completed questionnaires via Google Forms based on adapted NOS and HPS-related instruments drawn from the literature (Allchin, 2011; Ayala-Villamil & García-Martínez, 2021; Lederman, 2007; Lederman et al., 2022). Items were adapted from existing NOS and HPS-oriented instruments, reviewed through a preliminary content-validation process, and subsequently refined following pilot administrations with graduate and secondary-school students. Internal consistency was checked using Cronbach's alpha (α), showing good reliability (α = 0.81).

The questionnaire items and interview prompts used in the study are reported in **Appendix A**, together with an indication of the NOS / HPS dimensions to which each item primarily refers.

Semi-structured interviews were conducted with a purposive subsample of 48 participants (30 in-service and 18 pre-service teachers) within two weeks after the end of each trial by the authors of the study. The purposive subsample was selected to include both in-service and pre-service teachers, participants from different trial cohorts, different disciplinary backgrounds, and different levels of engagement, as inferred from attendance, completeness of questionnaire responses, and participation in group activities. The aim was not to select only highly positive or high-performing participants, but to represent a range of experiences within the intervention. Participants whose written responses were short, uncertain, or only partially aligned with the intended learning outcomes were deliberately included in order to reduce success bias.

Since the interviews were conducted by the authors, who had also designed the intervention, possible social desirability effects cannot be fully excluded. To mitigate this risk, participants were informed that there were no expected "correct" answers, that critical comments on the course were welcome, and that responses would be analyzed in aggregated and anonymized form. Moreover, interview data were triangulated with written questionnaire responses and group-work materials.

Responses were coded and classified through consensus among researchers following an initial independent coding phase by two researchers. The main coding categories included:

(1) references to NOS features (e.g., tentativeness and theory-experiment interplay),

(2) historical reasoning,

(3) ethical or cultural reflections,

(4) pedagogical integration.

Inter-rater reliability was assessed using Cohen's kappa (κ), which measures agreement beyond chance levels (κ = 0.80), prior to consensus coding.

For the qualitative analysis, responses were segmented into meaning units, defined as a sentence or group of sentences expressing a coherent and identifiable idea. Coding categories were not treated as mutually exclusive. When a meaning unit contained more than one relevant dimension—for example, a reference both to the provisional nature of quantum models and to the historical succession of models (Lovisetti & Giliberti, 2026)—it could receive multiple codes, such as NOS—tentativeness and historical reasoning. For the quantitative comparison reported in **Table 1**, indicators were then operationalized as presence / absence variables at the level of each participant's response. Thus, the percentages indicate the proportion of participants whose answers contained at least one explicit reference to the corresponding dimension. In the examples reported in the text, we indicate the primary code only when one dimension was clearly dominant, but overlapping codes were retained in the full coding procedure.

For example, participants were asked: "How did the historical development of quantum models influence your understanding of the role and nature of scientific models in physics?" A typical response stated that "scientific models are not definitive representations of reality, but provisional constructions that can be revised or replaced when new experimental evidence emerges." This response was coded as NOS—tentativeness, as its primary emphasis concerned the provisional and revisable status of scientific models. Responses emphasizing the gradual succession of models over time were coded as historical reasoning, while statements highlighting experiments forcing revisions of theoretical assumptions were coded as NOS—theory-experiment interplay.

In this paper, the term "trial" refers to the entire 30-hour educational intervention, while "lessons" indicate individual instructional sessions within each trial. During the lessons, it was shown how the shift from classical physics to quantum theory was gradual (Giliberti & Lovisetti, 2024a), marked by early efforts to explain phenomena like blackbody radiation, atomic spectra, and the photoelectric effect. Moreover, great attention was paid to experimental aspects and selected crucial experiments (such as Lenard, Millikan, and Stern-Gerlach) were discussed through historical reconstructions, analysis of original experimental data, and comparison with modern textbook representations. Participants engaged with these experiments by examining historical descriptions, graphical results, and guided interpretative questions rather than by performing laboratory activities, given the online format of the course.

Insights From History: Scientific Knowledge as a Multi-Contributor and Incremental Process

First of all, participants stated that discussing historical aspects illustrates how scientific knowledge evolves incrementally (Kortam et al., 2021). This shows that scientific theories are often refined and built upon by successive contributions from multiple scientists, even from a mathematical and formal perspective. Below we report an example of a question taken from one of the Google Forms and related answers (high-school in-service teachers are denoted by "T" and university students pre-service teachers by "S").

> Q: "What has the historical development of quantum theory taught you about how science works?"
>
> S: "Studying the historical development of quantum theory has really helped me to understand how science works in practice. Through the historical perspective, I could see more clearly how scientific theories are justified and what it actually means for a theory to be considered 'true'."
>
> S: "Working on the transition from classical to quantum models made me realize much more directly that scientific progress is not linear or certain. Experiencing this through history helped me understand that scientific knowledge is always provisional and open to revision."
>
> T: "Although I primarily teach mathematics, I find value in discussing the historical evolution of scientific concepts to foster interdisciplinary thinking and illustrate the broader and "cumulative" context in which mathematical tools are applied to physical models. This interdisciplinary perspective reinforces the idea that mathematics is not only about internal consistency, but also about its power to model and interpret the physical world."

Insights From History: Interplay Between Theory and Experiments

Discussing the historical development of the old quantum theory showcases the dynamic interplay between theoretical predictions and experimental verification (Kragh, 1984). For example, the theoretical quantization rules for the hydrogen atom proposed by Bohr not only explained the hydrogen spectrum but also accounted for the isotope effect and reinterpreted the Pickering lines as originating from ionized helium. They further predicted the Brackett and Pfund series. This highlights that scientific progress often involves a feedback loop between theory and experiment.

Additionally, the history of QM emphasizes the importance of experimentation and observation. The theory was developed through a combination of theoretical insights and experimental discoveries, highlighting the iterative nature of scientific inquiry. Participants engaged with historical experiments such as Franck-Hertz and double-slit experiments through source analysis and guided discussion of experimental outcomes, highlighting differences between original setups and contemporary educational representations (Heering, 2023).

> Q: "What does the history of quantum theory reveal about how science progresses through the interaction of theory and experiment?"
>
> S: "Discussing the history of quantum theory helped me realize that scientists didn't just come up with ideas out of nowhere—many theories were created because experiments gave unexpected results that older models couldn't explain. It showed me that science moves forward when theories and experiments sort of 'push' each other: experiments reveal problems, and new

theories try to solve them. Understanding this made the whole topic feel less abstract and more like a real process of figuring things out."

T: "The development of quantum theory offers a compelling case study in how theoretical insights and experimental findings co-evolve. I find it pedagogically essential to help students see science not as a one-way path from theory to prediction, but as a dynamic interplay between conceptual frameworks and empirical data."

T: "I make a point of emphasizing that theory without experimental grounding risks becoming speculative, while experiments without theoretical interpretation often lack meaning. This dialectical tension is vividly illustrated in the evolution of QM. The way scientific concepts evolved in response to experimental results parallels the process of mathematical problem-solving: formulating hypotheses, experimentally testing them, and refining the model."

Insights From History: Ethical Issues and Cultural Value

Besides conceptual clarity, history allows discussions about ethics, ideology, and the social structure of science. For instance, after the 1930s, as physics became increasingly linked with national interests and military applications, a sharp divide emerged between applied and foundational research. Questions of interpretation—central to early quantum physicists such as Einstein and Bohr—became marginalized, particularly in the United States, where the pragmatic attitude summarized by "shut up and calculate" became dominant (Mermin, 1989). A concrete historical case discussed during the trials concerned the marginalization of foundational research on quantum interpretations in the 1950s-1970s, when funding agencies and journal editors favored technically productive and application-oriented work. Participants analyzed testimonies such as Clauser's (2002) account of editorial policies discouraging foundational studies. This case illustrates how institutional priorities can shape scientific agendas and limit certain lines of inquiry.

Q: "What impact did learning about the suppression or marginalization of certain lines of inquiry in the history of quantum mechanics have on your understanding of science and your role as an educator?"

S: "I had never considered that even within scientific communities, which are typically seen as neutral and rational, certain lines of inquiry could be actively discouraged. Learning about Clauser's testimony has made me realize that academic freedom is not guaranteed, and that this has implications not only for scientific progress but also for education. As a future teacher, I now feel a responsibility to convey the idea that science evolves through both openness and contestation."

T: "I found this aspect particularly thought-provoking. In school, we often emphasize the objectivity and reliability of science, but we rarely explore how decisions about which research is pursued—or published—can be shaped by political or economic interests. Sharing examples like the editorial suppression of foundational work in QM can help students develop a more critical and reflective view of science as a human enterprise."

These ethical concerns extended beyond military applications. As noted above, editorial practices in major physics journals during the 1970s often discouraged research on quantum foundations unless it produced new mathematical formalisms or predictions (Kragh, 1984). This example enabled participants to reflect on how scientific knowledge is not only produced through experiments and theories but also filtered through institutional and cultural mechanisms.

COMPARISON WITH A CONTROL GROUP AND PERCENTAGES

We compared the answers obtained by participants to those given by a control group of 105 in-service teachers who had not attended the targeted course, and 42 pre-service graduate students enrolled in standard teacher education programs, who did not receive specialized training in the historical and philosophical foundations of QM but followed standard courses in physics or mathematics education. Control group participants were recruited from the same university network and professional development programs as the experimental group and followed comparable curricula. While demographic variables such as subject specialization were similar, in-service teachers in the control group showed slightly higher average teaching experience.

Responses of both groups were categorized by the presence of explicit indicators such as references to historical case studies, epistemological terminology related to the NOS, and reflections on science as a dynamic, theory-experiment iterative process. Percentages reported are based on qualitative and quantitative analysis of participants' responses collected through Google Forms and individual interviews (**Table 1**).

The data obtained reveal a marked difference between the participants and control groups across all evaluated aspects. Both in-service and pre-service teachers in the experimental group demonstrate significantly higher levels of awareness and recognition regarding the NOS, the iterative relationship between theory and experiment, the importance of historical experiments, ethical and social dimensions of science, and the incorporation of historical reflections into teaching practices. In contrast, the control groups show considerably lower percentages in these areas. However, given the quasi-experimental nature of the design, possible selection effects cannot be fully excluded, and alternative explanations for the observed differences should be considered. Given the overall sample size and the magnitude of the discrepancies between the experimental and control groups, chi-square tests of independence—supplemented by pairwise proportion z-tests and Cramer's V as a measure of effect size—were used to evaluate statistical significance. Cramer's V provides an estimate of the strength of association between group membership (experimental vs control) and the presence of specific educational indicators, with values between 0.3 and 0.5 typically interpreted as medium to large effects in educational research contexts.

Cramer's V values ranged from 0.39 to 0.57, indicating medium-to-large associations between group membership (experimental vs control) and all educational indicators considered. This highlights the potential of historical-epistemological approaches to not only change conceptual understanding but also influence participants' reported pedagogical orientations. In line with the quasi-experimental design, these findings should be interpreted as associations rather than as definitive causal effects. These results suggest that exposure to structured historical and philosophical content is associated with higher levels of conceptual understanding and pedagogical awareness among current and future science educators, particularly in relation to the NOS, the theory-experiment dynamic, and ethical or sociocultural aspects of science.

Limitations of the Study

Several limitations should be acknowledged. First, participation was voluntary, which may have attracted individuals already interested in reflective or historically oriented approaches to science education. Second, although control group participants followed comparable training paths, unmeasured differences (e.g., motivation and prior informal exposure to HPS topics) may have influenced outcomes. Third, the study relied on self-reported data rather than classroom observations, limiting conclusions about actual instructional practices.

A further limitation concerns possible social desirability bias, since interviews were conducted by the authors of the intervention. Indeed, as already observed, although anonymity, triangulation with written data, and explicit encouragement of critical feedback were used to reduce this risk, participants may still have tended to emphasize positive aspects of the course.

Future research should address these limitations through randomized designs and longitudinal follow-up.

CONCLUSIONS AND FUTURE PERSPECTIVES

The results of this study are consistent with the interpretation that integrating selected historical and philosophical perspectives into QM teaching is associated with higher levels of conceptual understanding, epistemological awareness, and ethical reflection among both in-service and pre-service teachers in our sample.

While the quasi-experimental design does not allow exclusion of all alternative explanations, the control-group comparison and observed effect sizes suggest a meaningful association between participation in the intervention and these educational outcomes. By confronting participants with the historical development of scientific ideas, the intervention appeared to support recognition of science as a dynamic and collective enterprise shaped by uncertainty, creativity, and cultural context, as reflected in self-reported responses.

Educational Implications

From a pedagogical standpoint, the outcomes point to the perceived educational value of historically informed approaches within teacher education contexts. History served as an entry point for conceptual clarification, bridging the gap between formalism and meaning in participants' reflections. Based on participants' self-reports, engagement with historical sources—such as the gradual refinement of the atomic model—was associated with increased awareness of the human dimension of science and with intentions to address conceptual difficulties through historical perspectives.

Moreover, embedding the history of science into instruction was perceived by participants as supporting broader scientific literacy, enabling learners to view physics as an evolving human endeavor that combines creativity, reasoning, and social negotiation. It should be noted, however, that the present study did not include classroom observations, and therefore no conclusions can be drawn about the long-term implementation of these approaches in actual teaching practice. Previous research suggests that the translation of reflective insights into sustained classroom practice may be challenged by institutional constraints, including curricular demands and assessment pressures (Coles et al., 2023).

Epistemological and Ethical Dimensions

Our findings suggest that engagement with historical case studies was associated with increased attention to epistemological and ethical aspects of science among participants. Discussions about the marginalization of foundational debates in mid-20th century physics, as well as the editorial suppression of unconventional ideas, were reported as particularly impactful. Such examples made visible the social and institutional mechanisms that influence which forms of knowledge gain legitimacy. According to participants' reflections, these discussions supported the development of critical perspectives on scientific practice.

By integrating these reflections into teacher education activities, educators may encourage critical thinking and ethical awareness, values central to both science and democratic societies. As participants themselves noted, ethical responsibility in science concerns not only the application of knowledge but also its production and dissemination.

Implications for Teacher Education and Research

For teacher education, our findings indicate that integrating HPS perspectives within professional development courses is associated with heightened reflective awareness among participants.

Courses combining conceptual, historical, and ethical inquiry were perceived as moving beyond a purely technical image of physics teaching, fostering a more reflective and inquiry-oriented mindset. As argued by Monk and Osborne (1997) and Abd-El-Khalick (2013), historical and epistemological perspectives can support both conceptual understanding and reflective practice. From a research perspective, the present study contributes further empirical evidence to the literature on HPS-based interventions in science education and illustrates the value of mixed-methods approaches for capturing conceptual and attitudinal change.

These implications should primarily be understood within educational contexts similar to the Italian and broader European teacher education systems.

Future Horizons

Future developments will include a cluster analysis of pre- and post-intervention responses to map the evolution of teachers' understanding of the NOS. Further cycles of experimentation will explore how specific historical case studies affect classroom discourse and student engagement.

Finally, future research will investigate how integrating HPS into physics curricula may support interdisciplinary dialogue between physics, philosophy, and ethics education. These broader societal impacts should be regarded as research hypotheses and long-term educational goals rather than outcomes demonstrated by the present study.

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Ethical statement: This study did not require ethics committee approval. All participants involved in the study were adults and took part voluntarily. The questionnaires and interviews did not collect sensitive personal data, nor did they include questions concerning personal, medical, psychological, political, religious, or otherwise sensitive information. The questions concerned only disciplinary content, conceptual understanding, and participants' reflections on the educational, historical, and epistemological aspects of QM. Participants' names were used only for organizational purposes, namely, to keep track of responses during the educational activities and, where necessary, to connect questionnaire responses with subsequent interviews. These identifiers were not used in the analysis reported in the manuscript and were never included in the published results. All data were analyzed and reported only in aggregated and anonymized form. No identifying information is included in the manuscript, and individual participants cannot be recognized from the reported results or quoted excerpts. For these reasons, given the educational nature of the study, the voluntary participation of adult participants, the absence of sensitive data collection, and the anonymized presentation of results, ethics committee approval was not required.

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REFERENCES

Abd-El-Khalick, F. (2013). Teaching *with* and *about* nature of science, and science teacher knowledge domains. *Science & Education, 22*(9), 2087-2107. https://doi.org/10.1007/s11191-012-9520-2

Allchin, D. (2011). *Teaching the nature of science: Perspectives and resources*. SHiPS Educational Press.

Ayala-Villamil, L. A., & García-Martínez, A. (2021). VNOS: A historical review of an instrument on the nature of science. *Interdisciplinary Journal of Environmental and Science Education, 17*(2), Article e2238. https://doi.org/10.21601/ijese/9340

Borish, V., & Lewandowski, H. J. (2024). Student reasoning about quantum mechanics while working with physical experiments. *Physical Review Physics Education Research, 20*, Article 020135. https://doi.org/10.1103/PhysRevPhysEducRes.20.020135

Born, M. (1926a). Quantenmechanik der Stoßvorgänge [Quantum mechanics of collision processes]. *Zeitschrift für Physik, 38*(11), 803-827. https://doi.org/10.1007/BF01397184

Born, M. (1926b). Zur Quantenmechanik der Stoßvorgänge [On the quantum mechanics of collision processes]. *Zeitschrift für Physik, 37*(12), 863-867. https://doi.org/10.1007/BF01397477

Bouchée, T., Thurlings, M., de Putter, L., & Pepin, B. (2021). Investigating teachers' and students' experiences of quantum physics lessons: Opportunities and challenge. *Research in Science & Technological Education, 41*(2), 777-799. https://doi.org/10.1080/02635143.2021.1948826

Buzzell, A., Atherton, T. J., & Barthelemy, R. (2025). Quantum mechanics curriculum in the U.S.: Quantifying the instructional time, content taught, and paradigms used. *Physical Review Physics Education Research, 21*, Article 010102. https://doi.org/10.1103/PhysRevPhysEducRes.21.010102

Clauser, J. F. (2002). Early history of Bell's theorem. In R. A. Bertlmann, & A. Zeilinger (Eds.), *Quantum (un)speakables. From Bell to quantum information* (pp. 61-98). Springer. https://doi.org/10.1007/978-3-662-05032-3_6

Clough, M. P. (2018). Teaching and learning about the nature of science. *Science & Education, 27*(1-2), 1-5. https://doi.org/10.1007/s11191-018-9964-0

Coles, A., Rodriguez-Muniz, L. J., Mok, I. A. C., Ruiz, A., Karsenty, R., Martignone, F., Osta, I., Ferretti, F., & Nguyen, T. T. A. (2023). Teachers, resources, assessment practices: Role and impact on the curricular implementation process. In Y. Shimizu, & R. Vithal (Eds.), *Mathematics curriculum reforms around the world. The 24th ICMI study* (pp. 291-321). Springer. https://doi.org/10.1007/978-3-031-13548-4_18

Dirac, P. A. M. (1939). A new notation for quantum mechanics. *Mathematical Proceedings of the Cambridge Philosophical Society, 35*(3), 416-418. https://doi.org/10.1017/S0305004100021162

Donhauser, A., Bitzenbauer, P. Q., Heusler, S., Küchemann, S., Kuhn, J., & Ubben, M. S. (2024). Empirical insights into the effects of research-based teaching strategies in quantum education. *Physical Review Physics Education Research, 20*, Article 020601. https://doi.org/10.1103/PhysRevPhysEducRes.20.020601

Erduran, S., & Dagher, Z. R. (2014). *Reconceptualizing the nature of science for science education: Scientific knowledge, practices and other family categories*. Springer. https://doi.org/10.1007/978-94-017-9057-4

Giliberti, M., & Lovisetti, L. (2024a). *Old quantum theory and early quantum mechanics: A historical perspective commented for the inquiring reader*. Springer. https://doi.org/10.1007/978-3-031-57934-9

Giliberti, M., & Lovisetti, L. (2025a). *Heisenberg's 1925 "Umdeutung" paper. A commented translation from a physicist's perspective*. Springer. https://doi.org/10.1007/978-3-031-96921-8

Giliberti, M., & Lovisetti, L. (2025b). Teaching quantum mechanics within a nature-of-science framework. *American Journal of Physics, 93*(2), 172-179. https://doi.org/10.1119/5.0210636

Giliberti, M., Karwasz, G., Lovisetti, L., Organtini, G., Rosi, T., Onorato, P., Oss, S., Surace, G., & Tufino, E. (2025). Cultural understanding of physics: Instruments and methods. In Z. Ješková, & J. Hanč (Eds.), *Advancing physics education. Innovations from early learning to higher education* (pp. 177-197). Springer. https://doi.org/10.1007/978-3-031-94207-5_11

Greca, I. M., & Freire Jr, O. (2014). Teaching introductory quantum physics and chemistry: Caveats from the history of science and science teaching to the training of modern chemists. *Chemistry Education Research and Practice, 15*(3), 286-296. https://doi.org/10.1039/C4RP00006D

Heering, P. (2023). Transformations: The material representation of historical experiments in science teaching. *The British Journal for the History of Science, 56*(3), 351-368. https://doi.org/10.1017/S0007087423000274

Heisenberg, W. (1925). Über quantentheoretische Umdeutung kinematischer und mechanischer Beziehungen [On the quantum-theoretical reinterpretation of kinematic and mechanical relationships]. *Zeitschrift für Physik, 33*(1), 879-893. https://doi.org/10.1007/BF01328377

Hennig, F., Tóth, K., Veith, J., & Bitzenbauer, P. (2024). Introducing quantum physics concepts and Dirac notation at the secondary school level: Insights into student reasoning from an acceptance survey *Physical Review Physics Education Research, 20*, Article 020147. https://doi.org/10.1103/PhysRevPhysEducRes.20.020147

Holton, G. (1978). *The scientific imagination: Case studies*. Cambridge University Press.

Irwin, A. R. (2000). Historical case studies: Teaching the nature of science in context. *Science Education, 84*(1), 5-26. https://doi.org/10.1002/(SICI)1098-237X(200001)84:1<5::AID-SCE2>3.0.CO;2-0

Justi, R., & Gilbert, J. (2000). History and philosophy of science through models: Some challenges in the case of 'the atom'. *International Journal of Science Education, 22*(9), 993-1009. https://doi.org/10.1080/095006900416875

Kortam, N., Hugerat, M., & Mamlok-Naaman, R. (2021). The story behind the discovery: Integrating short historical stories in science teaching. *Chemistry Teacher International, 3*(1), 1-8 https://doi.org/10.1515/cti-2019-0016

Kragh, H. (1984). Equation with the many fathers. The Klein-Gordon equation in 1926. *American Journal of Physics, 52*(11), 1024-1033. https://doi.org/10.1119/1.13782

Krijtenburg-Lewerissa, K., Pol, H. J., Brinkman, A., & van Joolingen, W. R. (2017). Insights into teaching quantum mechanics in secondary and lower undergraduate education. *Physical Review Physics Education Research, 13*, Article 010109. https://doi.org/10.1103/PhysRevPhysEducRes.13.010109

Lederman, N. G. (2007). Nature of science: Past, present, and future. In S. Abell, & N. G. Lederman (Eds.), *Handbook of research on science education* (pp. 831-879). Routledge.

Lederman, N. G., Abd-El-Khalick, F., Bell, R. L., & Schwartz R. S. (2022). Views of nature of science questionnaire: Toward valid and meaningful assessment of learners' conceptions of nature of science. *Journal of Research in Science Teaching, 39*(6), 497-521. https://doi.org/10.1002/tea.10034

Lovisetti L., Melli, E., Giliberti, M. (2024). "The elegance of quantum mechanics": A didactic path for high school. *Journal of Physics: Conference Series, 2750*, Article 012022. https://doi.org/10.1088/1742-6596/2750/1/012022

Lovisetti, L. (2024). "Can old quantum theoretical description of physics be rendered coherent?": A pilot experimentation for high schools. *Il Nuovo Cimento C, 47*(5), Article 277. https://doi.org/10.1393/ncc/i2024-24277-6

Lovisetti, L., & Giliberti, M. (2025a). Can old-quantum-theoretical description of physical reality be considered worth teaching? In I. Testa, M. Michelini, & S. Esposito (Eds.), *Connecting physics education research and practice* (pp. 155-172). Springer. https://doi.org/10.1007/978-3-031-86609-8_10

Lovisetti, L., & Giliberti, M. (2025b). Thomson's alleged "plum pudding": A model that could never stand (yet persists in the minds and imagination of many physicists). *Il Nuovo Cimento C, 48*(6), Article 290. https://doi.org/10.1393/ncc/i2025-25290-y

Lovisetti, L., & Giliberti, M. (2026). Scientific modeling and the nature of science: The case of Thomson's atom. *American Journal of Physics, 94*(7), 547–554. https://doi.org/10.1119/5.0318972

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), Article 200. https://doi.org/10.1393/ncc/i2023-23200-1

Matthews, M. R. (2014). *Science teaching: The contribution of history and philosophy of science*. Routledge. https://doi.org/10.4324/9780203123058

Matthews, M. R. (2024). Thomas Kuhn and science education. Learning from the past and the importance of history and philosophy of science. *Science & Education, 33*(3), 609-678. https://doi.org/10.1007/s11191-022-00408-1

McAfee, S. C., Watts, F. M, & Rodriguez, J.-M. G. (2025). A review of research on the teaching and learning of quantum mechanics. *Chemistry Education Research and Practice, 26*(3), 578-593. https://doi.org/10.1039/D5RP00030K

Mermin, N. D. (1989). What's wrong with this pillow? *Physics Today, 42*(4), 9-10. https://doi.org/10.1063/1.2811173

Merzel, A., Weissman, E. Y., Katz, N., & Galili, I. (2024). Mathematical structures in quantum physics education for high school students: Unveiling the power of Dirac notation for conceptual and problem-solving proficiency. *Physical Review Physics Education Research, 20*, Article 020134. https://doi.org/10.1103/PhysRevPhysEducRes.20.020134

Michelini, M., Pospiech, G., Faletič, S., & Stefanel, A. (2021). GIREP community on teaching/learning quantum physics in secondary school. *Journal of Physics: Conference Series, 1929*, Article 012044. https://doi.org/10.1088/1742-6596/1929/1/012044

Monk, M., & Osborne, J. (1997). Placing the history and philosophy of science on the curriculum: A model for the development of pedagogy. *Science Education, 81*(4), 405-424. https://doi.org/10.1002/(SICI)1098-237X(199707)81:4<405::AID-SCE3>3.0.CO;2-G

National Quantum Initiative. (2025). National quantum initiative. *Quantum*. https://www.quantum.gov/

Niaz, M., Klassen, S., McMillan, B., & Metz, D. (2010). Reconstruction of the history of the photoelectric effect and its implications for general physics textbooks. *Science Education, 94*(5), 903-931. https://doi.org/10.1002/sce.20389

Pronskikh, V., & Sorina, G.V. (2022). Expert text analysis in the inclusion of history and philosophy of science in higher education. *Science & Education, 31*(4), 961-975. https://doi.org/10.1007/s11191-021-00280-5

Quantum Flagship. (2025). Quantum flagship. *QT*. https://qt.eu/

Stadermann, H. K. E., & Goedhart, M. J. (2021). Why and how teachers use nature of science in teaching quantum physics: Research on the use of an ecological teaching intervention in upper secondary schools. *Physical Review Physics Education Research, 17*, Article 020132. https://doi.org/10.1103/PhysRevPhysEducRes.17.020132

von Neumann, J. (1932). *Mathematische Grundlagen der Quantenmechanik* [Mathematical foundations of quantum mechanics]. Springer.

APPENDIX A: QUESTIONNAIRE AND INTERVIEW INSTRUMENTS

Table A1 reports the questionnaire items and semi-structured interview prompts used in the study. The items were adapted from existing NOS and HPS-oriented instruments and reworded in order to fit the specific context of QM education. For each item, the table indicates the NOS / HPS dimension to which it primarily refers, the QM-contextualized formulation used with participants, and the data source from which responses were collected. In the case of semi-structured interviews, the prompts were used flexibly, allowing follow-up questions when clarification or further elaboration was needed.

Although each item is associated in the table with a primary NOS / HPS dimension, participants' responses were not necessarily coded with a single mutually exclusive category. During the qualitative analysis, responses were segmented into meaning units, and each unit could receive more than one code when multiple dimensions were present. For instance, a response concerning the provisional status of quantum models and their historical succession could be coded both as NOS—tentativeness and as historical reasoning. For the quantitative comparison, these dimensions were then operationalized as presence / absence indicators in participants' responses.

Prior to the study, the questionnaire and interview protocol underwent a preliminary validation process combining content and face validation. The correspondence between items and the intended NOS / HPS dimensions was reviewed by researchers involved in physics education and history of physics, while a pilot version of the instrument was administered to first-year graduate students enrolled in the University of Milan courses "Preparation of didactic experiences 1" and "Preparation of didactic experiences 2."

Selected items were also tested with upper-secondary-school students to examine comprehensibility across different educational levels. Participants were invited to identify ambiguous wording and explain how they interpreted the questions. Their feedback led to minor revisions of item formulations before the final administration.

Table A1. Questionnaire items and interview prompts used in the study, with the corresponding NOS / HPS dimensions and data sources

Item	Original NOS / HPS dimension	QM-contextualized formulation	Data source
Scientific models	Models as conceptual and epistemic tools	How did the historical development of quantum models influence your understanding of the role and nature of scientific models in physics?	Google Form / interview
NOS—tentativeness	Scientific knowledge is tentative but durable	How did the historical succession of quantum models affect your understanding of scientific knowledge as provisional, revisable, yet empirically grounded?	Google Form
General NOS understanding	Science as a human, dynamic, and historically situated enterprise	What has the historical development of quantum theory taught you about how science works?	Google Form / interview
Historical experiments	Experiments as historically situated practices	How did the discussion of historical experiments, such as the Franck–Hertz, Millikan, Lenard, or Stern–Gerlach experiments, affect your understanding of quantum physics?	Google Form
NOS-theory-observation relationship	Theory and observation are interdependent	How did the historical development of quantum theory affect your understanding of the relationship between theoretical assumptions and the interpretation of experimental observations?	Google Form / interview
Theory-experiment dynamics	Scientific progress through the reciprocal interaction of theory and experiment	What does the history of quantum theory reveal about how science progresses through the interaction of theory and experiment?	Google Form / interview
Historical reasoning	Historical development of scientific concepts	How did the transition from classical physics to quantum theory influence your understanding of scientific progress?	Google Form
Creativity and imagination in science	Science involves creativity and imagination	In what ways did the historical reconstruction of early quantum theory help you recognize the creative and imaginative aspects of scientific work?	Google Form
Non-linearity of scientific progress	Scientific development is complex and non-linear	What aspects of the history of quantum theory helped you understand that scientific progress is not always linear or cumulative in a simple way?	Google Form / interview
Textbook representations	Relation between historical experiments and modern educational reconstructions	Did comparing original historical experiments with their modern textbook representations change your understanding of how quantum physics is usually taught? If so, how?	Google Form / interview

Table A1 (Continued).

Item	Original NOS / HPS dimension	QM-contextualized formulation	Data source
Conceptual understanding of QM	Relation between formalism, concepts, and historical development	Did the historical approach help you clarify any conceptual aspects of QM that you had previously found difficult or obscure? Please explain.	Google Form
Distinction between old quantum theory and QM	Historical and conceptual differentiation between precursor models and formal theory	How did the course help you distinguish between early quantum models, such as Planck's, Einstein's, or Bohr's contributions, and the formulation of QM as a coherent theory?	Google Form / interview
Social and cultural embeddedness of science	Social and cultural factors can influence scientific development	What did the history of QM teach you about the role of social, institutional, or cultural contexts in the development of science?	Google Form
Ethical and cultural responsibility in science	Social responsibility, academic freedom, and cultural embeddedness of scientific knowledge	How did the historical development of QM affect your understanding of the ethical and cultural responsibilities involved in producing, communicating, and teaching scientific knowledge?	Google Form / interview
Ethical and socio-political dimensions of science	Influence of institutional power structures and processes of marginalization in scientific development	What impact did learning about the suppression or marginalization of certain lines of inquiry in the history of quantum mechanics have on your understanding of science and your role as an educator?	Google Form
Interpretative issues in QM	Role of interpretation in the construction and communication of scientific meaning	How did the historical discussion of interpretative debates in QM influence your understanding of the meaning of quantum concepts?	Interview
Pedagogical awareness	Recognition of the educational value of HPS perspectives	In what ways, if any, could historical and epistemological perspectives be integrated into your own teaching of quantum physics or modern physics?	Google Form / interview
Pedagogical integration	Translation of historical-epistemological reflection into teaching practice	Can you describe a possible teaching activity, lesson, or didactic pathway in which you would use the history of QM to support students' understanding?	Interview
Critical reflection on science education	Awareness of limitations of purely formal or ahistorical instruction	Did the course change your view of how QM is commonly presented in school or university teaching? Please explain.	Interview
Overall reflection on the intervention	Integrated understanding of the NOS through historical case studies	Looking back at the course, which historical or philosophical aspects of QM were most significant for your understanding, and why?	Interview