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Changes in Critical Thinking through Philosophical Strategies in Quantum Physics Education

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Abstract

This paper examines the effect of philosophical didactics on university students approaching for the first time the study of quantum phenomenology, as an ideal discipline to observe the reactions and modifications in the way of thinking, before the change of paradigm that supposes the transition between classical and modern physics, and the appearance of different interpretations of quantum physics. For this purpose, a transversal research is designed, with a qualitative approach and a methodology based on content analysis, on a group of twenty students, with the support of the theory of conceptual change, with which to encourage the use of the three highest levels of critical thinking (analysis, synthesis and evaluation) according to Bloom's taxonomy, through a didactic sequence based on Socratic debates on the topics proposed therein, without overemphasizing mathematical methods. The evaluation instrument, designed by the authors and validated by experts, consists of twenty-one open-ended questions, distributed over the ten sessions of the didactic sequence, collecting readings of popular articles and expert videos. During the intervention carried out in 2024, the examination of the answers to the questionnaire and the observation of the reactions and attitudes suggest that the strategy contributes to a progressive improvement of the skills of the analysis and synthesis abilities, but it is not conclusive for the evaluation. The changes detected in the mental structures and ways of thinking of the students are compatible with the acceptance of a coexistence between the classical models (often erroneous) and the modern ones, with one or the other being selected depending on the context and not always correctly. A longer intervention period is necessary to confirm these results.

Keywords: *Critical Thinking, Bloom's Taxonomy, Philosophical Didactics, Teaching Quantum, Conceptual Change.*

1. Introduction

1.1 Research Problem

The low level of critical thinking with which students enter university is one of the factors contributing to the increase in course cancellations and school dropouts [1], demanding innovative solutions from the pedagogical field to avoid repeating the same procedures that lead to negative outcomes [2]. Quantum physics offers an ideal field to study original methodologies that do not emphasize mathematics but instead aim to extract the full critical potential of students. For example, this can involve fostering less common practices such as philosophical reflections and Socratic debates, which are particularly suitable for addressing new paradigms and potential conceptual changes that arise in the transition from classical to modern physics.

1.2 Background

Although critical thinking can be measured with a generalist approach using classical instruments [3] such as the Watson Glaser Critical Thinking, California Critical Thinking Skills, California Critical Thinking Disposition Inventory, Cornell Critical Thinking Test, Halpern Critical Thinking Assessment using Everyday Situations (HCTAES), Ennis-Weir Critical Thinking Essay Test, etc., there are studies in the literature focused on the learning of quantum mechanics with their own methodologies and instruments [4-9]. Some of these studies examine the conceptual changes produced when transitioning from classical to modern physics [10], with the philosophical method becoming an

increasingly used resource by teachers, even with young children [11]. However, it is in quantum learning where its implementation is most applicable [7, 12, 13].

From an examination of this background, it was deduced that the approaches are predominantly quantitative, relying on closed-question surveys and lacking measurement instruments with open-ended questions in quantum physics to qualitatively assess the levels of critical thinking displayed. Furthermore, it was found that philosophical strategies in teaching methods are generally implemented superficially.

1.3 General Objective

Given this background, a study was designed with the general objective of qualitatively evaluating the evolution of critical thinking skills achieved through the primary use of philosophy among university students encountering the wave-particle duality for the first time in engineering programs. The research sought to answer the question: How do critical thinking skills change when philosophy is used as the main resource for university students encountering wave-particle duality for the first time in engineering programs at a Colombian Caribbean university over four weeks?

1.4 Justification

This study is educationally justified by the limited presence of philosophical thinking and Socratic debates in classroom development, which constrains problem-solving reasoning. Additionally, due to the unique features of quantum mechanics, with its standard and alternative interpretations, it provides an ideal experimental field to test critical thinking and philosophical interpretation. From a social perspective, it is justified by the need to combat school dropout rates with innovative strategies, addressing the shortage of engineering professionals in Colombia, where the research is being conducted.

2. Theoretical Framework

Based on the philosophical didactics proposed by Sumiacher [14], which rest on four pillars: knowledge reflection, identification of key teaching points, classroom dialogue, and reflective closure of all sessions, the study drew on Bloom's taxonomy of critical thinking skills [15]: Knowledge, Comprehension, Application, Analysis, Synthesis, and Evaluation, as outlined in his renowned work: Taxonomy of Educational Objectives. Additionally, the work of Cano & Álvarez [16] was considered: Critical Thinking: A Framework for its Measurement, Understanding, and Development from the Cognitive Perspective, which applies this taxonomy in a practical manner. For quantum physics concepts focused on the wave-particle duality issue, works addressing both the Copenhagen interpretation (the standard) and alternatives were considered [17], implementing the conceptual change-based educational learning theory developed by Moreira & Greca [18].

3. Methodology

A longitudinal study with a qualitative approach was designed, based on a content analysis of the responses provided by 20 engineering students to questions distributed throughout a didactic sequence over four weeks. This sequence was used while they were learning the basic concepts of wave-particle duality through a philosophical strategy.

3.1 Didactic Sequence

The sequence consisted of 10 sessions, each lasting 100 minutes. Each session began with a video or reading of a scientific dissemination article related to quantum principles or another thought-provoking reading, taking up 30 minutes. Students then had 30 minutes to write responses to an open-ended question related to the previous topic. Finally, a Socratic dialogue lasting 40 minutes—the core component of the philosophical strategy—was conducted. This didactic sequence was reviewed and adjusted after several pilot tests, culminating in the final version in 2024: (https://view.genially.com/65cb753ff6eacd001449cfd0/interactive-image-secuencia-didactica-final)

3.2 Evaluation Instruments

The design of the questionnaire, class planning, and development of Socratic debates followed the recommendations of the Inter-American Teacher Education Network [19], which provides rules for correctly drafting questions according to the critical thinking skill being investigated. Initially, 40 open-ended questions were included, distributed across the six levels of thinking and the ten sessions of the intervention, plus a final test. The instrument was validated by experts before being integrated into the final version of the didactic sequence. While the research was being conducted, notes were taken to record the students' reactions and confidence during the Socratic dialogues, gathering information on how they addressed new paradigms.

3.3 Content Analysis

Qualitative analysis was conducted through deductive (pre-assigned) categorization, classifying and coding the responses based on Bloom's work [15] and Cano & Álvarez's framework [16], resulting in the system presented in Table 1.

Table 1. Assignment of categories and codes for the qualitative analysis of critical thinking

Levels of Thinking	Categories	Main Codes	Subcategories and Subcodes		
			To Abstract	To Generalize	To Infer
Analysis	of Elements	AE	AEE	AEG	AEI
	of Relationships	AR	ARE	ARG	ARI
	of Principles	AP	APE	APG	API
			To Collect	To Predict	To Conclude
Synthesis	in Communication	SC	SCR	SCP	SCC
	In the Production of a Plan	SP	SPR	SPP	SPC
	In the Derivation of Abstract Relationships	SA	SAR	SAP	SAC
			To Assess	To Criticize	To Argue
Evaluation	According to Internal Criteria	EI	EIV	EIC	EIG
	According to External Criteria	EE	EEV	EEC	EEG

Additionally, for each category, an extra distinction was introduced: positive (+), when the skill demonstrated by the student was deep, meaningful, or accurate; and negative (–), when it was superficial, less meaningful, or inaccurate. For each of the final categories, a record was kept of the number of positive and negative assessments, yielding a ratio r, which was later analyzed to study its evolution. Using these codes, the responses provided in the questionnaire were categorized with the support of the qualitative analysis software Atlas.ti.

$$r = \frac{\mathrm{COD}(+) - \mathrm{COD}(-)}{\mathrm{COD}(+) + \mathrm{COD}(-)}$$

Definitions:

"COD" (+): Number of positive codings for the specific code COD
"COD" (–): Number of negative codings for the specific code COD

To associate a category with the questionnaire responses, the definitions and examples provided by theoretical frameworks on critical thinking were used as references. This categorization process was carried out in two distinct stages of the research to ensure the reliability of the process.

4. Results

4.1 Pilot Tests

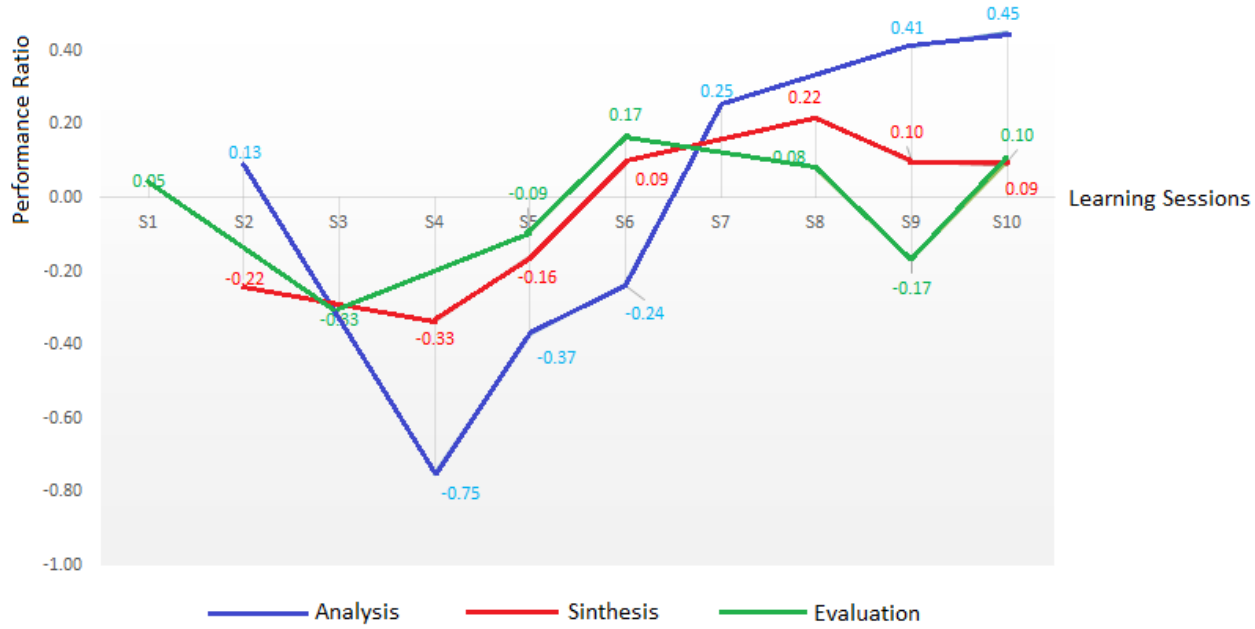
Two pilot tests were conducted during 2023, leading to the 2024 version, deciding that the study would focus solely on the higher levels (Analysis, Synthesis, and Evaluation), since the lower levels (Knowledge, Comprehension, and Application) are usually better developed through more traditional methodologies. Additionally, the final test was eliminated, as it was not considered necessary to assess the progression session by session during the intervention. The instrument was reduced to 24 questions, eight for each skill.

This version was submitted for validation by judges, requesting them to evaluate the coherence, relevance, clarity, and sufficiency of the questions. The panel of experts consisted of seven professors, all with experience teaching university students in science or engineering, three with doctoral training and the rest with master's degrees or specializations in education, university teaching, physics, or other scientific fields. Aiken's V coefficient was used as an index to determine the degree of agreement. Regarding the criteria for accepting a question as valid, the statistical information provided by 95% confidence intervals was used, adopting a minimum value for the lower bound of that interval [20], equal to 0.7. After some corrections and eliminations, the final version included a total of 21 open-ended questions, seven for each of the three higher-order critical thinking skills.

4.2 Analysis of Results

The process of categorizing the responses given by students during 2024 yielded the ratios shown in Figure 1, which, together with the session-by-session recorded reports, served to make an initial assessment of the evolution of critical thinking.

Fig. 1. Evolution of critical thinking components by session



Note. The three skills of critical thinking demonstrated divergent patterns during the 10 sessions: analysis exhibited the most variability, with a significant decline followed by a robust recovery; synthesis exhibited a more stable trend, with gradual improvement; and evaluation presented moderate oscillations. In summary, critical thinking skills demonstrated an improvement over the course of the study.

a) Analysis Skill: The first session that tested the Analysis skill showed an almost complete absence of Principle Analysis, revealing a clear reluctance to infer. During the next session, there was a sharp drop in performance when students had to analyze an article discussing the influence of Louis de Broglie's doctoral thesis on Einstein's thinking. The drop from a ratio of 0.13 to -0.75 for the Analysis skill should not be surprising, considering the greater difficulty of the topic and the reduced possibility

of making inferences without errors. The deficiencies in making abstractions, with a large number of negative codifications, resulted in empty reflections that hindered their ability to follow the Socratic debate. The students accepted new proposals with resignation, unable to rigorously analyze the article examined, mainly due to difficulties in identifying the principles underlying De Broglie's and Einstein's ideas, even confusing those of each scientist. The rest of the sessions reflected a progressive increase in the ratio and apparent consolidation during the last three sessions.

b) Synthesis Skill: At the beginning of the teaching sequence, students showed great difficulty combining ideas, which translated into poor synthesized communication. The topic of this first session (S2) forced students to draw on prior knowledge, revealing a wide range of information they possessed, although much of it was incorrect. In the next session where synthesis ability was evaluated (S4), attempts to combine ideas were still clumsy for most participants, as they debated the topic of the stable orbit of the electron in the hydrogen atom. The lack of technical resources and weak scientific foundation hindered their ability to associate the concept of a standing wave (proposed in the debate and questionnaire question) with that of a stable trajectory. The strategies they displayed, in the form of plans or models, recorded as many positive codifications as negative ones, demonstrating the ability to devise sound strategies for solving the problem, but again, they were unable to coherently communicate these ideas. From the following session onward, the ratio showed a clear upward trend, similar to what happened with the Analysis skill, introducing complex topics that drew out many students' capacities to derive abstract relationships and reach sound conclusions. The last two sessions showed a slight drop in performance, likely due to the high complexity of the topics discussed. Despite this, the ratios remained positive, driven by good results in the Synthesis category for Plan Production, indicating that, although some of the final conclusions or predictions were incorrect, the way ideas were gathered and combined to propose a meaningful solution was effective.

c) Evaluation Skill: From the first session, a tendency to use far more internal than external criteria was observed, something to be expected in these early weeks, with poorly reasoned opinions. However, the development of the remaining sessions did not show a clear trend in the ratio. With the exception of session 3, the rest remained within a ratio range of 0 ± 0.2. An avoidance of responses was evident, a symptom of a lack of confidence in basic principles, making them appear as unreliable arguers.

4.3 Discussion

There are no studies that, using philosophical strategies in quantum physics education, have assessed the evolution of higher-order critical thinking levels based on Bloom's taxonomy, making comparative studies challenging. The low abstraction capacity found at the start of the research—essential for analysis skills—aligns with the views and results of other researchers [6], while inferences and critical abilities, which decline when the topic delves into deeper aspects of the discipline, are consistent with works such as those of Stadermann & Godeart [8]. This may be due to the obstacle students face when connecting quantum concepts with real-world applications or because they are asked to debate concepts that are not well-defined, such as measuring, observing, and interacting [9].

The Evaluation skill—the highest level of critical thinking according to Bloom's original taxonomy—poses the greatest interpretative and comparative challenges with other studies. Moreover, the handling of internal and external criteria is expressed differently by other authors [21]. They consider external criteria those used by external sources and criticized by students; whereas, in this research and Bloom's taxonomy, they refer to criteria from external sources that students use to support their critiques, placing the argumentative burden outside the students.

It can be affirmed that, during the course of the teaching sequence, the use of philosophical strategy and Socratic debates had positive effects on critical thinking, as well as an increase in participation, aligning with observations from other researchers who have introduced this methodology in their physics and history of physics classes [22] or in quantum subjects [12]. Authors like Greca & Freire [23] prefer realistic interpretations as a philosophical approach to reach students' minds, which has been shown to be the method they naturally adopt [13]. Emphasizing the philosophical-qualitative aspect rather than the mathematical-theoretical one does not appear to have negatively impacted how students solved the exercises proposed during the sequence. Therefore, overloading classes with

mathematical formalism does not indicate that students will better apply higher-order critical thinking levels, something that can also be deduced from the results and conclusions presented in works like those of Böe & Viefers [7].

Regarding the examination of conceptual change, it is observed that classical paradigms remain deeply rooted in students' minds, and their misconceptions complicate the assimilation of new ones [24], making the transition to quantum models more challenging. This is particularly evident in problems such as measurement, which require greater abstraction efforts that are not necessary in classical physics [5]. Modifications in prior conceptual structures become noticeable when students analyze texts from the discipline, revealing the ontological conflicts predicted by Zuccarini & Malgieri [10], that is, a psychological need to bridge previous and new ideas naturally emerges. Among the patterns of conceptual change identified by these authors, categorical generalization stands out as the most commonly employed strategy by students — the extension of a known concept's meaning to encompass its quantum version. Field notes taken during the sequence show students' forced attempts to fit modern physics into their preconceived ideas, resulting in an apparent coexistence of two models [18]: they either apply entirely classical ideas or respond with the quantum paradigm, but without fully grasping the boundaries between the two models.

5. Limitations

In addition to the pending in-depth qualitative analysis, using co-occurrence tables of the categories generated during the research, the design of a measurement instrument focused on quantum learning—independent of the teaching strategy—has not achieved consensus within the research community [25], as revealed during the validation of the critical thinking assessment instrument used in this study. A similar issue arises with the arbitrary introduction of philosophy into a quantum physics course [26]. Furthermore, when viewing the research from a broader perspective, it seems clear that an intervention extended over a longer period, comparing results from different groups, ages, and prior training, could yield more significant outcomes. The revision of the questionnaire's own questions, despite passing the validation criteria set by judges, remains open to changes and improvements, even considering the nature of the debate topics proposed during the teaching sequence. The uniqueness of this strategy—isolated from other subjects and instructors—as well as the researcher's lack of experience in conducting Socratic debates, may also limit the effectiveness of the results.

6. Conclusion

After designing a sequence based on philosophical strategies that fostered higher-order critical thinking skills in engineering students as they approached quantum physics for the first time, progressive improvements were observed in their ability to Analyze and Synthesize. However, the assessment of Evaluation skills did not reveal any clear trends: this last skill, which demands the most advanced abilities, did not produce conclusive results, giving the impression that students only improve in it depending on the topic or context, without being able to consistently maintain the level required to critique and reason with sound arguments. This seems to stem from their inability to consolidate an effective method that systematically relies on external criteria — that is, supporting their claims with evidence. Students accumulate different mental models, resorting to one or another depending on the context, so there is no eradication of prior ideas; these may resurface naturally when faced with changes, for example, in the way a particular question is formulated. Therefore, previous (erroneous) and new (correct) ideas coexist, adapting to each other. The research remains incomplete without a deeper content analysis, supported by co-occurrence tables of identified categories, to more efficiently achieve the objective proposed in this study.

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