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STRUCTURAL KNOWLEDGE GAINS IN PHYSICS THROUGH CONCEPTUAL QUESTIONS AND PEER INSTRUCTION

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Abstract: This study examines the impact of integrating Conceptual Questions and Big Scientific Ideas (BSI) within Peer Instruction cycles on students' conceptual development in physics, with a focus on lifelong learning (LLL) competencies. Conducted in four 8th-grade classrooms in Moldova ($N = 110$), the intervention targeted a six-lesson unit on Electrokinetics. Two classes ($n = 57$) received instruction embedded with Conceptual Questions and peer dialogue, while two others ($n = 53$) followed traditional instruction. Results show that students in the experimental group achieved significantly higher post-test scores ($M = 7.37, SD = 2.23$) compared to the control group ($M = 5.98$, $SD = 2.14$), with a strong negative skew (skewness = –0.585) indicating a higher concentration of top scores (mode = 10). Paired-samples t-tests revealed a meaningful gain in the experimental group ($\Delta M = +0.895$, $d = 0.534$, $p < .001$), while no significant change occurred in the control group ($\Delta M = -0.075$, $d = 0.044$, $p = .752$). Correlation analyses demonstrated strong associations between final marks and both declarative ($r = .902$) and conditional knowledge ($r = .905$), particularly in the experimental group, where effect sizes exceeded $z = 1.49$. Procedural knowledge showed moderate correlations ($r = .635$). ANCOVA confirmed a significant group effect after controlling for pre-test scores ($F(1,107) = 9.528$, $p = .003$; $\eta^2_p = 0.082$), with the instructional method emerging as a consistent predictor of post-test performance beyond prior knowledge ($\eta^2_p = 0.399$). These findings validate the use of Conceptual Questions as a scalable strategy for enhancing conceptual reasoning, contextual transfer, and metacognitive engagement in physics education. The approach not only improved learning outcomes but also reduced variability and fostered equitable performance growth across diverse student profiles. Thus, embedding BSI and Conceptual Questions into instructional design can meaningfully advance LLL competencies without requiring curricular overhaul.

Key words: Conceptual Questions, peer instruction, lifelong learning competencies, physics education, dimensions of scientific knowledge.

1. Introduction

Within the broader educational imperative of promoting lifelong learning (LLL) skills, physics education holds significant potential for fostering conceptual reasoning, knowledge transfer, and self-regulated learning. This study builds on prior research on conceptual understanding in physics education (Crouch & Mazur, 2001; Buggé, 2023), emphasizing the role of Conceptual Questions and Big Scientific Ideas in cultivating deeper learning outcomes in school science. These LLL skills are not developed through rote memorization or formulaic approaches, but through instructional designs that prioritize reasoning, explanation, and metacognitive reflection.

This study investigates the use of Conceptual Questions, grounded in Big Scientific Ideas, as a tool to support students in constructing and articulating scientific understanding in physics. The aim is not only to assess conceptual comprehension but also to observe how such questions, used regularly throughout instruction, contribute to students' ability to explain phenomena, justify reasoning, and challenge misconceptions. While equation-based problem solving remains an important component of physics instruction, Conceptual Questions offer a complementary pathway by directing students' attention toward the underlying conditions, causal mechanisms, and reasoning that govern scientific principles. This shift supports not only conceptual clarity but also the broader aims of competence-based education and the development of lifelong learning skills.

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In order to analyze students' learning in more detail, the study adopts a three-dimensional framework of scientific knowledge: declarative knowledge (factual understanding), conditional knowledge (recognition of when and why concepts apply), and procedural knowledge (the ability to use concepts in solving problems). This classification allows for a more nuanced evaluation of conceptual development and supports differentiated insight into learning gains beyond overall test scores.

The research was carried out in the 2023–2024 academic year at "Mihai Eminescu" High School in Ungheni, Republic of Moldova, involving four 8th -grade classes totaling 110 students. An experimental group received instruction centered on Conceptual Questions across a full unit on Electrokinetics, while a control group was taught the same content using conventional methods, with both groups having access to the same curriculum, materials, and teacher. Learning outcomes were measured using pre- and post-tests specifically constructed to probe the three dimensions of knowledge described above.

The findings demonstrate that the experimental group showed substantial improvement compared to the control group in all knowledge categories. Notably, the most pronounced gains were observed in conditional knowledge, suggesting that students became better able to determine when and why to apply physical principles in varied contexts. Declarative and procedural knowledge also improved, though to a slightly lesser extent. These trends reflect the capacity of Conceptual Questions to deepen students' reasoning and promote flexible understanding of physics concepts.

From a pedagogical perspective, the study suggests that fostering LLL competencies in school physics does not require curriculum reform or additional resources. Rather, it calls for a deliberate reconfiguration of lesson structure in which reasoning, explanation, and conceptual challenge are placed at the forefront of instructional practice. By regularly engaging with well-structured Conceptual Questions, students consolidate factual knowledge while also developing the cognitive flexibility and metacognitive control essential to lifelong learning in science.

The structure of the article is as follows. Section 2 introduces the conceptual foundations of the study, including the role of Big Scientific Ideas, the use of Conceptual Questions, and the triadic model of scientific knowledge. Section 3 describes the instructional intervention, classroom context, and design of the assessment instruments. Section 4 presents the statistical analysis of learning outcomes in the Electrokinetics unit. It begins with descriptive statistics, followed by correlation analysis, paired and independent samples t-tests, and an ANCOVA model to control for initial differences. The results demonstrate that students in the experimental group made significantly greater gains across all knowledge categories, particularly in conditional understanding. These findings suggest that structured use of Conceptual Questions can enhance students' ability to reason with scientific principles in context, a core feature of lifelong learning competencies. Section 5 examines both the theoretical and empirical implications of the intervention. It highlights how the integration of Big Scientific Ideas, Conceptual Questions, and Peer Instruction fosters not only conceptual understanding but also key lifelong learning competencies such as self-regulation, adaptive transfer, and metacognitive reflection. The analysis also shows that the intervention led to significantly higher and more consistent learning outcomes compared to traditional instruction, with reduced variability and stronger alignment between conceptual reasoning and performance.

2. Theoretical framework

2.1. Learning Science through Conceptual Reasoning

In contemporary science education, the formation of lifelong learning (LLL) competencies is increasingly recognized as a core objective. These include not only conceptual understanding, but also the ability to transfer knowledge across contexts, engage in sustained inquiry, and self-regulate one's learning processes which are essential skills in both academic and real-world problem-solving (OECD, 2019).

Developing such competencies requires instructional models that go beyond factual recall. Theories of conceptual change emphasize that learners must confront and revise pre-existing mental models in order to construct deeper, more coherent scientific knowledge (Heddy et al., 2018). This process is facilitated by structured cognitive conflict and opportunities for students to actively engage with core disciplinary ideas.

Conceptual reasoning lies at the heart of this process. In physics, learners must grasp abstract relationships (e.g., between current, voltage, and resistance) and apply them across diverse contexts. Achieving this demands the integration of declarative (*what*), conditional (*when* and *why*), and procedural (*how*) knowledge. When students learn to reason across these dimensions, they develop flexible cognitive structures that support lifelong transfer and application (Chi, 2009).

Moreover, the development of LLL skills is tightly linked to metacognitive engagement or learners' ability to monitor, evaluate, and regulate their own thinking. This self-directed awareness supports perseverance in the face of cognitive challenges and fosters independence in scientific inquiry (Schraw & Moshman, 1995). A related perspective is proposed by Calalb (2023), who introduces the constructivist model of Learning by Being, emphasizing students' ownership of cognitive goals and the importance of guided self-scaffolding, intrinsic motivation, and the integration of Big Scientific Ideas in school physics lessons.

Instructional environments that incorporate peer discussion, reflection, and active knowledge construction, such as those based on Peer Instruction and Conceptual Questions, have been shown to cultivate these skills. When students explain their reasoning, challenge each other's ideas, and justify conceptual claims, they engage in high-level cognitive and metacognitive practices that align with lifelong learning goals (Pérez & Galli, 2024).

This study adopts such a framework by positioning conceptual reasoning not only as a path to disciplinary mastery, but also as a key enabler of transferable, durable, and self-regulated learning competencies essential for lifelong learning in science.

2. 2. Peer Instruction and Conceptual Questions: Mechanisms and Impact

Peer Instruction (PI), initiated by Eric Mazur, remains one of the most widely researched active learning methods in physics, having been adapted across diverse educational settings. A recent study published in Physical Review Physics Education Research investigates the specific elements of the PI cycle, such as conceptual questioning, voting, or peer discussion, and shows that these discussions play a central role in facilitating conceptual transfer, even when compared to instructor explanations (Gjerde & Hagane, 2024).

At the heart of the method are Conceptual Questions presented through clickers or polling systems. A recent study by Calalb and Dabija (2024) shows that using these questions regularly, even without a comprehensive formative assessment structure, fosters active learning and collaborative problem-solving. This approach improves students' conceptual understanding and engagement, making it a valuable strategy in physics instruction. Furthermore, multiple-choice questions, also referred to as Concept Tests, function as effective formative assessment tools by supporting the application of physics concepts in peer-based learning contexts (Gok, 2014). Similar diagnostic approaches, such as the use of Concept Cartoons to reveal and address misconceptions in science topics like pressure, have also proven effective in guiding targeted peer discussions and conceptual restructuring (Sari & Çakir, 2024).

An innovative approach introduced in 2022 is the use of isomorphic questions, posed immediately after peer discussions, to verify authentic conceptual understanding. A study in the field of mathematics education demonstrated that this sequence (initial question – peer discussion – isomorphic question) leads to improved authentic reasoning and reduces the chance of superficial answer copying (Lan et al., 2023).

In a 2025 multi-institutional comparative analysis, it was shown that PI generates significantly greater conceptual gains than traditional methods, placing it among the top active learning strategies in university-level physics (McInerny et al., 2025).

Finally, a study conducted during physics micro-lessons highlights that integrating Conceptual Questions during instruction transforms the lesson into an active dialogue, increases student engagement, and makes their thinking visible to the instructor (Bauer et al., 2023).

Thus, recent literature confirms that Conceptual Questions are more than diagnostic tools – they are catalysts for collaborative reasoning, co-construction of meaning, and metacognitive monitoring, all of which are essential for durable learning in physics.

2. 3. Types of Knowledge and Their Role in Learning Physics

Effective physics education develops students' capacity to integrate factual understanding, conditional reasoning, and procedural fluency into coherent knowledge structures that support long-term transfer, adaptive expertise, and self-directed learning. These characteristics lie at the core of lifelong learning (LLL) and are increasingly emphasized in science education research (Tong et al., 2025).

Declarative knowledge involves the ability to recall facts, definitions, and conceptual principles. It provides the semantic foundation for scientific discourse and theoretical reasoning. However, according to theoretical frameworks and empirical evidence, declarative knowledge, when isolated from contextual application, does not lead to durable or transferable learning (Bittermann et al., 2023). Its instructional value increases when it is mobilized in response to authentic problem settings that require students to interpret, compare, and justify relationships between concepts (Thacker, 2023).

Conditional knowledge refers to recognizing when and why specific principles or models apply. It is essential for navigating uncertainty, transferring knowledge across domains, and making informed decisions in novel situations. Recent research highlights that instructional designs such as Decision-Based Learning (DBL) explicitly aim to enhance students' conditional knowledge by guiding them through branching decision-making scenarios and contextualized scaffolding (Jeong et al., 2025). Recent findings in physics education research confirm that conditional knowledge is the strongest predictor of conceptual understanding, as it reflects the learner's ability to activate and adapt ideas based on context (Xu et al., 2020). This flexibility supports critical aspects of LLL competence, including cognitive adaptability and metacognitive awareness (Ulu & Yerdelen-Damar, 2024).

Procedural knowledge pertains to knowing how to execute operations, such as conducting experiments, applying formulas, or using instruments. While often associated with technical competence, procedural knowledge becomes more effective when paired with conceptual guidance and opportunities for self-explanation, enhancing both understanding and transfer (Matthews & Rittle-Johnson, 2009). Studies have demonstrated that when students articulate their procedural strategies and evaluate their effectiveness, they engage in metacognitive regulation that reinforces both understanding and autonomy—two central attributes of lifelong learners (Dulger & Ogan-Bekiroglu, 2025).

Instructional designs that intentionally connect these three knowledge types can transform classroom practice into a platform for building durable scientific thinking. One such approach is the Learning by Being (LBB) model, which emphasizes guided learning effort, student ownership of cognitive goals, and teacher–student feedback as key components for achieving conceptual understanding in science education (Calalb, 2021). This cyclic engagement fosters knowledge integration and reflective habits that sustain learning beyond the classroom and throughout life. Thus, Peer Instruction enhances both accuracy and confidence by engaging students in collaborative reasoning, fostering explanatory coherence and reflective thinking which are the key processes for deep, transferable learning (Tullis & Goldstone, 2020).

3. Research Design and Methodology

3. 1. Participants and Educational Context

This study was conducted in the context of lower secondary education (Grade 8) in the Republic of Moldova, within a theoretical high school located in the city of Ungheni. A total of 110 students participated in the research, drawn from four 8th-grade classes. Two classes (VIII-A and VIII-D, $N = 57$) formed the experimental group, and two others (VIII-B and VIII-C, $N = 53$) served as the control group.

All students were 14–15 years old and followed the national curriculum in physics, with the topic of Electrokinetics taught during the "Electromagnetic Phenomena" unit. Instructional content in both groups was aligned with the official curriculum of the Ministry of Education and Research of the Republic of Moldova (MECC, 2020), which emphasizes the development of conceptual understanding, practical skills, and scientific reasoning in lower secondary education.

The learning environment reflected standard classroom conditions. Students were seated in pairs, with the control group working predominantly in frontal lessons, while the experimental group engaged in structured group activities during at least four of the six sessions. These group-based sessions included collaborative experiments, problem-solving tasks, and peer discussions driven by Conceptual Questions. The aim was to foster interaction, collective reasoning, and the co-construction of knowledge, which are core tenets of research-based science education. Furthermore, the learning environment was designed to support socially shared metacognition, an attribute inherent to classrooms that implement Conceptual Questions which has been shown to foster multiple positive effects on learning (Krieger et al, 2022).

Classes were taught by the same physics teacher, who is familiar with research-based instructional strategies. Seating arrangements were preserved as originally established by the students and the school, based on their preferences at the beginning of the academic year. No external reshuffling or experimental grouping was introduced.

The unit on Electrokinetics was selected due to its conceptual richness and suitability for investigating higher-order learning. As a topic that links physical models, symbolic reasoning, and everyday applications, it provided an appropriate platform for testing the effectiveness of the integrated instructional approach involving Big Scientific Ideas (Harlen, 2010) and Conceptual Questions (Mazur & Somers, 1999). Moreover, Electrokinetics allows for the comprehensive assessment of all three types of knowledge – declarative, conditional, and procedural. Students are required to recall definitions and laws, apply formulas in varied contexts, construct electric circuits, and operate measurement instruments such as voltmeters and ammeters. This multifaceted structure makes the topic particularly well-suited for evaluating the depth, transferability, and coherence of student understanding.

3. 2. Instructional Design and Intervention

The instructional intervention spanned six consecutive lessons within the unit on Electrokinetics, based on the Grade 8 national curriculum (MECC, 2020). In the experimental group, the instructional design explicitly incorporated two pedagogical principles: the use of Big Scientific Ideas to frame conceptual learning, and Conceptual Questions to guide peer instruction and elicit metacognitive reflection.

Each lesson was anchored in one or two core ideas identified as central to understanding electric circuits, such as:

- *Electric current is the same at all points in a series circuit*;
- *Potential difference is shared among components*;
- *Resistance depends on both the properties and geometry of the conductor*.

These ideas were made explicit by the teacher at the beginning of each lesson, often as conceptual learning goals, and revisited through targeted questions and problem contexts. The teacher encouraged students to relate new content to these overarching scientific generalizations, helping them structure their understanding more coherently.

A total of six Conceptual Questions were implemented throughout the unit. These questions for formative evaluation:

- were aligned with the progression of conceptual complexity;
- contained well-constructed distractors reflecting common misconceptions (e.g., confusing current and voltage);
- were posed using the Turning Point clicker system, allowing students to respond individually and anonymously during class.

Furthermore, the use of Conceptual Questions functioned not only as a cognitive activation tool, but also as a mechanism of formative assessment within the instructional process. By providing immediate feedback, surfacing student thinking, and enabling the teacher to adjust instruction responsively, these questions supported what Hattie (2023) defines as Visible Teaching and Learning (VTL) which is a model where learning becomes transparent to both students and teachers, and teaching decisions are informed by real-time evidence of understanding. In this sense, formative use of Conceptual Questions played a dual role: facilitating conceptual development and enabling continuous instructional adaptation.

After the initial vote, students engaged in peer discussions in small groups, then voted again. This two-phase cycle fostered reflection and dialogue. The teacher facilitated brief plenary discussions after each question to clarify reasoning and connect student thinking with the relevant Big Ideas. This sequence promoted social metacognition and deeper conceptual processing (Krieger et al., 2022).

Lessons 2 and 3 involved guided inquiry-based labs, where students worked in teams to measure current and voltage, graph results, and infer relationships such as Ohm's Law and resistance equivalence. These sessions emphasized conceptual discovery grounded in experimentation, with real-time Conceptual Questions used to support transitions from observation to abstraction.

Lessons 4 and 5 shifted toward complex problem-solving tasks. These required students to analyze unfamiliar circuit configurations, justify conclusions using theoretical principles, and predict outcomes. Each task was introduced with a Big Scientific Idea reminder and concluded with structured reflection prompts (e.g., "*How does this problem demonstrate the distribution of potential difference in a series circuit?*").

Lesson 6 consisted of a common summative test administered identically in both groups.

In contrast, the control group received traditional instruction based on textbook exposition and direct problem solving, without explicit reference to Big Scientific Ideas or Conceptual Questions.

This intervention aimed to strengthen not only content retention but also the development of integrated and transferrable understanding, scientific reasoning, and metacognitive regulation which are key indicators of deep learning in science education (OECD, 2023).

3. 3. Instruments and Data Collection

In order to evaluate the cognitive impact of the instructional intervention, a pre-test/post-test design was employed (on a 1–10 scale). The pre-test scores were derived from students' results on the final summative assessment of the previous unit, entitled *"Thermal Phenomena"*, which had been taught using traditional instruction based on the *Physics Textbook for 8th Grade* (Botgros et al., 2024). This approach ensured that both groups began the Electrokinetics unit with documented performance levels based on similar content complexity and standard assessment practices.

The post-test, administered at the end of the six-lesson instructional sequence on Electrokinetics, consisted of six items aligned with three types of knowledge:

- Declarative knowledge (Items 1–3): factual recall, laws, definitions;
- Conditional knowledge (Items 4–5): conceptual application in varied contexts;
- Procedural knowledge (Item 6): operational use of instruments such as voltmeters and ammeters.

The test carried a total of 32 points, distributed proportionally: 43.75% for declarative knowledge, 40.63% for conditional, and 15.62% for procedural. The structure of the test reflects the specific cognitive weight of these knowledge domains within the topic of Electrokinetics, in line with both national curricular expectations and international research. Declarative and conditional knowledge were emphasized due to their stronger association with conceptual depth and transfer, while procedural knowledge, though essential, had a more supportive role.

In the experimental group, six Conceptual Questions were integrated into selected lessons using the Turning Point clicker system. These questions were not included in the data analysis but were used exclusively as a tool to support the construction of conceptual understanding through peer discussion and teacher feedback. They were employed primarily during lessons focused on the introduction of new concepts or laboratory exploration. In contrast, during the lessons devoted to problem-solving, Conceptual Questions were not used; instead, students engaged in the analysis of complex exercises and real-world problem scenarios that required deeper reasoning, integration of prior knowledge, and structured justification.

Together, these instruments enabled descriptive, correlational, and inferential statistical analyses which are presented in Section 4. The data allowed for evaluating not only the magnitude of learning gains but also the differential contribution of each knowledge domain to academic performance.

4. Statistical Analysis of Learning Outcomes in Electrokinetics

4. 1. Descriptive Statistics

The final evaluation results for the Electrokinetics unit were collected from two experimental classes (n = 57) and two control classes (n = 53), yielding a relatively balanced sample size between groups. This balance enhances the validity of group comparisons. As shown in Table 1, the experimental group demonstrated a notably higher level of performance: the mode was 10, indicating that a substantial number of students achieved the top mark. In contrast, the most frequent mark in the control group was 6, suggesting a tendency toward moderate performance levels and a lack of concentration near excellence (see Fig. 1 and Fig. 2).

Table 1. Descriptive statistics for final evaluation results in experimental and control groups

	Mark	
	Experimental	**Control**
Valid number of students	57	53
Mode	10.000	6.000
Median	8.000	6.000
Mean	7.368	5.981
Std. Deviation	2.225	2.144
Skewness	-0.585	0.013
Std. Error of Skewness	0.316	0.327
Shapiro-Wilk	0.918	0.957
P-value of Shapiro-Wilk	< .001	0.052
Minimum	1.000	2.000
Maximum	10.000	10.000

The median in the experimental group was 8.0, meaning that at least half of the students scored 8 or higher. In contrast, the control group had a median of 6.0, indicating a more modest level of achievement. The mean score further supports this observation: students in the experimental group averaged 7.37, while those in the control group averaged 5.98. This difference of approximately 1.4 points (on a 0–10 scoring scale) represents a substantial shift in central tendency, providing preliminary evidence of a global performance advantage in favor of the experimental group exposed to Conceptual Questions.

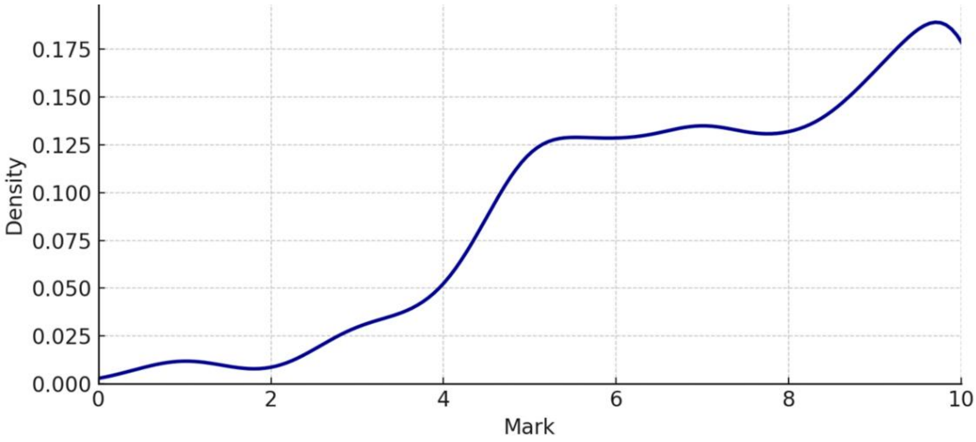

Figure 1. Kernel density estimate of post-test marks in the experimental group (*n* = 57).

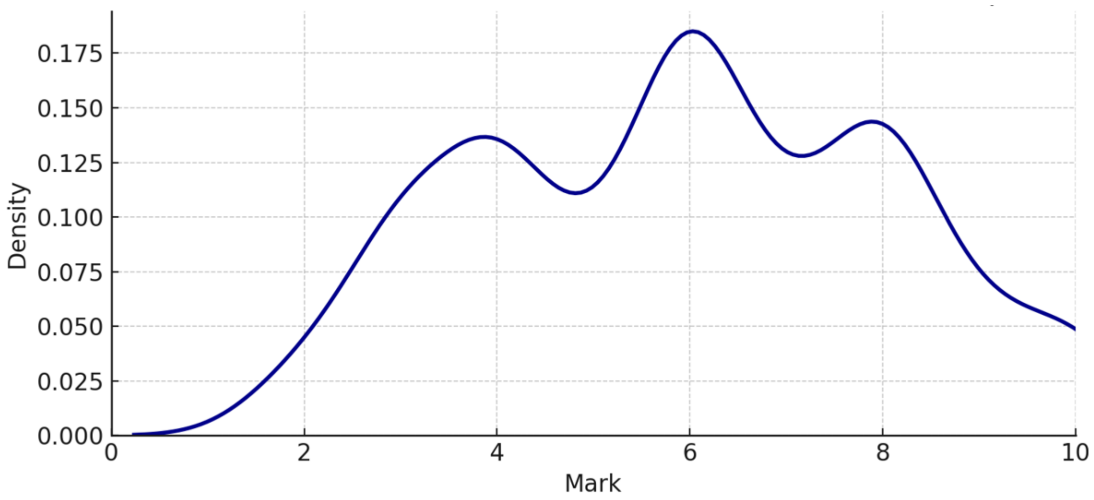

Figure 2. Kernel density estimate of post-test marks in the experimental group (*n* = 53).

The distribution curve in Figure 1 reveals a strong rightward skew, indicating a high concentration of top-performing students in the experimental group. In contrast, Figure 2 shows a more fragmented and symmetric profile in the control group, with marks distributed across a broader range and fewer clustered at the upper end.

Standard deviations were similar across the two groups (2.23 in the experimental group and 2.14 in the control group), indicating a comparable degree of variability in student performance. However, a standard deviation greater than 2 on a 10-point scale reflects a relatively wide spread of scores in both cases. This suggests that students' marks were not tightly clustered around the mean, but rather dispersed across a broader range of performance levels. In the experimental group, this dispersion may reflect a differentiated impact of the Conceptual Questioning approach—benefiting many students substantially, while others may have required more scaffolding to engage effectively with abstract reasoning.

The skewness statistic reveals further differences between groups. In the experimental group, skewness was negative (−0.585), indicating that scores were skewed toward the higher end of the distribution—i.e., most students achieved high marks, with fewer low-performing outliers. This aligns with the mode of 10 and reflects a right-weighted performance profile consistent with strong academic outcomes. In contrast, the control group had a skewness value near zero (0.013), suggesting a nearly symmetrical distribution of scores around the mean. This symmetry implies a more balanced spread of performance but also a lack of concentration at the top end of the scale.

Shapiro–Wilk normality tests confirmed these patterns. The distribution of scores in the experimental group deviated significantly from normality ($p < .001$), consistent with the clustering of high marks and a skewed profile. The control group's p-value (.052) indicated approximate normality, with no extreme tendencies toward high or low scores. Pedagogically, these results suggest that the Conceptual Questions method contributed to a meaningful shift in student performance for a significant portion of the class—though not uniformly—whereas traditional instruction maintained a more evenly distributed, average-level outcome.

The range of marks adds another dimension to the analysis. In the experimental group, scores ranged from 1 to 10, whereas in the control group, the lowest mark was 2 and the highest was also 10. Despite the lower minimum in the experimental group, the fact that 10 was both the maximum and the mode suggests a strong concentration of top performers. This indicates that the Conceptual Questions approach enabled a substantial number of students to reach high levels of achievement. At the same time, the presence of very low marks points to variability in how individual students responded to this strategy—some may have struggled with the abstract nature of conceptual reasoning or lacked prerequisite knowledge.

By contrast, the narrower range in the control group (2 to 10), combined with a mode and median of 6, reflects a more constrained learning outcome. Traditional instruction appears to have produced a moderate but uniform level of performance, with fewer outliers—either positive or negative. Pedagogically, the broader score range in the experimental group implies greater cognitive activation and diversity of learning outcomes. It also highlights the importance of incorporating differentiated support strategies to ensure that all students can benefit from conceptual teaching methods.

4. 2. Correlation Analysis

Table 2 presents the strength of association between students' final marks and their levels of declarative, conditional, and procedural knowledge in both instructional groups. Results show that declarative and conditional knowledge are highly and consistently correlated with performance, with Pearson's *r* values exceeding 0.89 across the board. In the experimental group, where Conceptual Questions were applied, correlations surpass 0.90, reinforcing the relevance of factual mastery and contextual reasoning in supporting learning outcomes.

Table 2. Pearson and Spearman correlations between final mark and students' declarative, conditional, and procedural knowledge in experimental and control groups

		Overall			**Experimental group**			**Control group**		
		Knowledge			Knowledge			Knowledge		
		Decl.	Cond.	Proced.	Decl.	Cond.	Proced.	Decl.	Cond.	Proced.
Mark	Pearson's r	0.894	0.898	0.620	0.902	0.905	0.635	0.887	0.923	0.582
	p-value	< .001	< .001	< .001	< .001	< .001	< .001	< .001	< .001	< .001
	Effect size (Fisher's z)	1.440	1.460	0.725	1.480	1.498	0.750	1.409	1.608	0.666
	SE Effect size	0.097	0.097	0.097	0.136	0.136	0.136	0.141	0.143	0.141
	Spearman's rho	0.890	0.911	0.640	0.868	0.917	0.602	0.888	0.947	0.581
	p-value	< .001	< .001	< .001	< .001	< .001	< .001	< .001	< .001	< .001
	Effect size (Fisher's z)	1.422	1.532	0.758	1.326	1.569	0.696	1.414	1.806	0.664
	SE Effect size	0.107	0.108	0.102	0.148	0.150	0.142	0.154	0.160	0.147

Procedural knowledge, although significantly associated with final marks ($r \approx 0.58–0.64$), plays a more modest role. This difference in predictive power is further evidenced by the effect sizes (Fisher's *z*), which range from 1.4–1.6 for declarative and conditional knowledge (large effects), and approximately 0.66–0.76 for procedural knowledge (moderate effects).

Interestingly, the control group exhibited even stronger conditional correlations (*z* up to 1.81), despite the absence of explicit conceptual scaffolding. This suggests that conditional reasoning is a robust and general predictor of performance, possibly reflecting prior learning habits or intuitive understanding.

In contrast, the experimental group demonstrated slightly higher procedural correlations, hinting at a better integration between conceptual understanding and practical execution. This synergy may result from instructional emphasis on "*when*" and "*why*" to apply scientific principles, not just "*how*".

Pedagogically, these findings highlight that instructional strategies influence not only what students learn, but how different types of knowledge interact to support academic success. The correlation patterns suggest that Conceptual Questions may enhance the coherence of students' knowledge structures, fostering flexible reasoning even in procedural tasks.

Furthermore, the magnitude of observed effects—particularly for conditional knowledge—exceeds the average impact of established instructional techniques, such as feedback ($d \approx 0.73$) or metacognitive training ($d \approx 0.69$) (Hattie, 2023). This positions conceptual teaching as a high-leverage strategy for improving science learning outcomes.

These results are consistent with theories of deep learning and conceptual change (e.g., Sawyer, 2014), underscoring the value of instruction that cultivates transferable reasoning patterns rather than rote procedures.

4. 3. Paired samples T-test and independent T-test

In order to evaluate the internal learning gains within each instructional group, a paired samples *t*-test was applied to compare students' pre- and post-test scores. As presented in Table 3, the experimental group achieved a statistically significant improvement, with an average gain of nearly one point (mean increase from 6.47 to 7.37; *d* = 0.534). This reflects a moderate effect size and indicates meaningful progression in learning throughout the instructional sequence.

Table 3. Pre–Post Comparisons and Effect Sizes in Experimental and Control Groups on Electrokinetics Unit

		N	**Mean**	**SD**	**SE**	**Coeff. of variation**	**t**	**p**	**Cohen's d**	**SE Cohen's d**
Experimental	Pre-Test	57	6.474	1.428	0.189	0.221	4.030	1.000	0.534	0.117
	Post-test	57	7.368	2.225	0.295	0.302				
Control	Pre-Test	53	6.057	1.646	0.226	0.272	0.318	0.752	0.044	0.121
	Post-test	53	5.981	2.144	0.294	0.358				

Note. For all tests, the alternative hypothesis specifies that Post-Test is greater than Pre-Test.

In contrast, the control group showed no substantial change in performance (*d* = 0.044), and their post-test average slightly decreased. This stagnation, despite traditional instruction, raises concerns about the ability of conventional methods to generate cognitive advancement when abstract reasoning is required (Buggé, 2023).

A notable pattern emerges when examining the coefficients of variation: post-instruction variability increased in both groups, but far more steeply in the control group (from 0.27 to 0.36, compared to 0.22 to 0.30 in the experimental group). This suggests a polarization effect—greater disparity in student outcomes when support for conceptual processing is lacking. Meanwhile, the broader variation in the experimental group may reflect divergent but productive learning paths, typical of constructivist environments (Chi, 2009).

Beyond average improvement, these findings illustrate how differentiated learning trajectories can emerge from the same pedagogical intervention. While not all students progressed equally, the trend toward growth in the experimental group points to the potential of Conceptual Questions to stimulate individual cognitive engagement, a cornerstone of learner-centered instruction (Gjerde & Hagane, 2024).

In sum, the observed within-group progress highlights not only the efficacy of the intervention, but also the importance of instructional designs that accommodate variability in how students assimilate and reorganize knowledge. These dynamics, often overlooked by global metrics, are central to building responsive and equitable science education practices (Hattie, 2023).

To complement the within-group analysis, an independent-samples comparison was conducted to evaluate whether learning gains differed significantly between groups. Descriptive statistics for the gain scores (Post-Test minus Pre-Test) are summarized in Table 4. Given that the marking system operates on a scale from 1 to 10, the learning gain observed in the experimental group (mean = 0.895) reflects a notable improvement. In contrast, the control group's negative mean (–0.075) suggests a slight decline, highlighting divergent trajectories of learning impac

Table 4. Group Descriptives for Independent T-test

	Group	**N**	**Mean**	**SD**	**SE**	**Coeff. of variation**	**Mean rank**	**Sum rank**
Gain	Control	53	-0.075	1.730	0.238	-22.927	45.981	2437.000
	Experimental	57	0.895	1.676	0.222	1.874	64.351	3668.000

Although standard deviations were similar (1.676 vs. 1.730), the coefficient of variation draws a sharper contrast. The negative Coeff. Var. in the control group (–22.93%) reflects a lack of coherent learning pattern—possibly symptomatic of fragmented understanding or random performance shifts. In contrast, the low and positive Coeff. Var. of the experimental group (1.87%) signals a more stable and convergent learning effect, despite individual differences. See Fig. 3 for a visual representation of group gain differences.

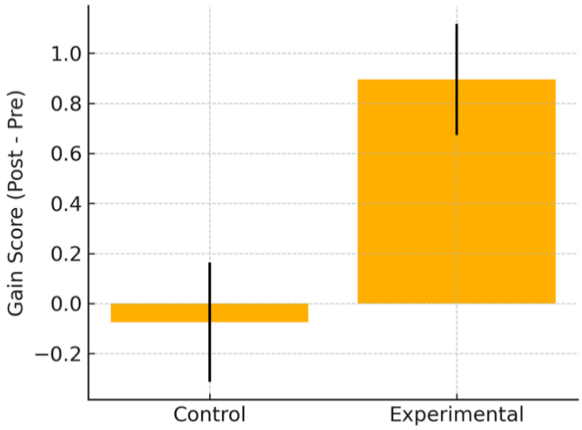

Figure 3. Mean gain scores by group.

Rank-based measures further reinforce these findings: the higher mean rank of the experimental group (64.35 vs. 45.98) indicates that gains were not only larger on average but also more consistently distributed across students. This pattern is pedagogically significant, as it suggests that the intervention fostered collective improvement rather than isolated successes.

From a teaching perspective, these data underscore an important outcome: when instruction is structured around conceptual scaffolding, learning gains become more coherent across the group. This reduces performance volatility often observed under conventional instruction and creates a more equitable cognitive trajectory for a diverse classroom.

Further, to determine whether the observed learning gains differed significantly between groups, both a parametric (Student's *t*-test) and a non-parametric (Mann–Whitney *U*) test were employed. As shown in Table 5, the results of both analyses confirmed the advantage of the experimental group.

Table 5. Independent Samples T-Test

	Test	Statistic	df	p	Effect Size	SE Effect Size
Gain	Student	2.986	108	0.002	0.570	0.199
	Mann-Whitney	1006.000		0.001	0.334	0.110

The *t*-test yielded $t(108) = 2.986$, $p = .002$, with a moderate effect size (Cohen's $d = 0.570$), suggesting that the intervention produced a meaningful shift in learning outcomes. The Mann–Whitney test supported this conclusion from a rank-based perspective ($U = 1006$, $p = .001$), with a smaller but still notable effect size ($r = 0.334$), reinforcing the robustness of the result across different statistical assumptions.

Rather than highlighting absolute gain values already discussed, these dual-confirmation results emphasize an essential pedagogical point: well-designed instructional interventions can yield effects that are not only statistically significant but also consistent across measurement frameworks. Such robustness strengthens the case for incorporating concept-driven teaching strategies in science education.

This convergent statistical evidence aligns with prior meta-analyses that identify moderate-to-large effects for strategies like formative feedback and metacognitive scaffolding (Hattie, 2023). The findings here suggest that Conceptual Questions represent a comparably effective approach, particularly in content areas requiring abstract reasoning and knowledge integration.

4. 4. Analysis of Covariance (ANCOVA)

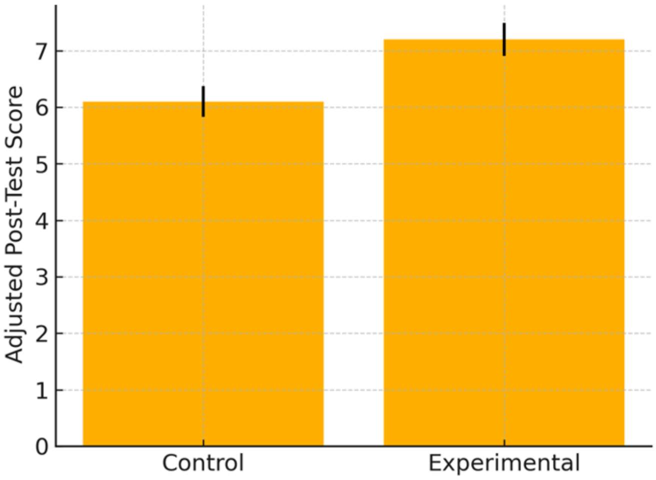

Figure 4. Estimated marginal means of post-test scores

To isolate the net instructional effect while controlling for baseline differences in student knowledge, an ANCOVA was conducted with post-test scores as the dependent variable, group (experimental vs. control) as the fixed factor, and pre-test scores as covariate. As presented in Table 6, the analysis revealed a statistically significant effect of instructional group, $F(1, 107) = 9.528$, $p = .003$. The corresponding partial eta squared ($\eta^2_p = 0.082$) indicates a small-to-moderate but educationally meaningful effect, independent of initial performance levels. The adjusted post-test scores, visualized in Figure 4, clearly show the advantage of the experimental group after controlling for baseline differences.

In addition, the pre-test score was a strong and significant covariate ($F = 70.941$, $p < .001$; $\eta^2_p = 0.399$), confirming the critical role of prior knowledge in predicting learning outcomes. This aligns with longstanding research emphasizing the cumulative nature of science learning (Buggé, 2023; Hattie, 2023).

Table 6. ANCOVA – Post Test Results

Cases	Sum of Squares	df	Mean Square	F	p
Exp-Control	27.643	1	27.643	9.528	0.003
Pre-test	205.814	1	205.814	70.941	< .001
Residuals	310.430	107	2.901		

To verify the validity of ANCOVA assumptions, Levene’s test for equality of variances was applied (see Table 7). The result ($p = .616$) indicates that the assumption of homogeneity was met, supporting the appropriateness of the model. Moreover, the use of Type III sums of squares ensured robust estimation in the presence of unequal sample sizes.

Table 7. Assumption Checks. Levene’s Test for Equality of Variances

F	df1	df2	p
0.253	1.000	108.000	0.616

Pedagogically, these findings are particularly relevant in diverse classroom contexts. While prior knowledge explains a large portion of performance variance, the instructional method exerted a distinct, additional effect. This suggests that conceptually structured instruction not only amplifies learning for high-performing students but also serves as a compensatory mechanism for those with weaker initial understanding.

Thus, ANCOVA provides converging evidence that the observed advantages in the experimental group are not artifacts of pre-existing ability, but rather direct consequences of the pedagogical intervention.

The statistical control reinforces the broader conclusion that Conceptual Questions foster robust, equitable learning gains in physics education.

5. Discussions and Conclusions

5. 1. Theoretical Reappraisal of the Pedagogical Model

The results of this study reinforce the growing consensus that physics education at the secondary level can serve not only to develop conceptual knowledge but also to foster lifelong learning (LLL) competencies such as reflective thinking, adaptive transfer, and self-regulation, skills essential for actively participating in a knowledge-based society. These conclusions are consistent with findings from other studies conducted in Moldova, which have shown that constructivist instructional models such as the 5E approach, laboratory-based inquiry, and peer collaboration significantly improve academic performance in middle and high school physics education (Calalb & Zelenschi, 2024). This view is substantiated by studies in Physical Review Physics Education Research, which show that Research-Based Science Education (RBSE) strategies such as Peer Instruction and structured collaboration enhance students' capacity to build durable, transferable knowledge frameworks (Gjerde & Hagane, 2024; Tong et al., 2025). Moreover, evidence suggests that collaborative argumentation, when dialogic patterns emphasize deliberation and co-construction, can trigger lasting conceptual shifts, reinforcing learning beyond short-term performance gains (Li, 2023).

In this context, our instructional framework, grounded in Conceptual Questions and Big Scientific Ideas (BSI), has demonstrated its relevance not only for assessment improvement but also for promoting scientific reasoning that mirrors authentic disciplinary practice. This model combines BSI, Conceptual Questions, and Peer Instruction to form a learning ecosystem that privileges dialogue, critical engagement, and peer scaffolding over memorization or procedural training. Moreover, research confirms that Conceptual Questions alone can generate significant gains in conceptual understanding even outside full PI protocols, making them an efficient and scalable pedagogical tool (Lichtenberger et al., 2024). Thus, within our model, the systematic use of Conceptual Questions encouraged learners to verbalize, revise, and stabilize their mental models through socially mediated reasoning processes, activating lifelong learning components such as metacognitive monitoring and flexible problem-solving (Choudhary, 2024). This orientation toward active participation aligns with the view of Lamanauskas (2008), who emphasizes that engaging students in scientific research activities is a key component of science education in comprehensive schools, fostering both conceptual mastery and metacognitive development.

The pedagogical model applied in this research is founded on the premise that robust physics learning stems from integrating declarative, conditional, and procedural knowledge into coherent conceptual structures. Research on topics such as momentum confirms that instruction organized around conceptual coherence fosters deeper learning, particularly when students must interrelate definitions, rules, and applications into unified frameworks (Xu et al., 2023). Similarly, our intervention relied on Conceptual Questions embedded in Peer Instruction cycles to mobilize metacognitive processes. Students monitored their reasoning, questioned assumptions, and progressed toward conceptual alignment. As shown in a study on measurement uncertainty, such dialogic instruction promotes a transition from fragmented to expert-like explanatory patterns (Lu et al., 2023).

The greater internal consistency and reduced variability observed in the experimental group point to the role of peer-mediated conceptual clarification. Through structured discussion, learners revisited and refined their ideas, contributing to smoother learning curves and more predictable cognitive trajectories. Recent research confirms that peer interaction in science instruction mitigates disparities in prior knowledge and supports convergence in reasoning strategies (Sundstrom et al., 2025). Furthermore, analyses of classroom discourse patterns during Peer Instruction reveal that networked reasoning enables students to negotiate meaning effectively, operating as a compensatory force in diverse academic settings (Commeford et al., 2020).

In sum, the integration of Big Scientific Ideas, Conceptual Questions, and Peer Instruction constitutes a coherent and evidence-based pedagogical architecture capable of cultivating both conceptual understanding and lifelong learning competencies. Rather than merely enhancing performance in traditional evaluations, this model equips students with intellectual habits such as self-regulation, critical transfer, and reflective thinking that underpin sustained learning. This theoretical stance is aligned with comprehensive instructional frameworks such as the CIBSE model, which advocates for inquiry-based education grounded in conceptual reasoning and scaffolded metacognitive support, avoiding superficial investigation-centric implementations (Morris, 2025).

Finally, we have to underline that recent work has highlighted that pedagogies centered on epistemic cognition and metacognitive activation, such as our model, do more than improve test scores. They shape long-term learner identity and self-efficacy in physics. These traits are essential for preparing students not just to perform but to engage meaningfully with scientific knowledge throughout life (Ulu & Yerdelen-Damar, 2024).

5. 2. Key Empirical Findings and Educational Significance

Descriptive statistics show that students in the experimental group obtained higher mean, median, and modal post-test scores than those in the control group. This suggests a potential advantage of instruction based on Peer Instruction and Conceptual Questions over traditional teaching (Cheng, 2024). The negatively skewed distribution in the experimental group (skewness < 0, mode = 10) reflects two important aspects: (a) the method's potential to enhance performance among medium- and high-achieving students, as indicated by the clustering of marks near the top end; and (b) the presence of low scores, highlighting the need for additional support for lower-performing students. These findings underscore the need to further investigate the method's differential impact on high-, medium-, and low-achieving students.

Since declarative and conditional knowledge showed very strong correlations with post-test marks in both groups ($r > 0.89$), it can be concluded that conceptual understanding and contextual application are more predictive of performance in electrokinetics than procedural knowledge. Thus, conceptual change strategies—such as metacognitive prompts and Conceptual Questions—are associated with substantial improvements in physics learning, outperforming traditional approaches (Pacaci et al., 2024). Moreover, the slightly higher correlation for procedural knowledge in the experimental group suggests that Peer Instruction may support the integration of scientific reasoning with practical execution.

The significant difference between pre- and post-test scores in the experimental group ($d = 0.534$), in contrast to the non-significant change in the control group, can be attributed to the instructional design of the intervention, which involved the systematic use of Conceptual Questions (Kjolsing & van den Einde, 2016). These encouraged students to reason through problems, apply principles in varied contexts, and engage in metacognitive processing, thereby fostering cognitive restructuring and deeper knowledge retention. By contrast, the traditional instruction used in the control group did not provide sufficient stimulus for measurable improvement. Additionally, the gain variability was lower and positive in the experimental group (Coeff. Var. ≈ 1.87%), compared to the negative and unstable variation in the control group, suggesting that Peer Instruction may promote more coherent and balanced learning trajectories.

According to the ANCOVA results, the group effect remained statistically significant ($F(1, 107) = 9.528$, $p = .003$), indicating that the observed advantage in the experimental group cannot be explained by initial differences in prior knowledge, but rather by the quality of the intervention. While the pre-test score accounted for a substantial proportion of post-test variance ($\eta^2_p = 0.399$), the Peer Instruction approach provided an additional benefit, suggesting its potential role as a compensatory mechanism that helps reduce achievement gaps in heterogeneous classrooms (Theobald et al., 2020), particularly by enabling some medium achievers to reach higher performance levels.

5. 3. Limitations and Perspectives for Further Research

This study on structural knowledge gains in physics through Conceptual Questions and Peer Instruction marks an initial step toward understanding how these strategies can be leveraged to foster lifelong learning competencies. While our findings highlight clear benefits, the scope of this work also reveals natural avenues for expansion. The present investigation focused on a single 8th -grade cohort and on one curricular unit, Electrokinetics, which invites exploration of how the same instructional framework might be adapted to other physics topics or interdisciplinary contexts. The relatively short duration of the intervention leaves open important questions about long-term retention, transfer of knowledge to unfamiliar situations, and the sustained development of metacognitive and self-regulatory skills. Finally, although reflective prompts were systematically integrated into the learning process, we did not directly measure their impact on students' metacognitive regulation, an area that could yield valuable insights into how scientific reasoning matures over time. We see these elements not as limitations but as interconnected pathways for advancing research on how Conceptual Questions and learner-centered strategies can strengthen the structural, transferable knowledge that underpins lifelong learning in physics.

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