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Empowering Scientific Reasoning in Physics Education: An Integrated aPBL-STEAM and Cognitive Conflict Strategy for SDGs 4

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Abstract: In line with Sustainable Development Goal 4 (Quality Education), this study aims to enhance students' scientific reasoning skills in Newton's Laws by implementing the Authentic Problem-Based Learning (aPBL) model integrated with STEAM and Cognitive Conflict Strategies (CCS). Using an embedded experimental mixed-methods design, the study involved 69 high school students, divided into an experimental class (34) taught using the aPBL-STEAM-CCS model and a control class (35) using the standard aPBL model. Data collected via tests, observations, and interviews were analyzed using N-gain, t-tests, and qualitative coding. Quantitative results from the t-test confirmed that the experimental class performed significantly better than the control group ($p < 0.05$), supported by a high-category N-gain score of 0.73 compared to the control's moderate score of 0.45. Substantial gains were observed in correlational, proportional, and conservation reasoning. Qualitatively, CCS restructured logical frameworks by resolving misconceptions, while the Engineering Design Process (EDP) as the core framework of STEAM facilitated hypothesis testing. In conclusion, the integration of aPBL-STEAM-CCS provides a significantly more effective and contextual approach to improving scientific reasoning in physics education.

Keywords: aPBL; Cognitive conflict strategy; Newton's law; Scientific reasoning; STEAM

Introduction

Newton's Laws are a fundamental topic that students must master when studying mechanics (Rusilowati et al., 2021). Failure to master these laws will result in students facing difficulties with subsequent materials (Azzahidah et al., 2024). Previous research on Newton's Laws indicates that students struggle to connect one concept to another, leading to erroneous conclusions (Huda et al., 2022). Other studies also state that students are not yet capable of determining the relationships between variables, which results in low scientific reasoning abilities (Pascaeka et al., 2023). Scientific reasoning is crucial as it fosters students' capacity to apply logical and critical thinking skills in understanding and analyzing scientific concepts and phenomena (Kamaluddin et al., 2023). However, prior research shows that students' scientific reasoning remains suboptimal, particularly in specific indicators such as correlational, proportional, and conservation reasoning. Therefore, identifying an effective instructional strategy that can systematically bridge these conceptual gaps and foster optimal scientific reasoning in Newton's Laws is highly imperative.

Furthermore, advancing the targets of SDG 4 in the modern era necessitates the scaffolding of virtual technology and interactive digital packages, which effectively bridge raw abstract parameters into visible configurations, thereby boosting students' learning confidence and scientific literacy (Fitri et al., 2026). Implementing structured virtual classroom models explicitly ensures that the adoption of educational

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technology does not merely serve as a content delivery tool but actively functions as a high-level cognitive environment to reinforce students' critical thinking capacities (Lestari, 2026). In line with this, modern science pedagogy demands a paradigm shift that integrates global sustainability challenges into the curricula, framing abstract topics into context-rich scenarios to enhance classroom relevance and foster socially connected, independent thinkers (Poya, 2026). This global urgency is further highlighted by the recent decline in Indonesia's PISA science scores, which dropped from 396 in 2018 to 383 in 2022, signaling an immediate need for robust pedagogical interventions to rescue students' scientific competencies (Susilawati et al., 2026). Therefore, evaluating and mapping these contextual thinking profiles serves as a critical benchmark for designing targeted educational strategies in secondary physics education (Anjiana et al., 2026; Wati et al., 2026).

In the last five years, several efforts have been made to improve scientific reasoning. Various learning models and methods have been implemented, such as PjBL-STEM (Lorensia et al., 2024), e-scaffolding in instructional models (Yana et al., 2023), Problem-Based Learning (Ningrum et al., 2024), Creative Problem Solving (Nabillah et al., 2022), the Inquiry model (Ajijah et al., 2023), and the SSCS model (Nasir & Hayya, 2023). While these models encourage contextual hands-on activities, they often overlook the deep-rooted misconceptions students hold regarding forces, thereby failing to resolve the cognitive dissonance required to advance high-level scientific reasoning. A comprehensive review of modern science education reveals that traditional classroom activities remain heavily trapped under severe curriculum pressure and formula-centered tasks, leaving students structurally weak in constructing claims, evaluating counter evidence, or engaging in reflective scientific reasoning (Triana et al., 2026).

Furthermore, a bibliometric overview of recent educational trends confirms that while models like STEM/STEAM (21%), PjBL (11%), and PBL (6%) dominate modern science pedagogy to foster 21st-century skills, their successful execution remains deeply hindered by traditional, rote-centered classroom practices (Cahayana et al., 2026; Rahmawati et al., 2026). This procedural dominance traps students into superficial problem-solving, making them incapable of conducting deep conceptual analysis or identifying complex inter-variable correlations (Ardita et al., 2026; Cahayana et al., 2026). Consequently, students' scientific reasoning skills in understanding Newton's Laws have not yet developed optimally (Lorensia et al., 2024; Pascaeka et al., 2023). To address these limitations, the implementation of the STEAM-integrated aPBL model supported by CCS is proposed. A key characteristic of the aPBL model is its role in guiding students to identify specific variables through authentic real-world problems (Yuliati et al., 2018).

The novelty of this study lies in the systematic synergy of the aPBL-STEAM framework and CCS to address the gaps in students' logic during physics learning. While aPBL guides initial variable identification through authentic problems (Yuliati et al., 2018) and the Engineering Design Process (EDP) within STEAM provides a physical framework to concretely manipulate these variables (Nurtanto et al., 2020), CCS acts as the crucial cognitive bridge. Through CCS, students are prompted to resolve their misconceptions and restructure their logical frameworks when facing contradictory inter-conceptual relationships (Akmam et al., 2023). This integrated approach ensures that students do not merely identify isolated variables (Juliharti et al., 2024), but actively analyze the correlations, ratios, and conservation laws inherent in Newton's Laws (Juliharti et al., 2024; Subiki et al., 2023). By linking these theoretical physics principles to authentic sustainability outcomes, the learning cycle efficiently bridges classroom activities with real-world complexities, cultivating the necessary meta-skills for advanced scientific reasoning (Poya, 2026). Thus, the objective of this study is to enhance scientific reasoning on Newton's Laws through this unique triple strategy integration, providing a more holistic and robust conceptual transformation in physics education.

Method

This study employed a mixed methods approach with an embedded experimental design (Creswell, 2022), as illustrated in Figure 1.

The research was conducted in three sequential phases to ensure a comprehensive evaluation. The first phase, the pre-intervention phase, integrated both quantitative and qualitative techniques; it began with preliminary qualitative interviews with teachers and students, followed by a quantitative pre-measure involving a scientific reasoning pretest to map students' initial abilities regarding Newton's Laws. This quantitative baseline was further explored through qualitative interviews with a selected sub-sample of students. The second phase, the intervention phase, involved the implementation of the aPBL model integrated with STEAM and CCS (experimental group) and the standard aPBL model (control group). During this process, qualitative data were collected simultaneously through classroom observations, field notes, and documentation to monitor implementation fidelity according to the lesson plans (RPP). The final phase, the post-intervention phase, assessed the outcomes through a quantitative posttest using the same instrument as the pretest, accompanied by qualitative data from final interviews and student response questionnaires.

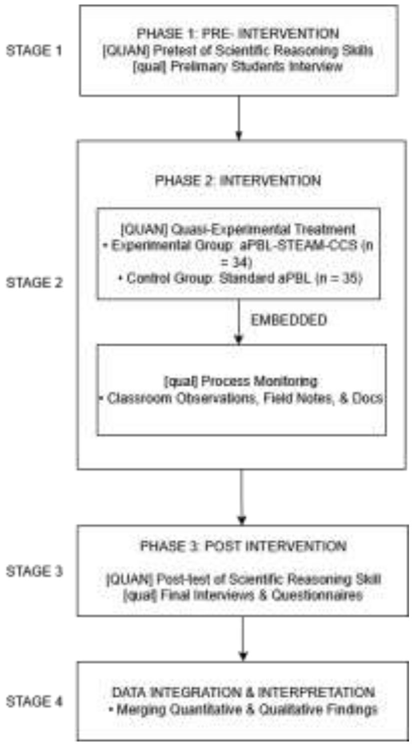

Figure 1. Research flowchart

The research subjects were 11th-grade high school students. The quantitative sample was selected through cluster random sampling, resulting in two intact classes: an experimental group taught using the aPBL-STEAM-CCS model and a control group using the standard aPBL model, totaling 69 students. For the qualitative phase, a sub sample of 4 students (consisting of 1 high, 2 medium and 1 low ability students) was selected using purposive sampling to ensure comprehensive representation. The quantitative instrument was a scientific reasoning skills test comprising 6 open-ended items. This instrument underwent empirical validity testing, demonstrating Cronbach's alpha reliability coefficient of 0.89. To ensure grading objectivity and minimize subjectivity in assessing these open-ended items, student responses were evaluated using a highly structured and validated scoring rubric, with grading consistency maintained through an intra-rater reliability approach. Meanwhile, qualitative instruments included learning observation sheets and a semi-structured interview guide, validated through source and method triangulation. Quantitative data were analyzed using normality and homogeneity tests, independent sample t-tests, and calculations of average normalized gain (N-gain) and effect size via IBM SPSS Statistics software (Creswell, 2022). Qualitative data were analyzed using data reduction, coding, and interpretation to derive comprehensive conclusions (Creswell, 2022).

Results and Discussion

Descriptive Statistics

The scientific reasoning scores were calculated based on the pretest and posttest scores for the topic of Newton's laws. Descriptive statistics for scientific reasoning are presented in Table 1.

Table 1. Descriptive statistics scientific reasoning

Statistic	Experimental class		Control class	
	Pre	Post	Pre	Post
N	34	34	35	35
Mean	40.59	84.24	42.97	69.26
Std. Dev	10.29	8.41	11.20	8.96

Table 1 shows that both classes were not significantly different. However, post-test scores indicate that the intervention in the experimental class used aPBL integrated with STEAM supported by CCS resulted in significantly higher scientific reasoning skills among students compared to the control class, which used aPBL.

Tests of Equivalence (Pretest) and Tests of Difference (Posttest)

To evaluate the baseline equality of the groups, an independent samples t-test was conducted after ensuring that the pretest data met the assumption of normality. Subsequently, an independent samples t-test was applied to the posttest data to determine the statistical significance of the intervention. The results are summarized in Table 2.

Table 2. Distribution score of independent sample t-test test

SR	F	Sig (2-tailed)	description
Pretest	.002	.361	Not significant
Posttest	.038	.000	significant

Based on the initial equivalence test, the two-tailed significance value for the pretest was 0.361 ($p > 0.05$), confirming that both classes shared an equivalent baseline performance before the intervention. In contrast, the posttest difference test yielded a significance value of 0.000 ($p < 0.05$), demonstrating a statistically significant difference between the two groups. This statistical evidence proves that the integrated aPBL-STEAM-CCS framework is significantly more effective at enhancing students' scientific reasoning skills than the standard aPBL model alone. This advantage emerges because the Cognitive

Conflict Strategy (CCS) in the experimental group intentionally triggers cognitive dissonance, forcing students to re-evaluate their prior misconceptions regarding forces and restructure their mental frameworks. Theoretically, confronting students with anomalous data acts as a powerful cognitive scaffold that shatters naive intuitions, prompting System 2 reflective thinking to establish a new, scientifically valid equilibrium (Shofiyah et al., 2025). This finding aligns with contemporary literature suggesting that embedding STEAM into problem-based learning architecture optimizes higher-order thinking skills (Akmam et al., 2023; Fatmawati & Azhar, 2024).

Normalized Gain

The improvement in students' scientific skills was measured using the N-gain calculation. The N-gain score was used to assess the extent to which the CCS-supported STEAM-integrated aPBL model in the experimental class and the aPBL model in the control class improved students' scientific reasoning skills. The N-gain results for scientific reasoning skills are presented in Table 3.

Table 3. N-gain value for scientific reasoning

Statistic	Experimental Class		Control Class	
	Value	Category	Value	Category
N-gain	0.73	High	0.45	Medium

As displayed in Table 3, the mean N-gain score for the experimental class reached 0.73, placing it within the high category, whereas the control group achieved a moderate gain of 0.45. This descriptive difference supports the t-test results, reinforcing that the synergy of aPBL, STEAM, and CCS drives superior conceptual growth. This pedagogical superiority is enhanced by the Art and Engineering components of STEAM via the Engineering Design Process (EDP). While the control group limited its scope to abstract problem identification, the experimental group progressed through comprehensive EDP stages including problem identification, information gathering, solution search, model building, and redesign (Mariani & Indriyanti, 2024; Nurtanto et al., 2020; Suryani et al., 2025). Constructing physical miniatures provided students with concrete, tangible opportunities to manipulate and verify complex physics variables.

To gain deeper insights into these effects, the N-gain values were analyzed across specific scientific reasoning indicators, as detailed in Table 4.

Based on Table 4, the Correlational Reasoning (CR) indicator showed the highest improvement in the experimental group with a high N-gain score of 0.84, while the control class achieved a moderate score of 0.42. Prior to instruction, both the experimental and control classes faced difficulties; students' initial ability to reason about relationships between variables was still very low, as evidenced by the absence of students capable of providing logical and comprehensive conclusions. This was attributed to the students' low initial scientific reasoning skills regarding the correlational reasoning indicator. After instructions using the proposed framework, the structured introduction of authentic problems within the aPBL model significantly improved students' higher-order thinking skills and science learning outcomes. This improvement aligns with previous research which states that integrating STEAM into a problem-based learning model enhances reasoning through cooperative problem-solving, social interaction, and the practical application of STEM concepts (Juliharti et al., 2024; Wiratman et al., 2023). By embedding a constructivist-driven deep approach to learning, students transition from passive observers into active investigators who are highly skilled in manipulating variables, drawing data-driven conclusions, and communicating their scientific findings (Susilawati et al., 2026).

Table 4. N-gain value based scientific reasoning indicator

SR indicator	Experimental Class		Control Class	
	N-gain	Category	N-gain	Category
CSR	0.81	High	0.42	Medium
PR	0.82	High	0.49	Medium
PBR	0.35	Medium	0.23	Low
CR	0.84	High	0.42	Medium
CoV	0.76	High	0.49	Medium
HDR	0.70	High	0.51	Medium

CSR = Conservation Reasoning; PR = Proportional Reasoning; PBR = Probabilistic Reasoning; CR = Correlational reasoning; CoV = Control of Variable; HDR = Hypothetical Deductive Reasoning; SR = Scientific Reasoning

For the Proportional Reasoning (PR) indicator, the experimental class achieved an N-gain score in the high category (0.82) compared to the control class, which received a score in the moderate category (0.49). Before instruction, most students exhibited "one-sided" logic, focusing strictly on a single aspect of conceptual differences. After implementing the aPBL model integrated with STEAM and supported by the Cognitive Conflict Strategy, there was a significant improvement in this indicator. This is because the Cognitive Conflict Strategy forces students to realize that such biased logic is incorrect when faced with real-world problems, thereby motivating them to actively seek and calculate the correct proportional relationships. This finding aligns with previous research showing that PBL, when integrated with STEAM, significantly enhances students' cognitive, affective, and psychomotor abilities, resulting in better learning outcomes compared to conventional methods (Rahim et al., 2024).

Furthermore, the third-highest average N-gain score was obtained by the Conservation Reasoning (CSR) indicator, reaching a high category (0.81) in the experimental class and a moderate category (0.42) in the control class. Before instruction, some students relied heavily on intuitive guessing regarding conservation principles, facing extreme challenges in constructing logical, structured scientific explanations to support their answers. After instructions using the integrated model, students showed significant improvement because the Cognitive Conflict Strategy successfully confronts students with phenomena that contradict their initial understanding, while STEAM requires them to view physics problems from various interdisciplinary perspectives. These findings align with previous research on STEM-driven inquiry, which indicates that applying the engineering design process during the problem identification stage and model creation substantially enhances students formal scientific reasoning skills (Atqiya et al., 2021).

For the Control of Variables (CoV) indicator, the experimental class achieved a high N-gain score of 0.76, while the control class received a moderate score of 0.49. Before the intervention, most students could only name a single variable or provided answers that were entirely inconsistent with established physics theories due to low foundational reasoning skills. The implementation of the STEAM-integrated aPBL model effectively resolved this, which aligns with previous research indicating that problem-based learning architectures explicitly help students develop higher capabilities in identifying, manipulating, and analyzing scientific variables (Setyorini et al., 2021).

For the Hypothesis Deductive Reasoning (HDR) indicator, the experimental class achieved an N-gain score in the high category (0.70), while the control class achieved a moderate score (0.51). Prior to instruction, students were only able to provide correct answers without any valid explanation, or formulated claims entirely unfounded by the available mechanical information. Implementing instruction supported by CCS and STEAM systematically guided students to formulate valid hypotheses along with their underlying scientific logic. This finding aligns with previous research stating that group discussions and structured interventions allow students to efficiently exchange ideas and consider various logical perspectives in problem-solving (Ariadi et al., 2025).

Finally, for the Probabilistic Reasoning (PBR) indicator, the experimental class achieved an N-gain value of 0.35 (moderate), while the control class achieved an N-gain value of 0.23 (low). Following instructions, there was a noticeable improvement in this indicator; however, it yielded the lowest N-gain value compared to the other indicators. Qualitative data revealed that the low score on this indicator was due to students providing only qualitative scientific explanations while completely failing to back them up with quantitative or statistical data. This severe limitation in formal reasoning is highly typical in secondary physics classrooms; empirical profiles show that while students can master concrete reasoning (like controlling variables), they systematically fail at abstract, relational thinking tasks such as correlation and probability parameters due to a heavy reliance on descriptive guessing (Anjiana et al., 2026). This finding aligns with previous research stating that students are often able to provide correct descriptive arguments but make incorrect predictions due to their inability to formulate complete and numerically correct probability parameters (Erlina et al., 2018).

Effect Size

The statistical test used to assess the strength of the effect is the effect size. The effect size aims to measure the extent to which the implementation of the STEAM-integrated aPBL model supported by CCS in the experimental class and the aPBL model in the control class improved scientific reasoning skills. The effect size results are presented in Table 5.

Table 5. Effect size value in scientific reasoning

Statistic	Value	Category
Effect size	1.798	High

The analysis revealed a remarkably high effect size of 1.798. This high index statistically confirms that the implementation of the STEAM integrated aPBL model supported by CCS exerts a powerful, practical impact on students' scientific reasoning skills compared to the standard model. This outcome emphasizes the essential value of CCS when students encounter cognitive conflict through contradictory tasks, they are compelled to engage in rigorous hypothesis testing and critical evaluation to reach a stable cognitive equilibrium (Akmam et al., 2023; Fatmawati & Azhar, 2024). Ultimately, this high effect size confirms that problem solving enriched by interdisciplinary STEAM concepts and cognitive dissonance management provides a superior framework for fostering advanced scientific reasoning in physics education (Juliharti et al., 2024; Setyorini et al., 2021; Wiratman et al., 2023). This empirical success statistically validates that shifting toward a tech integrated, context rich, and conceptual driven learning media provides an effective operational pathway to advance the quality of modern physics education in line with the global 2030 sustainability agenda (Ardita et al., 2026; Cahayana et al., 2026; Wati et al., 2026).

Conclusion

The implementation of the Authentic Problem-Based Learning (aPBL) model integrated with STEAM and supported by the Cognitive Conflict Strategy (CCS) exerts a statistically significant impact on enhancing senior high school students' scientific reasoning skills in Newton's Laws. This empirical success is robustly supported by a high-category overall N-gain score of 0.73 for the experimental group, which substantially outperforms the moderate gain of 0.45 achieved by the standard aPBL control group. Indicator-based analysis further confirms that the integrated triple-strategy framework generates the most substantial growth in correlational (0.84), proportional (0.82), and conservation reasoning (0.81), driven by the synergy of CCS in shattering deep-rooted misconceptions and the Engineering Design Process (EDP) within STEAM in providing a physical framework to concretely manipulate variables. Ultimately, this research provides an effective operational pathway to advance pedagogical quality in secondary physics education, directly supporting the global mandate of Sustainable Development Goal 4 (Quality Education). Nevertheless, this study acknowledges a critical limitation: The Probabilistic Reasoning indicator remains low in both the experimental (0.35) and control classes (0.23) because students heavily rely on descriptive, qualitative arguments while failing to incorporate quantitative parameters into their explanations. Additionally, the external generalizability is constrained by the quasi-experimental design conducted within a specific localized school context. For future research, it is highly recommended to explicitly strengthen the Mathematics (M) component within the STEAM framework such as integrating calculation-concept crossovers to foster students' probabilistic thinking capacities, while employing randomized controlled trials across larger, more diverse student populations to comprehensively validate the long-term retention of this integrated instructional model.

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Author Contributions

Conceptualization, data analysis, R.A.P., P., and A.T.; methodology, manuscript writing, R.A.P. and P.; data collection, revision, and editing, R.A.P.; supervision, A.T. and M.A. All authors have read and approved the published version of the manuscript.

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Conflict Interest

The authors declare no conflict of interest.

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