

Making Physics Problem Solving Visible Through Synchronous Online Problem-Based Learning: Patterns of Student Discourse Across Two-Semester

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ABSTRACT

Problem-based Learning (PBL) is widely used to promote problem solving, yet outcome measures alone provide limited insight how students reason, negotiate ideas, and regulate inquiry while solving authentic problems. This study examined patterns of problem-solving discourse across repeated synchronous written online PBL discussions among pre-university physics in Malaysia. A comparative two-semester qualitative content analysis, supported by descriptive discourse coding, was conducted using 18 Microsoft Teams discussion sessions: three groups per semester and three discussions per group. Semester 1 represents 21 students and Semester 2 represent 22 students.

The corpus comprised 890 substantive students turns and 1390 PIM eligible meaning units. Cognitive presence was classified using the Practical Inquiry Model (PIM), while supplementary turn-level indicators captured mathematical reasoning, evidence use, concept integration, uncertainty awareness and limitation awareness, peer interaction, reflection, and peer facilitation. Semester 1, showed a modest rise in the study-specific Higher-Order Inquiry Ratio (HOIR) (Integration plus Resolution), from 27.8% in Discussion 1 to 33.6% in Discussion 3. Semester 2 displayed different pattern, beginning at 41.8% and stabilizing at approximately 31% in later discussions. Group-level trajectories were heterogeneous, indicating that semester averages did not represent a uniform progression.

Across the two semesters, concept integration and explicit attention to uncertainty and limitations were prominent in the second semester corpus, whereas mathematical and evidence-based reasoning varied with problem demands. Peer correction also became more visible in later Semester 2 discussions.

The findings suggest that synchronous written PBL can make the structure of scientific problem-solving observable, while also showing that inquiry patterns are shaped by task and group context. The study highlights the value of analyzing how students' reason together, rather than relying only on final answers or participation counts.

Keywords: online problem-based learning; physics education; cognitive presence; synchronous online discussion; problem solving discourse

INTRODUCTION

Background of the Study

Physics education is expected to develop more than students' ability to recall principles and substitute

numerical values into equations. Proficiency in Physics problem solving requires learners to organize relevant knowledge, identify relationships between physical quantities, select appropriate principles, interpret mathematical representations, monitor their reasoning, and evaluate whether a solution is physically meaningful. Research in physics education therefore distinguishes proficient problem solving from simply obtaining the correct numerical answer, expertise involves conceptual organization, reasoning, metacognition, and the ability to apply knowledge to unfamiliar situations (Maries & Singh, 2023). A recent systematic review similarly identified active, inquiry-oriented and structured problem-solving approaches as important strategies for developing problem-solving abilities in physics.

Problem-based learning (PBL) offers a pedagogical environment that is well aligned with these aims. In PBL, students encounter a complex problem before a complete solution is provided, identify what they already know and what they need to learn, investigate relevant information, discuss possible explanations, and collaboratively construct a solution. Rather than positioning students as passive recipients of information, PBL requires them to take an active role in analysing problems and determining their learning needs. Hmelo-Silver (2004) explains that PBL can support both content learning and the development of thinking strategies through facilitated problem-solving, collaborative learning, self-directed inquiry, and reflection. These characteristics are particularly relevant to physics, where authentic problems rarely resemble well-structured textbook exercises. Real situations may contain incomplete information, multiple interacting variables, assumptions, measurement uncertainty, and more than one plausible explanation. Consequently, students need to progress from asking which formula should be used toward asking what evidence is available, what assumptions are reasonable, how different concepts interact, and how reliable the resulting conclusion is. Reviews of physics problem-solving research have emphasized the importance of developing these reasoning and metacognitive processes rather than relying solely on routine mathematical procedures (Maries & Singh, 2023).

The expansion of digital learning has also enabled PBL to be implemented online. Synchronous online PBL allows students to interact at the same time despite being physically separated. Previous research has demonstrated that synchronous online PBL is feasible, although the quality of participation and interaction may depend strongly on facilitation and learning design. Earlier Malaysian work, for example, examined synchronous web-based PBL collaboration, while later studies in other disciplines found that synchronous online PBL could provide flexibility and accessibility but might also require additional effort to maintain interaction and depth of discussion (Tangney et al., 2024; Erickson et al., 2021; Sulaiman et al., 2004).

The present study focuses on a more specific form of online interaction: synchronous written PBL discussion. Students participated simultaneously during scheduled sessions but communicated through written messages in Microsoft Teams. This format provides an important methodological advantage because the reasoning process remains visible as a textual record. Questions, explanations, disagreements, calculations, corrections, evidence, reflections, and facilitator interventions can therefore be examined directly rather than reconstructed retrospectively from questionnaire or interviews. Written online discourse has previously been used to investigate cognitive presence and knowledge construction, and the Practical Inquiry Model proposed by Garrison, Anderson, and Archer (Garrison et al., 2001) provides a well-established framework for examining progression from a triggering problem through exploration and integration toward resolution. Within the pre-university physics context, previous work on integrated online PBL has demonstrated the feasibility of assessing learning outcomes such as motivation and problem-solving skills using questionnaires and quasi-experimental designs (Eldy et al., 2023). The present study extends this line of inquiry by examining the learning process itself. Rather than asking only whether students report stronger problem-solving skills or achieve better outcomes after PBL, the present study examines how patterns of written reasoning and interaction vary across repeated PBL discussions and between two semester-specific discourse corpora.

Problem Statement and Research Gap

Two limitations in the existing literature motivate this study. First, PBL research frequently evaluates achievement, perceptions, or other end-point outcomes, even though the quality of problem solving depends on the reasoning processes enacted during the task. Evidence across disciplines also shows that PBL outcomes are not uniformly superior to conventional approaches, reinforcing the need to examine what learners actually do during PBL rather than infer cognitive processes from post-intervention measures alone. Second, online-

discussion research has often concentrated on asynchronous environments, higher education contexts, or broad participation measures. A process-oriented analysis of synchronous written PBL is particularly relevant in pre-university physics, where students are transitioning from structured school problem solving toward more autonomous and complex forms of scientific reasoning.

The present study addresses these gaps by analysing authentic written PBL discourse across two semesters and repeated problem cycles. Because the discussion problems, group composition, and disciplinary demands were how patterns of cognitive presence, scientific problem-solving practices, collaboration, and learner regulation vary across the discussion corpus.

Purpose and Research Questions

The purpose of this study was to examine how problem-solving discourse was manifested and how its patterns varied across repeated synchronous written online PBL discussions in pre-university physics. The analysis focused on cognitive presence as the primary framework, supported by indicators of scientific reasoning, collaborative knowledge construction, and learner regulation.

- RQ1: How are patterns of cognitive presence manifested across synchronous written online PBL discussions in pre-university physics?
- RQ2: How do scientific problem-solving practices, including mathematical reasoning, evidence use, concept integration, and awareness of uncertainty and limitations, vary across discussion cycles and two-semester specific discourse corpora?
- RQ3: How are collaborative knowledge construction, peer correction, and learner regulation manifested across groups and repeated PBL discussions?

LITERATURE REVIEW

Problem-Based Learning in Physics Education

Problem-based learning (PBL) is a learner-centred instructional and curriculum approach that gives students the freedom to conduct research, combine theory and practice, and use their knowledge and abilities to create a workable solution to a given problem (Savery, 2006). Unlike conventional instruction in which concepts are commonly introduced before students attempt structured exercises, PBL begins with a problem that creates a need for learning. Student are therefore required to determine what they already know, identify gaps in their knowledge, seek relevant information, test possible explanations, and construct solutions collaboratively. Hmelo-Silver (2004) similarly emphasizes that PBL combines facilitated problem solving with collaborative learning and self-directed inquiry, enabling students to develop both disciplinary knowledge and thinking strategies.

This approach is particularly relevant to physics because successful physics problem solving involves more than recalling equations. Proficient solvers must organize conceptual knowledge, interpret representations, identify relevant principles, manage multiple variables, evaluate assumptions, and monitor whether a solution is physically reasonable. Recent reviews of physics problem solving emphasizes the importance of knowledge organization, metacognition, cognitive processing, and explicit problem-solving strategies in supporting the transition from novice to more proficient reasoning (Maries & Singh, 2023).

Evidence specific to physics education also supports the pedagogical potential of PBL. A systematic review of empirical research on PBL in physics identified positive outcomes across most included studies, including academic achievement, problem-solving ability, critical and creative thinking, cooperative learning, mental-model development, and science-process skills (Nicholus et al., 2023). However, these benefits should not be interpreted as automatic consequences of using PBL. The quality of the problem, the level of scaffolding, the nature of interaction, and the role of the facilitator can substantially influence whether students move beyond superficial participation toward meaningful inquiry. Consequently, examining the processes occurring within PBL discussions is necessary for understanding how such competencies develop.

Problem-Solving as a Developing Process

Problem solving in physics can be understood as a developmental process rather than a single act of obtaining the correct answer. Novice problem solvers often focus on surface features, search quickly for formulas, or manipulate equations without first constructing an appropriate conceptual representation (Maries & Singh, 2023; Nehru et al., 2020). In contrast, proficient problem solvers tend to identify the underlying principles, organize information meaningfully, monitor their progress, and evaluate the plausibility of their conclusions (Maries & Singh, 2023). Within PBL, this development may become visible through changes in how students approach successive problems. Early participation may involve identifying facts, formulate hypotheses, connect multiple concepts, use quantitative reasoning, question assumptions, evaluate evidence, and justify proposed solution. Such progression is especially important in authentic physics problems because the necessary variables or equations are not always immediately apparent. Students may need to decide which information is relevant, what additional information is required, and whether a particular assumption is justified.

Problem solving in this sense is closely connected to critical and scientific reasoning. Scientific problem solving requires learners not only to apply principles but also to evaluate the quality of evidence, recognize uncertainty, compare alternative explanations, and identify limitations in their models. For this reason, the present study conceptualizes problem-solving discourse as a process extending from initial problem recognition through exploration, conceptual integration, evaluation, and eventual resolution. This view enables the analysis to capture not only whether students proposed a solution, but also how the quality of their reasoning changed during repeated PBL participation.

Cognitive, Collaborative, and Self-Regulated Processes in Online PBL

To examine how students' reasoning develops during online PBL, the present study draws on the concept of cognitive presence, which refers to the extent to which learners construct and confirm meaning through reflection and discourse in a community of inquiry. Garrison et al. (2001) operationalized cognitive presence through the Practical Inquiry Model (PIM), which consists of four phases, Triggering Event, Exploration, Integration, and Resolution. A Triggering Event involves identifying or recognizing a problem, Exploration refers to searching for information and considering possible explanations, Integration involves connecting and synthesizing ideas, and Resolution reflects the application or defence of a proposed solution. This framework is particularly suitable for analysing synchronous written discussions because students' reasoning can be traced directly through the sequence of their contributions.

Within the present study, the distinction between Exploration and the higher-order phases of Integration and Resolution is especially important. Students may participate actively in an online discussion without necessarily demonstrating advanced reasoning. For example, recalling a formula, suggesting a concept, or listing possible causes represents meaningful exploration, but stronger evidence of cognitive development is shown when students compare explanations, connect multiple concepts, evaluate assumptions, justify claims using calculations or evidence, and apply these ideas to reach a defensible solution. Previous research using the Community of Inquiry framework has similarly shown that online discussions often contain substantial Exploration, whereas progression toward Integration and Resolution is more difficult to achieve (Sadaf et al., 2021). This makes the higher-order phases useful indicators when examining the development of problem-solving discourse over repeated PBL experiences.

However, cognitive development in PBL does not occur independently of social interaction. Collaborative learning becomes more meaningful when students do more than post separate answers or simply express agreement. Collaborative knowledge construction occurs when learners extend a peer's idea, ask probing questions, challenge assumptions, correct misconceptions, combine several contributions, or negotiate a shared conclusion. Such interaction allows knowledge to be constructed collectively rather than merely exchanged. Recent research on online learning has continued to emphasize the importance of shared metacognition, co-regulation, and collaborative engagement in supporting deeper learning (Maré & Mutezo, 2025).

This social dimension is closely connected to learner regulation. During repeated PBL experiences, students may gradually move from relying on lecturer prompts toward managing more of the inquiry themselves. This can be seen through behaviours such as initiating questions, and deciding when the group is ready to move toward a solution. Such behaviours reflect increasing learner autonomy and self-regulation, rather than merely reduced lecturer participation. Importantly, autonomy in PBL does not mean the facilitator becomes unnecessary. Instead, the facilitator's role becomes more selective, intervening when students require redirection, when misconceptions persist, or when participation becomes unbalanced.

Accordingly, the present study treats cognitive presence, collaborative knowledge construction, and learner autonomy as interconnected processes. Together, they provide a framework for understanding how students may progress from basic information sharing toward more integrated, evidence-based, and collaboratively constructed problem solving.

Scaffolding, Facilitator Support and the Three-Step Cycle

Although PBL places substantial responsibility on students, novice learners may still require structured support to manage complex and unfamiliar problems. Scaffolding refers to temporary guidance that enables learners to perform tasks that may initially exceed their independent capability (Van Nooijen et al., 2024). In PBL, such support may include guiding questions, structured templates, prompts for justification, sequencing of discussion stages, or facilitator feedback. The aim is not to simplify the problem excessively, but provide sufficient structure for students to engage productively with it.

In this study, the online PBL discussions were organized using a Three-Step Cycle consisting of: (1) What we have from the scenario, (2) What we need to know, and (3) Summary (Hasani et al., 2025). The first stage requires students to identify information explicitly provided in the problem. The second stage prompts them to recognize knowledge gaps, concepts requiring revision, missing variables, and additional evidence needed to continue the inquiry. The final stage requires students to integrate what they have learned and formulate a coherent explanation or proposed solution.

The Three-Step Cycle serves as an organizational scaffold rather than as a separate theoretical model. Its structure is broadly compatible with the Practical Inquiry Model. "What we have" supports problem recognition and initial exploration, "What we need to know" encourages inquiry and information seeking, while "Summary" promotes integration and movement toward resolution (Sadaf et al., 2021). This alignment makes the scaffold particularly useful for examining whether repeated PBL exposure is accompanied by a shift from externally guided participation toward more self-directed reasoning.

An important aspect of repeated PBL participation is whether the level of facilitator support changes over time. Early discussions may require explicit prompts, reminders, and procedural guidance, whereas more experienced students may increasingly regulate the inquiry themselves (Sharma et al., 2024). This may be reflected in students initiating questions, directing the discussion, challenging peers, identifying information needs, synthesizing ideas, and summarizing conclusions without continuous lecturer intervention.

In this study, such changes are interpreted as indicators of developing learner autonomy and shared regulation. Learner autonomy does not imply the complete absence of a facilitator, rather, it refers to a gradual transfer of responsibility from lecturer-supported inquiry toward more student-directed problem solving (Suwastini et al., 2021). Accordingly, facilitator intervention is examined alongside cognitive and collaborative indicators to determine whether repeated synchronous written PBL discussions are associated with increasingly independent, organized, and student-led inquiry.

Conceptual Framework of the Study

The conceptual framework of this study integrates online PBL, cognitive presence, collaborative knowledge construction, scaffolding, and learner autonomy. Repeated synchronous written PBL discussions provide the learning context, while the Three-Step Cycle structures problem exploration and synthesis. Cognitive development is examined using the Practical Inquiry Model phases of Triggering Event, Exploration,

Integration, and Resolution (Garrison et al., 2001). Increasingly sophisticated problem-solving discourse is reflected not only in movement toward Integration and Resolution, but also in stronger use of evidence, mathematical reasoning, evaluation of assumptions, peer co-construction, and reflective regulation. Facilitator support is viewed as a dynamic scaffold that may gradually decrease as students become more capable of directing their own inquiry. Accordingly, problem solving is conceptualized as an outcome emerging from the interaction of cognitive, evidential, and self-regulatory processes across repeated PBL discussions.

METHODOLOGY

Research Design

This study employed a comparative two-semester qualitative content-analysis design supported by descriptive discourse coding. The analysis examined how cognitive, scientific, collaboration, and regulatory features of students' problem-solving discourse were manifested across repeated synchronous written online PBL discussions. The study was observational and process-oriented. Because the two semester corpora only partially overlapped in student membership and group membership was reorganised, Semester 1 and Semester 2 were not treated as a strict same-person longitudinal design. Instead, within-semester Discussion 1-3 patterns and between-semester corpus-level variation were described using coded frequencies, percentages, standardized turn-level rates, qualitative excerpts, and group-level HOIR values. The analysis therefore characterizes variation in the discussion corpus and does not estimate causal effects or individual developmental growth.

Research Setting and Participants

This study was conducted at the Preparatory Centre for Science and Technology, Universiti Malaysia Sabah (UMS), Malaysia, involving pre-university students enrolled in the Foundation in Science programme. Semester 1 PBL discussions were embedded in mechanics and Thermal Physics, while Semester 2 discussions were embedded in Optics, Modern Physics, and Electricity. The final analysed corpus comprised 18 synchronous written PBL sessions: nine sessions in Semester 1 and nine sessions in Semester 2. In each semester, Groups 1-3 participated in three discussion cycles. The participants were partially overlapping rather than fully longitudinal. Semester 1 represented 21 students, with seven students in each of Group 1-3. Semester 2 represented 22 students, comprising eight students in Group 1 and seven students each in Group 2 and 3. Across the complete corpus, 29 unique students coded were identified, of whom 14 were represented in both semesters. Group membership was not maintained across semesters, only three of the 14 overlapping students remained in the same nominal group, while 11 were regrouped. Consequently, a group label such as G1 in Semester 1 does not represent the same membership as G1 in Semester 2. Semester comparisons were therefore interpreted as comparisons between partially overlapping discourse corpora rather than repeated measurements of the same students or groups.

PBL Implementation

The PBL implementation was conducted across one semester through three sequential problem-based discussion sessions. Students were first organized into groups in consultation with their tutor and assigned either PBL Problem A or Problem B. Before each discussion, the relevant problem scenario was released to students, who were expected to read and understand the case, identify key issues, and gather relevant information independently. All three discussions were conducted synchronously in written form using the online platform determined by the tutor. Students were required to attend every session and participate actively. Each discussion focused on a different problem and set of learning objectives; however, the problem was intentionally interconnected, with each subsequent problem extending the context and knowledge developed in the preceding discussion. Each session was supported by the Three-Step Cycle, identifying what is known from the scenario, determining what needs to be known, and developing a summary of the group reasoning.

Unit of Analysis and Corpus Preparation

Two complementary units of analysis were used. A substantive student turn was defined as a written student contribution containing meaningful content related to the PBL problem-solving process. Greetings, attendance response, routine acknowledgements, emojis, technical messages, and other administrative exchanges were excluded. After cleaning the corpus contained 890 substantive student turns: 406 in Semester 1 and 484 in Semester 2. For cognitive-presence coding, substantive turns were segmented into meaning units. A meaning unit represented one distinct cognitive idea or reasoning function. Therefore, a single turn could contain more than one meaning unit when it performed multiple cognitive functions. Consistent segmentation rules were applied because coding-unit size can influence transcript-analysis results (De Wever et al., 2006; Garrison et al., 2001). The current segmented corpus contains 1390 PIM-eligible meaning units, comprising 603 in Semester 1 and 787 in Semester 2. Because individual students contributed multiple turns and meaning units within groups and discussion sessions, the discourse units were nested rather than statistically independent. The study therefore interprets coded units as descriptive features of the discussion corpus and not as independent observations of individual student performance.

Coding Framework

The primary coding framework based on the Practical Inquiry Model (PIM) developed by Garrison et al. (2001) to operationalize cognitive presence in text-based educational discourse. The model represents inquiry through four phases: Triggering Event, Exploration, Integration, and Resolution. Triggering Event represents recognition or definition of a problem, Exploration involves information sharing, questioning, brainstorming, and consideration of possibilities, Integration involves connecting ideas and constructing coherent explanations, and Resolution concerns the application, testing, or defence of proposed solution.

The PIM has widely employed for analysing cognitive presence in online discussion transcripts. A systematic review by Sadaf et al. (2021) found that content analysis of discussion transcripts to be prominent method for investigating cognitive presence and confirmed continued use of the four PIM phase for characterizing the development of online inquiry. Each of the 1390 eligible meaning units was therefore assigned one mutually exclusive PIM category. Particular attention was given to Integration and Resolution because these phases represent movement beyond information exploration toward connected explanation, application, evaluation, and solution-oriented reasoning. For descriptive comparison, Integration and Resolution were combined to calculate a Higher-Order Inquiry Ratio (HOIR):

$$\text{HOIR} = \frac{\text{IN} + \text{RE}}{\text{TE} + \text{EX} + \text{IN} + \text{RE}} \times 100$$

Because the PIM primarily captures cognitive presence, additional supplementary indicators were coded separately at the substantive-turn level to represent disciplinary, collaborative, and self-regulatory features of the PBL discourse. These included mathematical reasoning, evidence-based reasoning, conceptual integration, counterfactual or hypothesis testing, assumption awareness, uncertainty and limitation recognition, peer co-construction, peer correction, synthesis, reflection, and peer leadership or facilitation. These indicators were non-mutually exclusive; thus, one student could demonstrate several features simultaneously. Conceptual accuracy was considered separately from cognitive depth, since an apparently sophisticated explanation could still contain incorrect physics. Relevant scientific claims were therefore classified as accurate, partially accurate, inaccurate, or not assessable. This distinction enabled the analysis to differentiate between the complexity of students' reasoning and the scientific validity of that reasoning.

To strengthen coding consistency in the absence of an independent second coder, an intra-coder verification procedure was adopted. Following the initial coding, approximately 20% of the corpus was selected through stratified sampling to ensure representation from both semesters, Groups 1-3, and Discussions 1-3. After several interval, the selected data were recorded without reference to the original coding decisions. The two rounds of coding were then compared, and discrepancies were reviewed against the operational codebook and original transcript context. Ambiguous cases and coding refinements were documented in an analytical

decision log. This procedure provides a transparent means of examining coding consistency when qualitative content analysis is undertaken by a single researcher.

Coding Procedure

The coding process was conducted in several sequential stages. First, all discussion transcripts were reviewed for familiarization and cleaned by removing administrative exchanges and other non-substantive contributions. The remaining student discourse was then prepared for analysis according to the units and segmentation procedures described previously. An operational coding manual was developed before full analysis to ensure consistent application of the coding categories. The initial coding was conducted systematically across the complete corpus, beginning with the PIM classification of eligible meaning units, followed by coding of the supplementary discourse indicators at the substantive-turn level. Conceptual accuracy was subsequently examined separately for students' contributions containing assessable physics claim. Throughout the analysis, ambiguous cases and changes to coding decisions were documented in an analytical decision log to maintain transparency and consistency. The intra-coder verification was used to evaluate coding consistency in this study.

Qualitative Analysis

Following the qualitative analysis coding of the discussion transcripts, descriptive analysis was used to summarize patterns in students' cognitive and problem-solving discourse. Frequencies and percentage of Triggering Event, Exploration, Integration, and Resolution meaning units were calculated for each semester, discussion cycle, and group. Integration and Resolution were additionally combined to calculate the Higher-Order Inquiry Ratio (HOIR), representing the proportion of discourse characterized by connected explanation, application, evaluation, and solution-oriented reasoning. Supplementary indicators were analysed at the substantive-turn level. Because the number of student contributions varied across sessions, raw frequencies were standardized and reported as coded occurrences per 100 substantive student turns. This enabled comparison of mathematical reasoning, evidence-based reasoning, concept integration, uncertainty and limitation awareness, peer correction, synthesis, reflection, and peer facilitation without assuming that longer discussions represented stronger performance. All cross-discussion and cross-semester comparisons were descriptive. No individual-level repeated-measures interference was made because participant overlap was incomplete, group composition changed across semesters, and discourse units were nested within students, groups, and sessions.

RESULTS

Overview of the Analysed Discussion Corpus

The final analysis comprised 18 synchronous written online PBL sessions: nine from Semester 1 (Groups 1-3 across Discussions 1-3) and nine from Semester 2 (Group 1-3 across Discussions 1-3). The two corpora represented 29 unique students in total. Semester 1 included 21 students and Semester 2 included 22 students, with 14 students represented in both semesters. Because most overlapping students were regrouped, semester and group labels were treated as semester-specific analytical units rather than as identical longitudinal groups. After transcript cleaning, 890 substantive students turn were retained for supplementary discourse coding, comprising 406 turns in Semester 1 and 484 in Semester 2. Cognitive-presence segmentation yielded 1390 PIM-eligible meaning units, including 603 units in Semester 1 and 787 units in Semester 2. Accordingly, the findings describe corpus-level patterns and variation rather than individual repeated-measures effects.

Patterns of Cognitive Presence Across Repeated PBL Discussions

Table 1 presents the detailed distribution of the four PIM phases across discussion cycles. Exploration was the most frequent PIM phase across the corpus, but the relative balance between Exploration, Integration, and Resolution changed across discussion cycles. In semester 1, the HOIR defined as the proportion of Integration and Resolution units, increased from 27.8% in Discussion 1 to 31.7% in Discussion 2 and 33.6% in Discussion

3. The third discussion also contained the largest Semester 1 proportion of Resolution units (8.0%), indicating more frequent application and evaluation of proposed solutions.

Semester	Cycle / Discussion	n	TE n (%)	EX n (%)	IN n (%)	RE n (%)	HOIR (%)
1	1	176	6 (3.4)	121 (68.8)	44 (25.0)	5 (2.8)	27.8
1	2	189	1 (0.5)	128 (67.7)	57 (30.2)	3 (1.6)	31.7
1	3	238	0 (0.0)	158 (66.4)	61 (25.6)	19 (8.0)	33.6
2	1	208	4 (1.9)	117 (56.2)	80 (38.5)	7 (3.4)	41.8
2	2	256	3 (1.2)	173 (67.6)	76 (29.7)	4 (1.6)	31.3
2	3	323	0 (0.0)	221 (68.4)	94 (29.1)	8 (2.5)	31.6

Table 1. Distribution of PIM phases across discussion cycles

Semester 2 demonstrated a more variable pattern of cognitive presence across the three discussion cycles. The HOIR was highest in Discussion 1 (41.8%) and subsequently remained at a lower but relatively stable level in Discussion 2 (31.3%) and Discussion 3 (31.6%). This suggests that the higher-order inquiry did not develop in a strictly manner across successive discussions. Rather, the distribution of cognitive actively appeared to vary according to the demands of the problem context. In Discussions 2 and 3, a substantial proportion of discourse remained within the Exploration phase while Integration was also investigating wave behaviour, compare sensing approaches, consider physical limitations, and evaluate competing design choices.

Figure 1 shows different patterns of higher-order inquiry across the three PBL discussion cycles. In semester 1, HOIR increased from 27.8% in Discussion 1 to 31.7% in Discussion 2 and 33.6% in Discussion 3, indicating a modest increase in discourse involving integration and resolution. In contrast, Semester 2 began with a comparatively high HOIR of 41.8% in Discussion 1, before decreasing to 31.3% in Discussion 2 and remaining relatively stable at 31.6% in Discussion 3. Thus, the trajectories differed between semesters: Semester 1 showed a gradual upward patter, whereas Semester 2 demonstrated a high initial level followed by stabilization at approximately 31%. These patterns suggest that higher-order inquiry did not develop uniformly across successive PBL discussions and may have varied according to the cognitive demands of the problem addressed in each cycle.

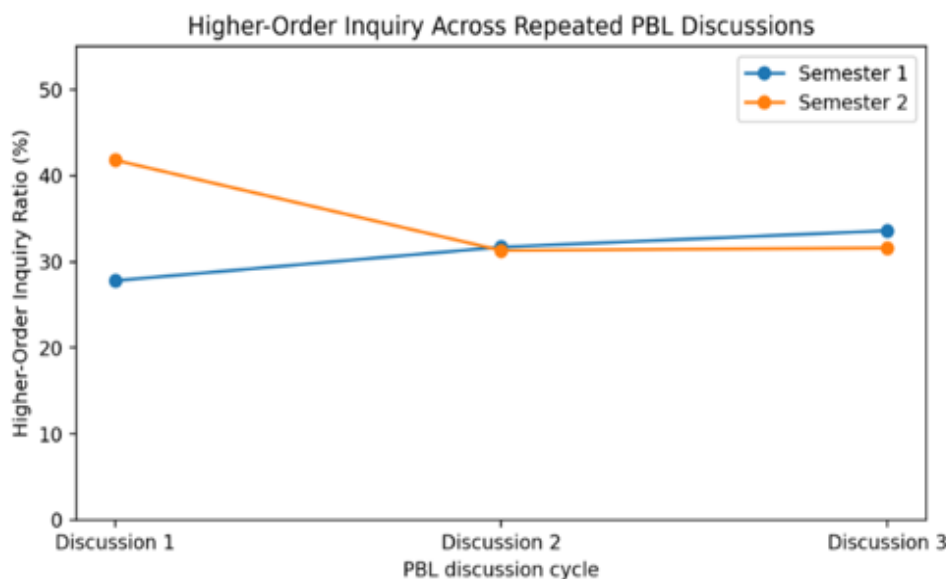


Figure 1. HOIR across repeated PBL discussions

Table 2 further demonstrated heterogeneity between group-level. Semester 1 Group 3 showed the clearest increasing trajectory (26.7% to 38.7% to 44.2%), whereas Groups 1 and 2 did not. In semester 2, group 3 displayed consistently high higher-order discourse and reached 66.7% in Discussion 3, while Group 2 showed

a declining HOIR. Consequently, the group-level data demonstrate substantial heterogeneity in higher-order inquiry patterns; the same nominal group labels across semesters should not be interpreted as continuous groups with unchanged membership.

Semester	Group	Discussion 1	Discussion 2	Discussion 3
1	1	22.6	17.0	19.4
	2	37.8	36.1	32.3
	3	26.7	38.7	44.2
2	1	39.5	26.1	32.1
	2	34.0	27.1	23.2
	3	50.0	42.7	66.7

Table 2. Group-level Higher-Order Inquiry Ratio (%)

Patterns of Scientific Problem-Solving Practices

Beyond PIM phase distributions, the substantive-turn analysis identified changes in the scientific practices used to construct solutions. The patterns were not uniform across all indicators as shown in Table 1. Some practices, particularly concept integration and recognition of limitations, were more frequent in Semester 2, whereas mathematical and explicit evidence-based reasoning were more frequent in Semester 1. This pattern was consistent with the differing demands of the mechanics and optics/electromagnetic-wave PBL problems.

Indicator	Semester 1	Semester 2	Difference (S2 – S1)
Mathematical reasoning	18.2	14.0	-4.2
Evidence-based reasoning	8.1	4.5	-3.6
Concept integration	22.7	35.7	+13.0
Counterfactual/hypothesis testing	3.0	1.7	-1.3
Assumption awareness	1.0	1.4	+0.4
Uncertainty/limitations	9.6	19.2	+9.6
Explicit peer co-construction	0.2	0.8	+0.6
Peer correction	4.7	7.0	+2.3
Synthesis	5.2	5.4	+0.2
Reflection	8.1	4.8	-3.3
Peer leadership/facilitation	3.7	5.0	+1.3

Table 3. Supplementary Discourse Indicators per 100 Substantive Students Turns

Mathematical and Quantitative Reasoning

Mathematical reasoning occurred at a rate of 18.2 coded turns per 100 substantive turns in Semester 1 and 14.0 in Semester 2. The Semester 1 mechanics problems frequently required students to estimate speed, friction, force, torque, energy, and braking behaviors. Importantly, later Semester 1 discussions increasingly used mathematics to support interpretation rather than merely identify a formula.

“T hold=(800)(9.81) + 200 = 8.048 N, τ hold=(8048)(0.20)=1,609.6 N·m ...” (S1-G2-D2)

“if the elevator has a mass of 1000 kg and moves at 2 m/s, the energy is $0.5 \times 1000 \times 2^2 = 2000$ J.” (S1-G3-D3)

The lower overall rate in Semester 2 did not indicate weaker problem solving. The Semester 2 problems often required students to compare conceptual models and technological methods rather than perform repeated numerical reconstruction. Quantitative reasoning was therefore interpreted as task-dependent.

Integration of Multiple Physics Concepts

Concept integration was one of the clearest semester-level differences, increasing from 22.7 to 35.7 coded turns per 100 substantive turns. Semester 1 discussions commonly connected friction, momentum, energy, force, tension, and torque. Semester 2 discussions more frequently combined geometrical optics, physics optics, diffraction, wavelength, frequency, electromagnetic-wave penetration, material properties, and sensing technology. The shift was particularly visible when students recognized that no single physics model was sufficient to explain or solve the whole problem.

“So even if the geometrical optics predicts a sharp image position, diffraction can cause blurring ... small cracks may not be resolved.” (S2-G3-D3)

This form of integration represented a more system-oriented approach to problem solving: concepts were used in combination to explain why a method would work, where it would fail, and what additional model or technology was required.

Evidence-Based Reasoning

Explicit evidence-based reasoning occurred at 8.1 turns per 100 in Semester 1 and 4.5 in Semester 2. Therefore, the current results do not support simple claim that students progressed from opinion-based to increasingly evidence-based reasoning across semesters. Rather, evidence use varied by problem context. Semester 1 contained frequent use of numerical estimates, friction coefficients, reference values, simulations, and proposed field measurements. Semester 2 more often relied on theoretical reasoning about wavelength, resolution, penetration, and material response. Evidence-based reasoning was therefore retained as an important problem-solving practice, but not interpreted as a uniformly increasing outcome.

Patterns of Uncertainty, Assumptions, and Model Limitations

One of the clearest corpus-level patterns was the greater prominence of explicit uncertainty and limitation reasoning in Semester 1 discussions and throughout the Semester 2 corpus. The overall rate doubled from 9.6 coded turns per 100 substantive turns in Semester 1 to 19.2 in Semester 2. Within Semester 1, uncertainty/limitations reasoning increased from approximately 3.0 per 100 turns in Discussion 1 to 15.4 in Discussion 3. Semester 2 began at a higher level (approximately 14.6 per 100 turns) and rose to approximately 23.5 by Discussion 3.

“If μ is slightly off, say... its ± 0.05 , our calculated speeds can vary by $\pm 5-10\%$.” (S1-G1-D3)

“As frequency increases, the wavelength decreases ... which improves resolution. However, higher frequencies scatter more easily ... So, we face a 'Resolution vs. Penetration' paradox.” (S2-G1-D2)

The nature of these contributions suggested a movement beyond asking only whether an answer could be obtained. Students increasingly considered how reliable that answer was, which assumptions were required, and which environmental or technological constraints could change the conclusions. Examples included road condition and friction, incomplete accident data, diffraction limits, soil conductivity, penetration depth, image resolution, and calibrations limitations.

Patterns of Collaborative Knowledge Construction

Collaboration was examined through the context and sequence of student turns rather than participation frequency alone. Explicit peer co-construction, as narrowly coded, was uncommon (0.2 and 0.8 occurrences per 100 substantive turns in Semester 1 and 2, respectively). However, sequential qualitative analysis showed that later discussions more frequently contained chains of linked contributions in which students extended, challenged, corrected, or synthesized one another's ideas. Peer correction increased from 4.7 to 7.0 coded turns per 100 substantive turns. This was important because it indicated that collaboration was not limited to agreement or encouragement, students increasingly evaluated the content of peers' contributions.

“My idea is to organize our proposal as a phased detection strategy with three interconnected phases ... a feedback loop where each phase informs the others.” (S2-G2-D3)

In this discussion, subsequent students developed the proposed structure by explaining how GPR could be used for broad detection, how endoscopic or geometrical-optics inspection could verify local features, how diffraction and other physics-optics effects could account for imaging limitations, and how observations could be fed back to improve calibration. The final solution therefore emerged from linked contributions rather than isolated individual answers. This pattern provided stronger evidence of collaborative knowledge construction than simple counts of agreement statements.

Learner Regulation and Facilitator Roles Across the Discussion Corpus

Students’ regulation of the discussion becomes more visible in later sessions. Peer leadership or facilitation increased from 3.7 to 5.0 coded turns per 100 substantive turns between semesters. Students increasingly initiated discussion stages, posed guiding questions, invited peer contributions, checked whether learning objectives had been addressed, and synthesized group conclusions.

“Let me start by setting the structure for today. My idea is to organize our proposal as a phased detection strategy with three interconnected phases.” (S2-G2-D3)

This change was accompanied by a more selective facilitator role in several later sessions. Early Semester 1 discussions more frequently contained lectured prompts reminding students how to organize the discussion or return to the Three-Step Cycle. In later sessions, some groups were able to manage these procedural functions themselves. Nevertheless, the pattern was not uniform. Certain sessions still required lecturer redirection or participation management. The observations indicate variation in the distribution of regulatory responsibility across discussions and groups rather than a uniform developmental shift toward independence from the facilitator.

Cognitive Sophistication Versus Conceptual Accuracy

Qualitative examination demonstrated that cognitively sophisticated discourse was not necessarily scientifically accurate. This distinction was important because the PIM captures the cognitive function of a contribution, not the correctness of its physics content. For example, an early Semester 1 contribution correctly recognized that momentum is conserved in an inelastic collision but incorrectly stated that kinetic energy is not lost to heat or deformation.

“real car crashes are inelastic, where momentum is conserved and kinetic energy is not lost to heat or deformation.” (S1-G1-D1)

Another early contribution suggested that a heavier elevator would necessarily accelerate faster because it experienced a larger gravitational force. This explanation was incomplete because the resulting acceleration depends on the net force relative to mass and the full elevator, pulley, and braking system.

“The heavier the elevator is ... the more gravitational force pulling it down so it eventually accelerates faster.” (S1-G2-D1)

These cases justify analyzing conceptual accuracy separately from cognitive depth.

Reflective and Metacognitive Awareness

Reflection was present throughout the corpus but did not show a simple quantitative increase. Reflection occurred at 8.1 coded turns per 100 substantive turns in Semester 1 and 4.8 in Semester 2. Consequently, the findings do not support describing reflection as a uniformly increasing skill across semesters. Qualitatively, however, some reflective contributions moved beyond expressions of enjoyment or general teamwork toward awareness of how evidence, accuracy, assumptions, limitations, and discussion strategies influenced problem

solving. These contributions indicated metacognitive awareness among some students, particularly when they evaluated what they had understood, recognized remaining uncertainty, or reflected on the value of structured group reasoning. Reflection was therefore interpreted as a supporting feature of the PBL discourse rather than a primary developmental outcome.

Integrated Summary Across Groups and Semesters

Overall, the strongest finding was not a uniform developmental progression but variation in the character of problem-solving discourse across discussion cycles, groups, and semester-specific corpora. Some discussions contained more connected explanations, model comparison, uncertainty evaluation, peer-supported reasoning, and student-led regulation than others. These patterns were heterogenous and were also shaped by the differing problem contexts. Therefore, the findings should interpret as corpus-level variation in problem-solving discourse rather than as evidence that some students or groups developed linearly across two semesters,

Dimension	Earlier / less developed pattern	More advanced pattern observed
Problem framing	Clarifying terms and listing facts	More explicit identification of conditions, missing information, and problem constraints
Cognitive inquiry	Exploration and information sharing dominated	Greater integration and occasional solution evaluation, but trajectories varied by group/problem
Physics reasoning	More isolated concepts	More frequent connection of multiple concepts and models
Mathematics	Formula identification and calculation	Calculation increasingly used to support interpretation; strongly task-dependent
Evidence	Opinion, recall, calculations, and selected external information	Evidence remained important but did not uniformly increase across semesters
Uncertainty	Relatively limited in early discussions	More explicit assumptions, limitations, trade-offs, and reliability concerns
Collaboration	Parallel answers and agreement common	More peer correction, linked contributions, and collaborative synthesis
Regulation	More lecturer procedural prompting	More student-led structuring and selective lecturer intervention
Reflection	General learning/teamwork comments	Some deeper reflection on reasoning quality and limitations, but no overall frequency increase
Conceptual accuracy	Misconceptions could coexist with active participation	Higher cognitive depth still required separate checking for scientific correctness

Table 4. Integrated Patterns Across the Discussion Corpus

Overall, the strongest finding was not a uniform increase in every coded behavior but a change in the character of students' problem-solving discourse. Repeated synchronous written PBL discussions provided visible evidence of students moving, in many sessions, from fact identification and isolated concept recall toward connected explanations, model comparison, evaluation of uncertainty, peer-supported reasoning, and greater student regulation of the inquiry. The development was heterogeneous across groups and problem contexts, and some indicators, notably explicit evidence use and reflection which did not increase consistently. The results therefore support a nuanced interpretation of development in the quality of problem-solving discourse rather than a claim of universal or linear improvement.

DISCUSSION

The present study examined how problem-solving discourse varied across repeated synchronous written PBL discussions in two partially overlapping semester-specific corpora. The findings should not be interpreted as

individual longitudinal development because only 14 of the 19 unique students were represented in both semesters and group membership was reorganized. Instead, the analysis identifies corpus-level variation in cognitive presence, scientific reasoning, collaboration, and learner regulation across discussion cycles, groups, and different physics problem contexts. Within these boundaries, concept integration, uncertainty and limitation awareness, and peer correction were more prominent in selected later discussions and in parts of the Semester 2 corpus, whereas mathematical reasoning, explicit evidence use, reflection, and peer facilitation varied according to task and group context.

Cognitive Presence and Context-Sensitive Variation in Problem-Solving Discourse

The PIM analysis showed that Exploration remained the dominant phase across most discussions, while Integration and Resolution varied across problem cycles. Semester 1 demonstrated a modest increase in higher-order inquiry across Discussions 1-3, whereas Semester 2 began with a comparatively high proportion of Integration before later discussions returned to a stronger balance between Exploration and Integration. This pattern is consistent with previous cognitive-presence research showing that online discourse frequently concentrates in the Exploration and Integration phases and that progression toward Resolution is not necessarily automatic or sequential (Sadaf et al., 2021). The findings therefore suggest that the four PIM phases should not be interpreted as a rigid staircase through which must progress in every discussion. A new or conceptually demanding problem may legitimately require students to return to Exploration even after they have demonstrated higher-order reasoning in an earlier activity. Reviews of cognitive presence similarly indicate that the level of inquiry is affected by task design, learner characteristics, facilitation, disciplinary context, and the nature of online interaction (Maranna et al., 2022).

This interpretation is particularly relevant to the current PBL design because each discussion addressed a different but interconnected problem with specific learning objectives. Thus, lower HOIR values in a subsequent discussion should not automatically be interpreted as regression. Students may have needed to explore unfamiliar concepts before integrating them into the broader problem. The Semester 2 discussions, for example, required consideration of geometrical optics, physical optics, electromagnetic waves, sensing technologies, material properties, and practical detection constraints. The substantial Exploration observed in these discussions may therefore represent productive inquiry rather than superficial engagement.

These findings reinforce the importance of analysing the process of problem solving, rather than judging PBL solely through final products or achievement scores. The written transcripts make visible when students are identifying unknowns, connecting concepts, revisiting explanations, and testing possible solutions. This process-based perspective complements previous physics PBL research, including a recent Kazakhstan study by Sagatbek et al. (2024), which found that PBL significantly improved high-school students' physics learning compared with traditional instruction. The present findings extend that outcome-oriented evidence by showing some of the discourse processes through which students collectively work with physics knowledge during PBL.

Scientific Problem-Solving Across Different Task Demands

One of the clearest semester-level differences was the greater prevalence of concept integration in the Semester 2 corpus. Semester 1 discussions frequently connected force, friction, momentum, energy, tension, and torque, whereas Semester 2 discussions more frequently connected wavelength, diffraction, resolution, electromagnetic-wave penetration, conductivity, optics, and sensing technologies. This difference should not be interpreted as evidence that the same students became more integrative over time; rather, it shows that the Semester 2 discourse contained a greater proportion of contributions connecting multiple concepts, which may also reflect the different cognitive demands of the problems.

Such reasoning is important in authentic physics problem solving because real-world situations often contain incomplete information and interacting constraints. The developmental value of PBL may therefore lie partly in creating conditions in which students must determine which physics concepts are relevant and how those concepts work together. Recent physics-education studies continue to emphasise PBL and STEM-based problem solving as approaches for supporting analysis, planning, communication, and solution development.

For example, Sydykova and Naushabekov (2024), working within the Kazakhstan physics-education context, highlighted problem identification, formulation, resolution, and evaluation as central components of physics problem-solving competence.

A particularly notable corpus-level pattern was the greater visibility of uncertainty, assumptions, and model limitations in later discussions. Students discussed the sensitivity of friction coefficients, wet-road conditions, incomplete information, and frequency-resolution trade-offs. These contributions demonstrate conditional scientific reasoning within the discourse, while the study design does not allow this pattern to be attributed solely to individual development across semesters. This finding is important because scientific reasoning involves more than producing an answer. Students need to understand that physical models rely on assumptions and that predictions may change when those assumptions change. The increased attention to uncertainty therefore represents an epistemically important form of problem solving: student began to treat physics knowledge as a tool for evaluating competing possibilities rather than as a fixed collection of formulas.

Mathematical and evidence-based reasoning, however, did not increase uniformly across semesters. Mathematical reasoning was more prominent in the mechanics problems, whereas Semester 2 discussions contained more conceptual integration and evaluation of physical limitations. This indicates that quantitative reasoning should be interpreted as task-dependent. The absence of a numerical calculation does not necessarily indicate weaker problem solving when a problem instead requires students to compare models, technologies, assumptions, or physical constraints.

Collaborative Knowledge Construction and Learner Regulation

The findings also showed qualitative changes in how students worked with one another's ideas. Earlier discussion frequently involved parallel responses and simple agreement, whereas later discussions contained more sequences of proposal, questioning, extension, correction, and synthesis. Peer correction was also more frequent in Semester 2. This pattern supports the social constructivist foundation of PBL, in which learning develops through interaction rather than through individual information acquisition alone. Collaborative learning research within the Community of Inquiry framework similarly emphasises that meaningful interaction can support engagement and collective knowledge construction in online environments (Das & Madhusuda, 2023). The Kazakhstan-based study of Sagatbek et al. (2024) is particularly relevant here. Their implementation of social-constructivist PBL in high-school physics found that students could function as scaffolds for one another during disciplinary learning and problem solving. The present study provides complementary process evidence: peer scaffolding was visible when students added calculations to peers' explanation, challenged assumptions, identified model limitations, or contributed different parts of an integrated solution.

The findings also indicate a gradual redistribution of regulatory responsibilities. Early discussions frequently required lecturer reminders about how to organise the PBL process, whereas later discussions contained more student-led questioning, sequencing, summarisation, and monitoring of learning objectives. Recent work on learning presence within the Community of Inquiry framework similarly foregrounds learner agency, self-regulation, and responsibility for managing online learning, while also recognising that the strength and expression of these processes vary across contexts (Chang et al., 2026).

Importantly, greater autonomy did not mean that the facilitator becomes unnecessary. Some groups continued to require intervention to address participation imbalance or loss of direction. This supports the view that effective PBL facilitation involves adaptive scaffolding: the lecturer provides greater structure when students require it and withdraws support when learners can regulate the inquiry themselves (English & Kitsantas, 2013). The pedagogical objective is therefore not zero lecturer involvement, but a gradual movement from lecturer-regulated toward increasingly student-regulated inquiry.

Cognitive Sophistication Does Not Necessarily Indicate Conceptual Accuracy

An important contribution of the present analysis is the distinction between cognitive sophistication and disciplinary correctness. Some student contributions displayed questioning, explanation, or integration while

simultaneously containing inaccurate physics. This demonstrates a limitation of interpreting higher PIM categories as equivalent to successful disciplinary learning. For example, students could connect momentum and collision concepts while holding an incorrect conception about kinetic-energy transformation, or construct a causal explanation involving elevator mass while oversimplifying the relationship between force, mass, and acceleration. Such contributions may still constitute cognitively active discourse, but they require disciplinary correction.

This distinction has important implications for lecturers using discussion-based PBL. Promoting student autonomy should not mean allowing misconceptions to remain unexamined. The facilitator must monitor both the sophistication of the reasoning process and the scientific validity of the reasoning produced. Recent studies of online cognitive presence similarly indicate that reaching more advanced phases of inquiry may still depend on appropriate teaching support (Fathali, 2024).

Thus, the present study suggests that cognitive-presence analysis in disciplinary contexts such as physics can be strengthened by incorporating conceptual accuracy as an additional analytical dimension. A student may be demonstrating Integration, while integrating scientifically incorrect propositions. The distinction is therefore particularly useful when interpreting PIM data in STEM disciplines.

Pedagogical Implications for Physics Lecturers

Several implications arise from these findings. First, lecturers should not evaluate the success of PBL solely from whether students reach the Resolution quickly. Extensive Exploration may be necessary when students encounter unfamiliar physics. What matters is whether that exploration subsequently enables students to connect concepts, evaluate evidence, question assumptions, and construct defensible explanations. Second, discussion should itself be treated as an important learning outcome. The synchronous written format provided a visible record of how students questioned, calculated, corrected, and synthesised. For lecturers, these records offer richer evidence of students' thinking than participation counts or final answers alone. Third, scaffolding should be gradually adjusted rather than removed abruptly. A simple structure such as what we know-what we need to know-summary can help novice PBL students organise inquiry, but later discussions should provide opportunities for students to assume responsibility for these functions themselves.

In addition, lecturers should explicitly encourage students to discuss assumptions, uncertainties, and limitations. Questions such as What are we assuming?, How reliable is this value?, What would happen if this condition changed?, and What are the limitations of this model? may help move discussion beyond procedural equation solving toward more authentic scientific reasoning. Finally, cognitive depth and conceptual accuracy should be assessed separately. Students need opportunities to reason independently, but lecturers must remain attentive to misconceptions and intervene strategically when inaccurate ideas risk becoming embedded in the group's collective explanation. Overall, the findings suggest that the educational value of repeated synchronous written PBL lies not simply in producing more discussion, but creating a structured environment in which students can progressively connect, question, evaluate, correct and regulate scientific reasoning together.

CONCLUSION

This study demonstrates that repeated synchronous written PBL discussions can provide meaningful evidence of how students' physics problem-solving develops in practice. The findings highlight the value of examining discourse quality, not merely final answers or participation frequency. Importantly, cognitive development was neither uniform nor strictly linear, reinforcing the need for flexible scaffolding and careful facilitation. The study also shows that deeper reasoning should be distinguished from conceptual correctness. Several limitations are important when interpreting these findings. First, the participant structure was only partially overlapping across semesters: 14 of 29 unique students were represented in both semester corpora, and most of these students were regrouped. The study therefore does not provide a strict same-person or same-group longitudinal comparison. Second, student contributions were nested within students, groups, and discussion sessions, so the descriptive discourse units should not be treated as statistically independent observations.

Third, the PBL problems differed between semesters in disciplinary content and task demands; consequently, semester-level differences may reflect problem characteristics as well as prior PBL experience. Finally, the findings derive from a single pre-university institution and should be interpreted as context-specific corpus patterns rather than broadly generalizable developmental effects. Overall, synchronous written PBL offers a useful approach for making students' scientific reasoning, collaboration, and learner regulation visible within authentic problem-solving contexts.

Ethical Considerations

Ethical Approval: Ethical principles were observed throughout the study. Student's synchronous written PBL discussions were anonymised before analysis, and no personally identifiable information was retained. Participation did not affect academic grades, and all data were used solely for research purposes and stored securely.

Conflict of Interest: Authors declare no conflict of interest.

Data Availability

The data supporting this study are not publicly available due to student privacy and confidentiality considerations. De-identified data may be made available from the corresponding author upon reasonable request, subject to institutional and ethical requirements.

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