Effect of PhET-Assisted Problem-Based Learning on Students' Conceptual Understanding of Motion Dynamics

Muhammad Raihan[1]*; Desy Hanisa Putri[2]; Bodi Gunawan[3]

[1,2,3]*Physics Education, Universitas Bengkulu, Indonesia*
[1]**Corresponding Email: 4.muhamadraihan.12@gmail.com*

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Abstract: This quasi-experimental study examined the effect of Problem-Based Learning (PBL) assisted by PhET simulations on students' conceptual understanding of motion dynamics. The participants were 64 eleventh-grade science students at SMA Negeri 6 Bengkulu, divided into an experimental class receiving PhET-assisted PBL and a control class receiving PBL only. Students' conceptual understanding was assessed using essay tests based on the SOLO Taxonomy. Data were analyzed using descriptive statistics, the Mann–Whitney U test, normalized gain (N-Gain), and rank-biserial effect size. The results revealed no statistically significant difference between the experimental and control groups ($p = 0.204$). Nevertheless, the experimental group achieved a moderate N-Gain score (0.313) and a small effect size ($r = 0.158$), indicating that PhET-assisted PBL produced moderate learning improvement without providing a significant advantage over PBL alone. These findings suggest that PBL remains the primary contributor to conceptual understanding, while PhET serves as a complementary visualization tool that supports learning consistency.

Abstract: Penelitian kuasi eksperimen ini bertujuan menganalisis pengaruh model *Problem-Based Learning* (PBL) berbantuan simulasi PhET terhadap pemahaman konsep dinamika gerak peserta didik. Penelitian melibatkan 64 siswa kelas XI IPA SMA Negeri 6 Bengkulu yang dibagi menjadi kelas eksperimen dengan PBL berbantuan PhET dan kelas kontrol dengan PBL tanpa PhET. Pemahaman konsep diukur menggunakan tes esai yang disusun berdasarkan Taksonomi SOLO. Analisis data dilakukan menggunakan statistik deskriptif, uji Mann–Whitney, *normalized gain* (N-Gain), dan *rank-biserial effect size*. Hasil penelitian menunjukkan tidak terdapat perbedaan yang signifikan antara kedua kelompok ($p = 0{,}204$). Meskipun demikian, kelas eksperimen memperoleh nilai N-Gain kategori sedang (0,313) dengan *effect size* kecil ($r = 0{,}158$), yang menunjukkan bahwa penggunaan PhET dalam PBL memberikan peningkatan pembelajaran pada tingkat sedang, tetapi belum menghasilkan keunggulan yang signifikan dibandingkan PBL saja. Temuan ini mengindikasikan bahwa PBL menjadi faktor utama dalam meningkatkan pemahaman konsep, sedangkan PhET berperan sebagai media visual pendukung yang membantu konsistensi proses pembelajaran.

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A. Introduction

In the twenty-first century, rapid technological advancement has transformed various sectors, including education. This transformation requires educational systems to adopt innovative teaching approaches that integrate technology to improve learning quality and student achievement (Natifa et al., 2024). Advances in science and technology have become essential for creating more effective learning environments, particularly in science education, where students are expected to develop conceptual understanding through direct observation, experimentation, and scientific inquiry (Sriwahyuni et al., 2019). In physics education, practical activities play an important role in enabling students to connect theoretical concepts with real-world phenomena. However, the implementation of laboratory activities is often constrained by limited instructional time, safety concerns, and inadequate laboratory facilities. These limitations reduce opportunities for meaningful experimentation and ultimately hinder students' conceptual understanding. Therefore, effective and technology-supported learning media are needed to overcome these challenges (Bogar et al., 2023; Sati et al., 2022).

Conceptual understanding is one of the primary indicators of successful learning because it reflects students' ability to interpret, connect, and apply scientific concepts rather than merely memorising formulas. The SOLO Taxonomy (*Structure of the Observed Learning Outcome*) provides a comprehensive framework for evaluating the quality and depth of students' conceptual understanding through hierarchical cognitive levels, ranging from prestructural to extended abstract (Ismawati et al., 2023). Compared with conventional achievement measures, the SOLO Taxonomy enables researchers to evaluate how students construct conceptual relationships and transfer their knowledge to new situations. Meanwhile, technological developments have encouraged the widespread adoption of interactive digital simulations in education. Among these, PhET Interactive Simulations have become increasingly popular because they provide opportunities for students to explore scientific phenomena virtually while reducing the limitations associated with conventional laboratory activities (Sari & Nurannisa, 2024; Zulaeha et al., 2026).

Learning models also play a crucial role in determining students' learning outcomes. One instructional approach that has been widely adopted is Problem-Based Learning (PBL), which is grounded in constructivist learning theory and emphasises student-centred learning (Mayasari et al., 2022). Through authentic problem-solving activities, PBL encourages students to identify problems, formulate hypotheses, gather information, and collaboratively develop solutions. Numerous studies have demonstrated that PBL improves critical thinking, problem-solving ability, and learning engagement. Nevertheless, several studies and classroom observations indicate that students' conceptual understanding often remains limited because many learners focus primarily on procedural problem-solving rather than developing meaningful conceptual connections (Kelvin, 2025; Hotimah, 2020). These findings suggest that although PBL provides meaningful learning experiences, additional instructional support is still required to help students visualise abstract concepts and construct deeper conceptual understanding.

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One promising approach is integrating PBL with PhET Interactive Simulations. Within the PBL framework, students investigate authentic problems while PhET provides dynamic visualisations that enable them to explore scientific concepts through virtual experimentation. Such integration allows students not only to discuss and formulate hypotheses but also to verify their ideas through interactive simulations, thereby strengthening conceptual construction. Furthermore, PhET facilitates the visualisation of abstract physics concepts that are often difficult to demonstrate using conventional laboratory equipment. Previous studies have reported that PhET improves students' engagement, promotes conceptual exploration, and reduces misconceptions because students can manipulate variables and immediately observe their effects (Anitasari et al., 2019; Rizaldi et al., 2020; Singh et al., 2026).

Despite these promising findings, several important research gaps remain. First, previous studies have generally investigated the effectiveness of PBL or PhET separately or compared PBL with conventional instruction. Second, most existing studies have evaluated learning outcomes using Bloom's Taxonomy or cognitive achievement scores, whereas relatively few have examined students' conceptual understanding using the SOLO Taxonomy, which provides a more comprehensive evaluation of conceptual development. Third, limited research has investigated whether integrating PhET into an already active learning model such as PBL provides additional benefits beyond those achieved through PBL alone, particularly in schools with limited laboratory facilities. Consequently, empirical evidence regarding the incremental contribution of PhET within a PBL environment remains inconclusive.

The context of this study further highlights the importance of addressing this gap. Preliminary observations and interviews with physics teachers at SMA Negeri 6 Bengkulu revealed that students experienced low conceptual understanding of motion dynamics due to limited opportunities for laboratory activities, as school laboratory facilities were temporarily unavailable. Consequently, students tended to remain at lower levels of conceptual understanding and experienced difficulties in establishing meaningful relationships among physics concepts.

The novelty of this study lies in three aspects. First, this study integrates Problem-Based Learning with PhET Interactive Simulations to support conceptual learning in motion dynamics. Second, unlike previous studies that primarily relied on conventional cognitive achievement measures, this research evaluates conceptual understanding using the SOLO Taxonomy, enabling a more comprehensive assessment of students' hierarchical conceptual development. Third, this study investigates whether PhET provides additional instructional value when integrated into an already constructivist learning environment based on PBL, thereby extending previous findings that mainly compared PBL with traditional teaching methods.

Based on these research gaps, this study investigates whether integrating PhET Interactive Simulations into the Problem-Based Learning (PBL) model provides additional benefits in improving students' conceptual understanding of motion dynamics compared

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with the implementation of the PBL model alone. In addition, this study examines the extent to which the integration of PhET within the PBL framework influences students' conceptual understanding across the hierarchical levels of the SOLO Taxonomy. Accordingly, the null hypothesis (H_0) states that PhET-assisted Problem-Based Learning does not significantly improve students' conceptual understanding of motion dynamics compared with Problem-Based Learning alone, whereas the alternative hypothesis (H_1) states that the integration of PhET into the PBL model significantly improves students' conceptual understanding. Therefore, this study aims to examine the effectiveness of integrating PhET Interactive Simulations into the Problem-Based Learning model and to evaluate its contribution to enhancing students' conceptual understanding of motion dynamics at SMA Negeri 6 Bengkulu.

B. Method

This study employed a quantitative approach using a quasi-experimental design with a non-equivalent control group design, as this design allows comparison between experimental and control groups without random assignment of participants (Hunter et al., 2018). The research was conducted during the first semester of the 2025/2026 academic year at SMA Negeri 6 Bengkulu, Indonesia. The population consisted of all Grade XI science students distributed across five classes. Purposive sampling was employed based on the researcher's consideration and recommendations from physics teachers regarding students' academic characteristics and learning achievement (Firmansyah, 2022). Accordingly, Class XI-E was selected as the experimental group and Class XI-D as the control group, with 32 students in each class (N = 64). The experimental group received instruction through Problem-Based Learning (PBL) integrated with PhET Interactive Simulations, whereas the control group was taught using the same PBL model without PhET assistance. This design enabled the researchers to examine whether the integration of PhET provided additional benefits for students' conceptual understanding beyond those achieved through the PBL model alone. The overall research design is presented in Table 1 (Sugiyono, 2020).

Students' conceptual understanding was measured using an essay test developed according to the SOLO Taxonomy, focusing on three hierarchical cognitive levels: multistructural, relational, and extended abstract (Rahayu & Setiyadi, 2023). Initially, ten essay items were constructed based on the learning objectives of motion dynamics. The instrument underwent expert validation involving two university lecturers and one experienced physics teacher to ensure content relevance and alignment with the SOLO Taxonomy indicators. Following expert review, the instrument was piloted to examine item validity, reliability, difficulty index, and discrimination index using IBM SPSS Statistics version 29. Based on the psychometric analysis, five items demonstrating satisfactory validity, acceptable discrimination, and comprehensive representation of the measured SOLO levels were retained for the main study.

The research procedure was conducted through four sequential stages, as illustrated in Figure 1. The first stage involved research preparation, including a literature review,

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instrument development, expert validation, instrument revision, and pilot testing to ensure the quality of the research instrument. The second stage consisted of administering a pre-test to both the experimental and control groups to determine students' initial conceptual understanding before the instructional intervention. During the third stage, the experimental class participated in Problem-Based Learning assisted by PhET Interactive Simulations, whereas the control class received the same Problem-Based Learning instruction without simulation support. Finally, both groups completed a post-test using the validated instrument to measure changes in conceptual understanding after the intervention. This systematic procedure ensured consistency in the implementation of the learning model and the collection of comparable data between the two groups.

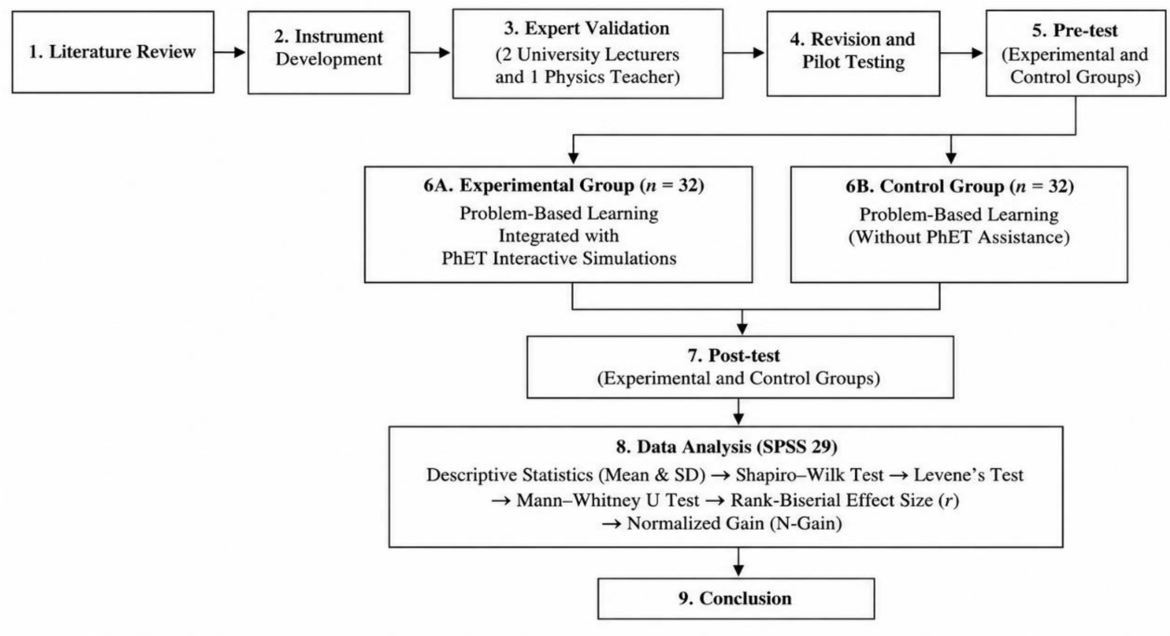

Figure 1. Research Flow

The collected data consisted of pre-test and post-test scores measuring students' conceptual understanding. Descriptive statistics, including the mean and standard deviation, were first calculated to summarize students' learning outcomes. Before hypothesis testing, the assumptions of normality and homogeneity were examined using the Shapiro–Wilk test (Quraisy, 2022) and Levene's test, respectively. If the data fulfilled the assumptions of normality and homogeneity, an independent-samples *t*-test would be employed. However, because the data violated both assumptions ($p < 0.05$), the non-parametric Mann–Whitney U test was used to compare post-test scores between the experimental and control groups. To determine the magnitude of the treatment effect, the rank-biserial correlation coefficient (effect size) was calculated (Salsabila et al., 2024). Furthermore, students' improvement in conceptual understanding was evaluated using the normalized gain (N-Gain), which measures the increase in learning outcomes between the

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pre-test and post-test (Wahab et al., 2021). The interpretation of N-Gain followed the criteria proposed by Zaqiah et al (2024). Collectively, these analyses provided comprehensive evidence regarding the statistical significance, practical significance, and instructional effectiveness of integrating PhET Interactive Simulations into the Problem-Based Learning model.

C. Result

Instrument Quality Analysis

Prior to the implementation of the learning intervention, the conceptual understanding test was evaluated to ensure its psychometric quality. The evaluation included item validity, reliability, difficulty index, and discrimination index. The results are presented in Tables 1 and 2.

Table 1. Results of Validity and Reliability Tests

Item	Pearson Correlation (r)	Validity Status	Cronbach's Alpha
1	0.446	Valid	
2	0.000	Invalid	
3	0.289	Invalid	
4	0.034	Invalid	
5	0.000	Invalid	
6	0.510	Valid	rowspan = 10 0.485 (Fair**)**
7	0.528	Valid	
8	0.567	Valid	
9	0.492	Valid	
10	0.576	Valid	

The results presented in Table 1 indicate that six out of ten essay items satisfied the empirical validity criteria. Overall, the instrument demonstrated a Cronbach's Alpha coefficient of 0.485, indicating fair internal consistency for exploratory classroom research. Although several items did not meet the required validity threshold, the statistically valid items were considered appropriate for further evaluation. To ensure that the selected items were not only valid but also capable of accurately measuring students' conceptual understanding, additional analyses of item difficulty and discrimination indices were subsequently conducted. These analyses are presented in Table 2.

Table 2. Results of Difficulty and Discrimination Index Tests

Item	Difficulty Index	Category	Discrimination Index	Category
1	0.92	Easy	0.473	Good
6	0.67	Moderate	0.355	Fair
8	0.91	Easy	0.216	Fair
9	0.77	Easy	0.212	Fair
10	0.80	Easy	0.386	Fair

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Based on the difficulty and discrimination analyses, all retained items demonstrated acceptable psychometric properties. Although six items satisfied the empirical validity criteria, only five items (Items 1, 6, 8, 9, and 10) were retained for the final instrument. Item 7 was excluded because it measured the same SOLO Taxonomy indicator as Item 6, resulting in conceptual redundancy. Consequently, the final instrument provided balanced coverage of the multistructural, relational, and extended abstract levels while maintaining adequate measurement quality.

Descriptive Statistics

The descriptive statistics of students' conceptual understanding before and after the learning intervention are presented in Table 3.

Table 3. Mean Scores and Standard Deviations of the Pre-test and Post-test

Class	Pre-test		Post-test	
	Mean	SD	Mean	SD
Control	18.18	10.57	80.50	14.04
Experimental	18.31	8.93	86.87	6.0

Both groups demonstrated substantial improvement following the instructional intervention. The experimental group achieved a post-test mean score of 86.87 (SD = 6.00), whereas the control group obtained a mean score of 80.50 (SD = 14.04). Although the experimental group obtained a higher average score, descriptive statistics alone are insufficient to determine whether the observed difference is statistically significant. Therefore, inferential statistical analyses were subsequently performed.

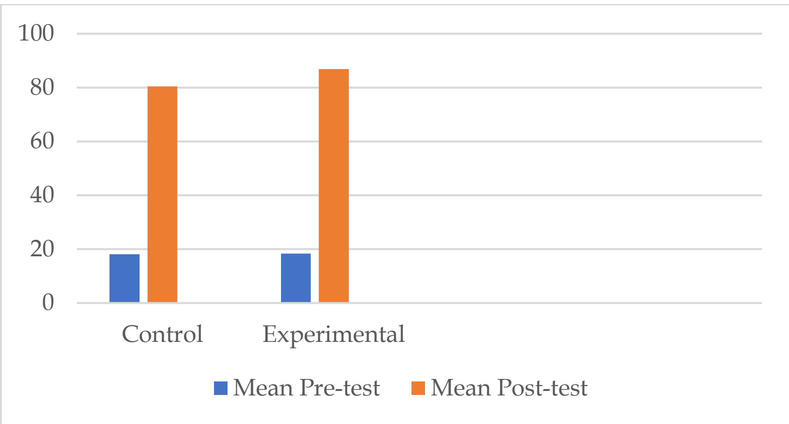

Figure 2. Illustrates the Comparison of Students' Pre-Test and Post-Test Mean Scores

The descriptive comparison indicates that both groups experienced substantial improvement following the instructional intervention. Although the experimental group obtained a higher post-test mean score than the control group, this descriptive difference does not necessarily indicate statistical significance.

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Assumption Testing

Before hypothesis testing, the assumptions of normality and homogeneity were examined.

Table 4. Shapiro–Wilk Normality Test

Test	Group	Statistic (W)	df	*p*-value	Interpretation
Pre-test	Experimental	0.710	32	< 0.001	Not normally distributed
	Control	0.930	32	0.044	Not normally distributed
Post-test	Experimental	0.870	32	0.001	Not normally distributed
	Control	0.790	32	< 0.001	Not normally distributed

The Shapiro–Wilk test indicated that all datasets violated the assumption of normality, with significance values below 0.05. In addition, Levene's test produced a significance value of 0.009, indicating unequal variances between groups. Therefore, the assumptions required for parametric analysis were not satisfied. Consequently, the Mann–Whitney U test was employed to compare the post-test scores between the experimental and control groups.

Hypothesis Testing

The results of the Mann–Whitney U test are presented in Table 5.

Table 5. Mann–Whitney U Test

Statistic	Value
Mann–Whitney U	419.500
Wilcoxon W	947.500
Z	-1.271
Asymp. Sig. (2-tailed)	0.204
Decision	Fail to Reject H_0
Interpretation	No significant difference between groups

The Mann–Whitney U test produced an Asymp. Sig. (2-tailed) value of 0.204, which exceeded the significance level of 0.05. Therefore, the null hypothesis was not rejected, indicating that no statistically significant difference was found between students who learned through PhET-assisted Problem-Based Learning and those who learned through Problem-Based Learning alone. Although the experimental group achieved a higher post-test mean score, the observed difference was not sufficiently large to be considered statistically significant.

Learning Improvement

Students' improvement in conceptual understanding was evaluated using the normalized gain (N-Gain), as presented in Table 6.

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Table 6. N-Gain Analysis

Indicator	Value	Category
Mean N-Gain Score	0.313	Moderate
N-Gain Percentage (%)	31.30	Moderately Effective

As presented in Table 6, the experimental group obtained a mean normalized gain (N-Gain) score of 0.313, which falls within the moderate category. This finding indicates that the implementation of PhET-assisted Problem-Based Learning resulted in a moderate improvement in students' conceptual understanding of motion dynamics. Furthermore, the N-Gain percentage reached 31.30%, suggesting that the instructional intervention achieved a moderately effective level of learning improvement during the study period.

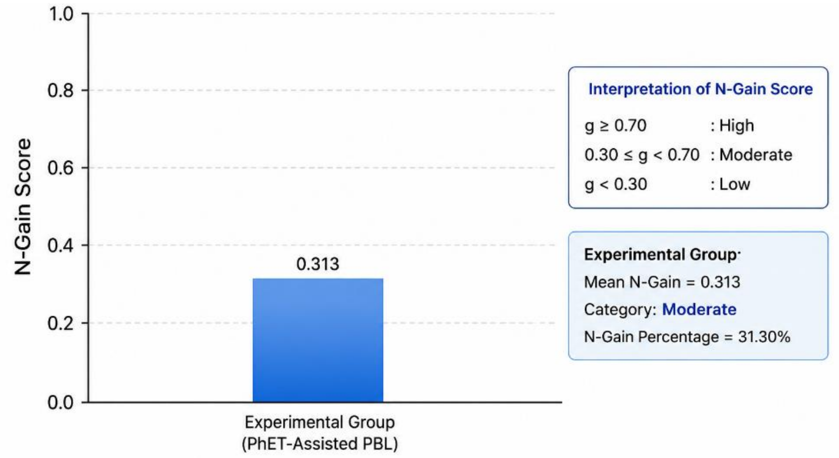

Figure 3. N-Gain Score

Effect Size

To determine the practical significance of the treatment, the rank-biserial correlation coefficient was calculated.

Table 7. Rank-Biserial Effect Size Analysis

Statistic	Value	Interpretation
Effect Size (*r*)	0.158	Small Effect
Practical Significance	Low	Limited practical impact
Statistical Decision	Consistent with Mann–Whitney U Test	No significant difference between groups

As presented in Table 7, the rank-biserial correlation coefficient yielded an effect size of 0.158, indicating a small practical effect of the PhET-assisted Problem-Based Learning intervention. Although the experimental group achieved a higher post-test mean score than the control group, the magnitude of the treatment effect was relatively limited. This finding

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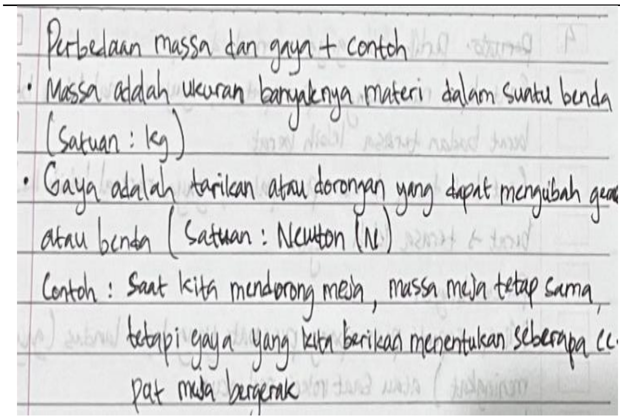
is consistent with the Mann–Whitney U test (p = 0.204), which indicated that the observed difference between the two instructional approaches was not statistically significant.

Analysis of Students' Conceptual Understanding Based on the SOLO Taxonomy

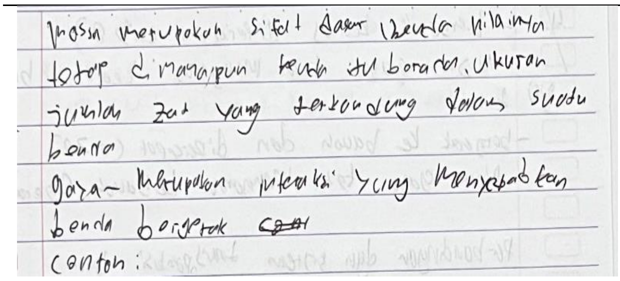
Students' conceptual understanding was further analysed using the SOLO Taxonomy through representative examples of responses at the multistructural, relational, and extended abstract levels.



The Difference Between Mass and Force with an Example

- Mass is the amount of matter contained in an object. *(Unit: kilogram (kg)).*
- Force is a push or a pull that can change the motion or shape of an object. *(Unit: newton (N))*

Example:
When we push a table, the mass of the table remains the same, but the force we apply determines how fast the table moves.



Mass is a fundamental property of an object, and its value remains constant regardless of where the object is located. Mass is a measure of the amount of matter contained in an object.
Force is an interaction that causes an object to move.
Example:

Figure 4. Students' Responses at the Multistructural Level

Analysis of students' responses at the multistructural level indicates that high-performing students successfully identified several relevant concepts and organised them appropriately, whereas lower-performing students were able to recall isolated facts but failed to establish meaningful contextual relationships among the identified concepts.

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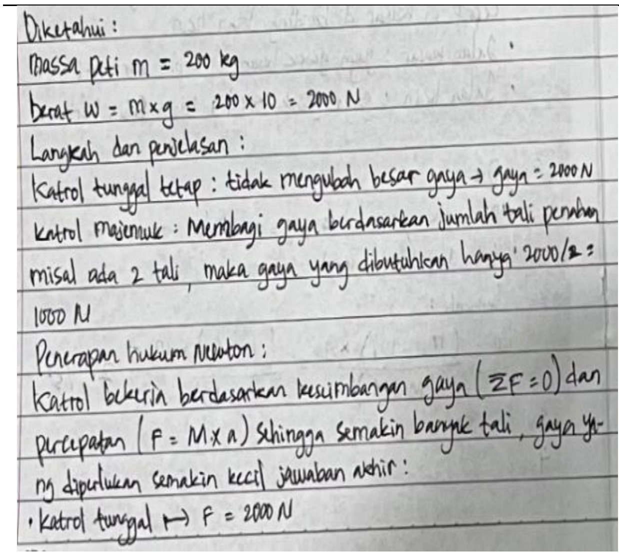

Diketahui :
massa peti m = 200 kg
berat w = m x g = 200 x 10 = 2000 N
Langkah dan penjelasan :
katrol tunggal tetap : tidak mengubah besar gaya → gaya = 2000 N
katrol majemuk : membagi gaya berdasarkan jumlah tali penahan
misal ada 2 tali, maka gaya yang dibutuhkan hanya 2000/2 =
1000 N
Penerapan hukum newton :
katrol bekerja berdasarkan kesimbangan gaya (ΣF = 0) dan
percepatan (F = M x a) sehingga semakin banyak tali, gaya ya-
ng diperlukan semakin kecil jawaban akhir :
• katrol tunggal → F = 2000 N

Given:

- Crate mass, $m = 200\text{kg}$
- Weight, $W = m \times g = 200 \times 10 = 2000\text{N}$

Solution:

- Single fixed pulley: does not change the magnitude of the applied force, so the required force remains 2000 N.
- Compound pulley (block and tackle): reduces the required force according to the number of supporting ropes.

For example, if there are 2 supporting ropes, the required force is:

$$F = \frac{2000}{2} = 1000\ \text{N}$$

Application of Newton's Laws

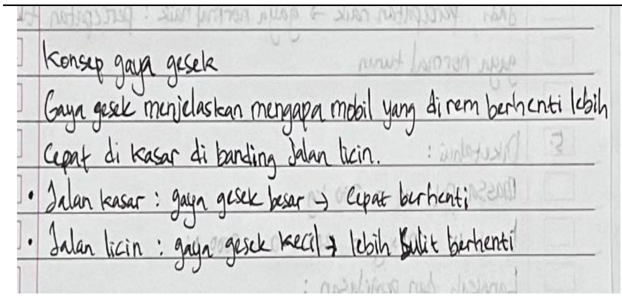
A pulley system operates based on the equilibrium of forces ($\Sigma F = 0$)and Newton's Second Law of Motion ($F = m \times a$). Therefore, the greater the number of supporting ropes, the smaller the force required to lift the load.

Final Answer:

- **Single fixed pulley:** $F = 2000\text{N}$

Figure 5. Students' Responses at the Relational Level

At the relational level, students with stronger conceptual understanding successfully integrated multiple physics concepts into coherent explanations and applied Newtonian principles appropriately. In contrast, lower-performing students established only partial relationships among variables, indicating incomplete conceptual integration.


Konsep gaya gesek
Gaya gesek menjelaskan mengapa mobil yang di rem berhenti lebih
cepat di kasar di banding jalan licin.
• Jalan kasar : gaya gesek besar → cepat berhenti
• Jalan licin : gaya gesek kecil → lebih sulit berhenti

Concept of Frictional Force

Frictional force explains why a braking car stops more quickly on a rough road than on a slippery road.

- Rough road: the frictional force is greater, so the car stops more quickly.
- Slippery road: the frictional force is smaller, making it more difficult for the car to stop

Figure 6. Students' Responses at the Extended Abstract Level

Students achieving the extended abstract level demonstrated the ability to generalise conceptual principles and apply them to unfamiliar situations. However, only a limited number of students reached this level, indicating that higher-order conceptual transfer remained challenging. The overall distribution of students' conceptual understanding across the SOLO Taxonomy is presented in Figure 7.

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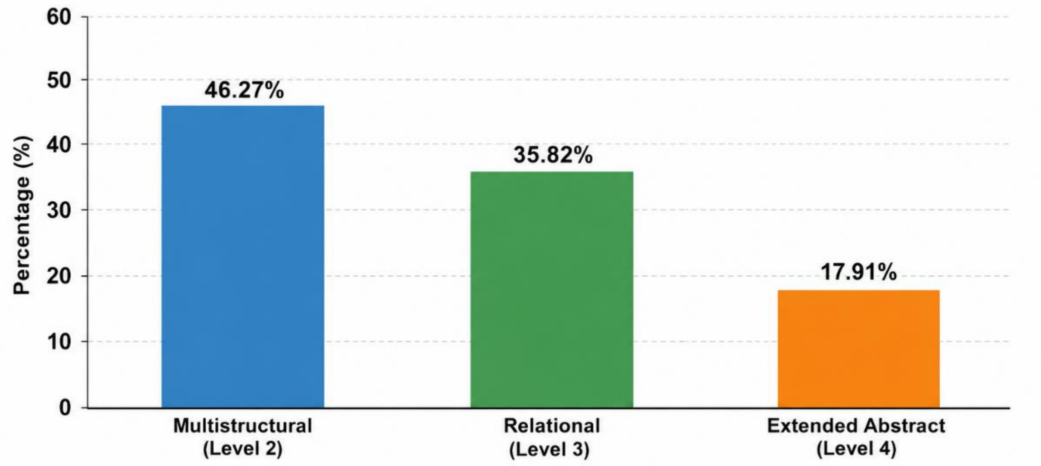

Figure 7. Distribution of Students' SOLO Taxonomy Levels

The distribution demonstrates that Multistructural responses accounted for 46.27%, followed by Relational responses (35.82%) and Extended Abstract responses (17.91%). These findings indicate that most students were capable of identifying and connecting relevant concepts, whereas relatively few demonstrated the ability to generalise and transfer conceptual knowledge to broader contexts.

D. Discussion

This study examined whether integrating PhET Interactive Simulations into the Problem-Based Learning (PBL) model provides additional benefits for students' conceptual understanding of motion dynamics compared with the implementation of PBL alone. The findings revealed that although students who learned through PhET-assisted PBL achieved a higher post-test mean score (86.87) than those who learned through conventional PBL (80.50), the Mann–Whitney U test indicated that the difference was not statistically significant ($p = 0.204$). Furthermore, the intervention produced a moderate normalized gain (N-Gain = 0.313) with a small practical effect size ($r = 0.158$). Analysis based on the SOLO Taxonomy further demonstrated that most students achieved the multistructural (46.27%) and relational (35.82%) levels, whereas only 17.91% reached the extended abstract level, indicating that higher-order conceptual transfer remained relatively limited. These findings suggest that integrating PhET into PBL contributed to learning improvement but did not produce a substantial advantage beyond the effectiveness already achieved through the PBL model itself.

One possible explanation is that both groups experienced the same constructivist learning environment because Problem-Based Learning was implemented in both classes. PBL encourages learners to identify problems, formulate explanations, discuss ideas collaboratively, and construct conceptual understanding through inquiry. Consequently, the essential mechanisms responsible for conceptual development were already present in both instructional conditions. The addition of PhET primarily functioned as a visualization and experimentation tool rather than as a fundamentally different instructional approach.

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As a result, although PhET helped students observe abstract physical phenomena more clearly and supported conceptual consistency, its incremental contribution was insufficient to generate statistically significant differences. This interpretation is also consistent with the relatively small effect size obtained in the present study, suggesting that visualization alone may not substantially improve conceptual understanding when students are already actively engaged in problem-solving activities.

These findings can be interpreted through constructivist learning theory proposed by Piaget and further developed in social constructivism by Vygotsky (Rigopouli et al., 2025). Constructivism argues that conceptual understanding develops when learners actively construct knowledge through meaningful experiences rather than passively receiving information. Within this perspective, PBL serves as the primary instructional strategy that facilitates cognitive conflict, collaborative inquiry, and conceptual restructuring, while PhET functions as a cognitive scaffold that assists learners in visualising scientific phenomena. From the perspective of cognitive load theory, PhET may reduce extraneous cognitive load by presenting dynamic visual representations of motion dynamics, thereby enabling students to process abstract concepts more efficiently (Peltzer et al., 2026; Sari et al., 2025). However, when the learning activities have already been well structured through PBL, the additional reduction in cognitive load may not be sufficiently large to produce significant differences in learning outcomes. This finding indicates that technology enhances learning most effectively when it complements rather than replaces pedagogical strategies.

The present findings are consistent with previous studies reporting that Problem-Based Learning effectively improves conceptual understanding because students actively engage in analysing authentic problems and constructing scientific explanations (Mayasari et al., 2022; Aristawati et al., 2018; Anggraini et al., 2023). Likewise, previous research has demonstrated that PhET simulations improve students' conceptual exploration, visualization, and engagement in physics learning (Anitasari et al., 2019; Rizaldi et al., 2020). However, the current findings differ from studies reporting significant superiority of PhET-assisted learning over conventional instruction, such as Wendra & Mandriesa (2025). A possible explanation for this discrepancy is that most previous studies compared PhET-assisted learning with teacher-centred or conventional teaching methods, whereas the present study compared PhET-assisted PBL with PBL itself. Because both instructional approaches were already grounded in active learning principles, the additional contribution of PhET naturally became smaller. Therefore, the effectiveness of PhET appears to depend on the instructional context into which it is integrated rather than on the technology alone.

Another important finding concerns students' conceptual development across the SOLO Taxonomy levels. Nearly half of the students demonstrated multistructural understanding, indicating that they were capable of identifying multiple relevant concepts but had not yet fully integrated these concepts into coherent scientific reasoning. Approximately one-third reached the relational level, suggesting that many students successfully established meaningful conceptual relationships. Nevertheless, only a small

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proportion achieved the extended abstract level, where learners are expected to generalise principles and transfer conceptual understanding to unfamiliar situations. This pattern suggests that although PBL and PhET effectively supported conceptual acquisition and integration, promoting higher-order conceptual transfer remains challenging. The finding reinforces previous SOLO Taxonomy studies showing that progression from relational to extended abstract thinking requires prolonged inquiry experiences, repeated reflection, and opportunities to apply concepts across multiple contexts rather than through a single instructional intervention.

This study also contributes to the existing literature in several important ways. First, unlike previous studies that primarily evaluated cognitive achievement using conventional test scores or Bloom's Taxonomy, this research employed the SOLO Taxonomy to examine the hierarchical development of conceptual understanding. This approach provides richer evidence regarding the quality of students' conceptual thinking rather than merely measuring achievement scores. Second, this study specifically investigated the incremental contribution of PhET within an already constructivist instructional model instead of comparing technology-supported learning with traditional instruction. The findings demonstrate that technological innovation should not automatically be expected to outperform well-designed active learning models. Rather, educational technology functions most effectively as a complementary learning support that enhances conceptual visualization and learning consistency. Consequently, this study provides empirical evidence that contributes to a more balanced understanding of the relationship between pedagogy and educational technology in physics education.

Overall, the findings answer the research question by demonstrating that integrating PhET Interactive Simulations into the Problem-Based Learning model moderately improves students' conceptual understanding of motion dynamics but does not provide a statistically significant advantage over the implementation of Problem-Based Learning alone. While PhET effectively supports visualization and conceptual exploration, the primary driver of conceptual understanding remains the inquiry-oriented learning processes embedded within the PBL model. Therefore, the effectiveness of educational technology depends not merely on its presence but on how it is pedagogically integrated into meaningful learning experiences.

E. Implication

The findings of this study have important pedagogical and theoretical implications for physics education. Pedagogically, the results suggest that teachers should prioritise the effective implementation of Problem-Based Learning (PBL) as the primary instructional approach for fostering students' conceptual understanding, while employing PhET Interactive Simulations as a complementary tool to enhance visualisation of abstract concepts and support students' conceptual exploration. The absence of a statistically significant difference indicates that educational technology alone is insufficient to substantially improve conceptual understanding unless it is meaningfully integrated into

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inquiry-oriented learning activities. Therefore, instructional planning should focus not only on technology adoption but also on designing learning experiences that promote conceptual integration, scientific reasoning, and knowledge transfer. Theoretically, this study reinforces constructivist perspectives by demonstrating that students' conceptual development is primarily driven by active knowledge construction through problem-solving, whereas digital simulations function as cognitive scaffolds that facilitate conceptual representation rather than replace pedagogical interaction. Furthermore, the application of the SOLO Taxonomy provides a more comprehensive framework for evaluating the depth of conceptual understanding beyond conventional cognitive achievement measures, offering valuable insights for future research investigating the quality of conceptual learning. Overall, these findings contribute empirical evidence that the educational value of PhET lies in strengthening the effectiveness of well-designed constructivist instruction rather than serving as an independent determinant of learning success.

F. Limitations and Suggestions for Further Research

Despite providing valuable insights into the role of PhET-assisted Problem-Based Learning in improving conceptual understanding, this study has several limitations that should be considered when interpreting the findings. First, the research involved a relatively small sample drawn from a single senior high school, which may limit the generalisability of the results to broader educational contexts. Second, the intervention was conducted over a relatively short instructional period, potentially restricting students' opportunities to develop higher-order conceptual understanding, particularly at the extended abstract level of the SOLO Taxonomy. Third, the study focused exclusively on students' conceptual understanding without examining other learning variables that may influence the effectiveness of technology-enhanced instruction, such as motivation, cognitive load, scientific reasoning, learning engagement, or self-regulated learning. Consequently, the present findings primarily reflect the immediate impact of integrating PhET into the PBL model rather than its long-term contribution to students' conceptual development.

Future research is therefore recommended to involve larger and more diverse samples across different schools and educational settings to improve the external validity of the findings. Longitudinal studies with longer intervention periods are also needed to investigate whether sustained exposure to PhET-assisted Problem-Based Learning can facilitate students' progression toward higher SOLO Taxonomy levels, particularly the extended abstract level, where conceptual transfer and generalisation occur. In addition, future studies should incorporate complementary variables, including cognitive load, learning motivation, scientific reasoning, metacognitive skills, and classroom engagement, to better explain the mechanisms through which digital simulations support conceptual learning. Comparative investigations involving other technology-enhanced learning environments, such as virtual laboratories, augmented reality, or artificial intelligence-based learning platforms, may also provide a more comprehensive understanding of how different instructional technologies interact with constructivist pedagogies to promote meaningful conceptual understanding in physics education.

G. Conclusion

This study concludes that integrating PhET Interactive Simulations into the Problem-Based Learning (PBL) model moderately improved students' conceptual understanding of motion dynamics but did not produce a statistically significant advantage over the implementation of PBL alone. Although the experimental group achieved higher post-test scores, a moderate N-Gain, and a small positive effect size, the findings indicate that the primary factor contributing to students' conceptual understanding was the inquiry-oriented learning process embedded within the PBL model, while PhET mainly functioned as a complementary visualisation tool that supported conceptual exploration and learning consistency. Analysis based on the SOLO Taxonomy further revealed that most students attained the multistructural and relational levels, whereas relatively few reached the extended abstract level, suggesting that transferring conceptual understanding to broader contexts remains challenging. Therefore, this study contributes empirical evidence that the educational value of digital simulations depends on their meaningful pedagogical integration within constructivist learning environments rather than on the technology itself. Furthermore, the use of the SOLO Taxonomy provides a more comprehensive perspective for evaluating the quality and depth of students' conceptual understanding, thereby enriching the literature on technology-enhanced physics learning and offering practical guidance for designing more effective conceptual learning experiences.

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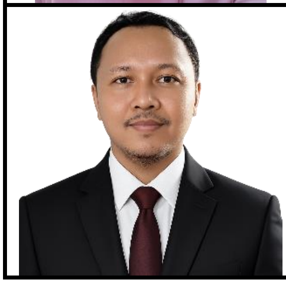
Author Biography

	**Muhammad Raihan.** He was born in Kepahiang on 22 January 2004. He is currently pursuing a bachelor's degree in the Physics Education Study Program at the Faculty of Teacher Training and Education, Universitas Bengkulu. Email: 4.muhamadraihan.12@gmail.com
	**Desy Hanisa Putri, S.Pd., M.Si.** She is a lecturer and Head of the Physics Education Study Program, Faculty of Teacher Training and Education, University of Bengkulu. Her research interests include research methodology, qualitative research, physics education, and the development of physics learning media. Email: dhputri@unib.ac.id
	**Bodi Gunawan, S.Pd., M.Si.** He is a lecturer in the Physics Education Study Program at Universitas Bengkulu. His research focuses on instrumentation, materials physics, renewable energy, computational physics, and physics education. He is actively involved in research, community engagement, and academic quality assurance. Email: bodi.gunawan@outlook.com