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Pictorial-Based Learning (PcBL) for Promoting Students' Critical Thinking Skills and Learning Outcomes on Reaction Rate

Aprendizagem Baseada em Imagens (ABI) para Promover Habilidades de Pensamento Crítico dos Alunos e Resultados de Aprendizagem na Taxa de Reação

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This study investigates the critical thinking skills (CTS) and cognitive learning outcomes (CLO) of students utilizing Pictorial-Based Learning (PcBL) as compared to those taught through Direct Instruction (DI). A quasi-experimental design with pretest and post-test measures was employed, involving 46 students from Class XI IPA at SMA Nasional Malang during the 2023/2024 academic year, selected via convenience sampling. The critical thinking skills test was developed based on Facione's framework, and the Cognitive Learning Outcomes Instrument has been previously validated. Data analysis utilized the Independent Samples t-test, N-gain scores, and Cohen's Effect Size. The findings reveal that students receiving instruction through PcBL demonstrated significantly better CTS and CLO in reaction rate material than their peers in the DI group. Specifically, the Independent Samples t-test results indicated a significant difference in CTS and CLO scores between the PcBL and DI classes. The average CTS score for the PcBL class was 70.83, while the DI class had an average score of 48.37. Regarding CLO, the PcBL class achieved an average score of 75.65, compared to 61.30 for the DI class. The N-gain score for CTS was calculated to be 0.54, falling within the moderate category, with a Cohen's effect size of 1.08, indicating a substantial effect. For CLO, the N-gain score was 0.56, also categorized as moderate, with a Cohen's effect size of 0.95, classified as very large.

Keywords: High level of thinking; cognitive outcomes; visual-based teaching in chemistry.

1. Introduction

The lack of critical thinking skills among Indonesian students could hinder the country's goal of becoming a Golden Generation by 2045. This phenomenon is associated with the inability of chemistry students to learn to extract valuable information from visual representations and transform it into chemical behaviour. Critical thinking is a vital skill in contemporary society and is indispensable in educational curricula.[1] Several studies have revealed that Indonesian students' critical thinking skills are still insufficient.[2,3] At the same time, the lack of understanding of chemistry among Indonesian students has persisted for ages. Developing critical thinking skills in chemistry is vital for comprehending abstract concepts and gaining the abilities necessary for students to engage with chemical topics responsibly and knowledgeably in daily life.[1]

Chemistry learning requires students not only to memorize theories but also to understand the concepts being studied. Generally, chemists present these concepts in three levels of knowledge representation: macroscopic, submicroscopic, and symbolic. The macroscopic level involves observable chemical facts or phenomena, such as those observed in chemical experiments. [4] The submicroscopic level refers to the mental models experts use to explain phenomena or facts at the microscopic level, including particles, atoms, molecules, ions, and structures.[5] Meanwhile, the symbolic level represents macroscopic chemical phenomena using chemical formulas, symbols, equations, algebra, graphs, and reaction mechanisms.[4,5] Symbolic representation also serves as a mediator between the macroscopic and microscopic levels.[6] Therefore, to facilitate chemistry learning, teachers should apply all three representations: macroscopic, submicroscopic, and symbolic. To gain a deeper understanding, students must be able to connect their chemical knowledge across these three levels of representation.[4]

The three levels of representation can emphasise observation skills in students, encouraging them to observe phenomena from various perspectives. This approach promotes systematic and in-depth thinking, even reaching critical thinking levels in interpreting these phenomena. Unfortunately, many studies have shown that students, including undergraduate chemistry students, struggle to understand visual representations of chemistry concepts.[7,8] Previous studies[9] indicate that students perform better in answering algorithmic questions than in responding to pictorial questions. This is due to students' difficulty in identifying relevant information from pictorial representations, such as graphs, diagrams, or tables. Furthermore, errors in transforming information obtained from pictorial representations into chemical behaviors can lead to misconceptions. An important responsibility for teachers today is to train students on how to extract critical information from pictorial representations and transfer that information into chemical behaviors.

Providing students with frequent opportunities to engage with pictorial representations, both in the learning process and during assessments, helps them become more familiar with submicroscopic and symbolic phenomena. Moreover, this practice boosts their confidence in handling such phenomena. Two main challenges students face with pictorial representations are difficulty in extracting relevant information and errors in converting that information into chemical behavior.[10,11] These findings suggest the importance of enhancing students' ability to interpret images, graphs, and tables, enabling them to extract crucial information from such representations.

One approach to addressing students' difficulties with visual representation and enhancing critical thinking is to integrate the Pictorial-Based Learning (PcBL) approach in chemistry instruction. Visual representations, including figures, graphs, tables, animations, diagrams, and any other visual representation, could help students properly understand chemistry.[11,12] Previous studies on chemical kinetics have demonstrated the contribution of PcBL in improving student understanding.[11] This learning model is applied by incorporating media that trains students' abilities to engage with submicroscopic and symbolic phenomena.

1.1. Measuring cognitive learning outcomes & critical thinking skills: theoretical framework

Learning outcomes refer to the knowledge, skills, attitudes, and positive behaviours students are expected to master and demonstrate after a specific period of teaching and learning. The most widely accepted principles regarding learning outcomes in any teaching process are emphasized across three domains: cognitive, affective, and psychomotor. Cognitive domains pertain to the acquisition of knowledge, information, and intellectual skills; affective domains relate to attitudes and perspectives toward learning and other relevant aspects in general; and psychomotor domains involve hands-on skills and the level of involvement in behavioral learning activities.[13–15] In our national context, learning outcomes are guided by the national education document issued by the Ministry of National Education. In this study, we focused on the cognitive learning outcome (CLO) due to limited time and resources.

Additionally, developing a high level of thinking, such as critical thinking, plays a pivotal role in education. Critical Thinking Skills (CTS) are considered, such as critical thinking, which enables students to tackle the complexities of modern society.[16] Consequently, critical thinking is frequently emphasized as a key educational goal and an essential graduate attribute for employment initiatives for graduates.[17] Due to the indispensable role of this skill for students, several platforms have been developed and utilized to measure students' CTS involving educators and even philosophers around the world. Ennis[18] advocates for a definition of critical thinking that is fundamentally based on specific skills, including observation, inference, generalization, reasoning, and the evaluation of reasoning. He defines critical thinking as 'the accurate evaluation of statements' and more broadly as 'reasonable reflective thought.'

Another scholar emphasizes the skills and methods associated with critical thinking.[19] He distinguishes between weak critical thinking and strong critical thinking. In a limited sense, it refers to the ability to critically evaluate perspectives different from one's own; in a broader sense, it includes the capacity to critically analyze one's own viewpoint, reasoning, assumptions, and worldview.[20] The core principles of CTS involve several indicators: interpretation, analysis, inference, evaluation, explanation, and self-regulation.[21] Facione's definition of critical thinking provides an essential introduction and a reliable foundation for any discussion about critical thinking in higher education.[22] For this reason, the platform from Facione is used to measure students' critical thinking in this study.

2. Research Objectives

This study aimed to evaluate the effectiveness of Pictorial-based Learning (PcBL) in enhancing students' Cognitive Learning Outcomes (CLO) and Critical Thinking Skills (CTS). To obtain a definitive answer regarding the objective, two groups of students were assigned as experimental and control groups. Specifically, the research question can be formulated as whether the implementation of PcBL has a greater impact on improving students' CLO and CTS compared to Direct Instruction (DI).

3. Method

This study utilized a quasi-experimental pretest-posttest design with two groups. The participants were all 11th-grade science students at SMA Nasional Malang during the 2023/2024 academic year. Pretest scores indicated that both groups had comparable initial abilities. The experimental group, consisting of 23 students, was taught using the PcBL model, while the control group, also composed of

23 students, received instruction through the DI model. The topic covered in this research was chemical kinetics, including the rate law and factors that affect reaction rates.

3.1. PcBL vs DI models

The two groups received instruction from identical textbooks for the same duration. The differences between the two models are outlined below. At the beginning of the kinetics course, the PcBL process was initiated by displaying images or graphics that illustrated the sub-microscopic processes in various chemical reaction scenarios. For the students, these visual representations acted as cognitive triggers. An example of a graphical trigger that introduces the catalyst role in chemical reactions is presented below. Students collaborated in pairs to extract information from the figure in the following process step. In class, the insights gained from the visual depiction were discussed. This led to the conclusion that although the catalyst is ultimately reformed in the end product, it remains chemically involved in the reaction. Other concepts were taught using similar procedures.

Meanwhile, DI began with a brief recap of the preceding topic from the previous class, and then proceeded to teach the current topic. Students then completed exercises either alone or in small groups, depending on the complexity of the activities. After that, the instructor provided helpful criticism and a brief recap of the material covered in the class. As previously mentioned, the DI group's and the PcBL class's textbooks were identical. Nevertheless, the textbook's visual aids were used only to supplement the teacher's explanation with additional information.

The intervention (PcBL and DI) was conducted over six meetings for each group, with each session lasting two 45-minute sessions. The first meeting began with a pretest, followed by the treatment, and concluded with a post-test. The learning instruments included the syllabus, lesson plans, and student worksheets for the PcBL and DI models. The assessment instruments consisted of essay tests to evaluate critical thinking skills based on Facione's indicators: interpretation, analysis, and inference, and a multiple-choice test for cognitive learning outcomes,[21] which had been validated by two chemistry education experts and tested for validity and reliability, ensuring their suitability for use.

3.2. Instruments

Students' Cognitive Learning Outcomes (CLOs) were assessed using a 10-item multiple-choice questionnaire that covered the rate law and factors affecting the rate. The difficulty level matched the national curriculum standards. Meanwhile, Critical Thinking Skills (CTS) were evaluated using short-answer Critical Thinking Questions in Chemical Kinetics (CTQ-CK). Examples of questions for CLO and CLS are shown in Figures 2 and 3, respectively. The complete instruments are available upon reasonable request. In Figure 2, students were asked to choose the correct collision orientation of HCl that could potentially lead to a reaction from five options. The CTS question in Figure 3 also pertains to collision theory, where students were required to determine which possible orientation might trigger a chemical reaction.

The two questions from Figures 2 and 3 required students to understand the concept of collision theory,

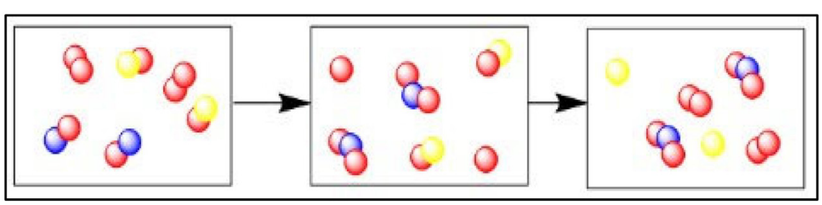

Figure 1. Pictorial trigger for the catalyst role

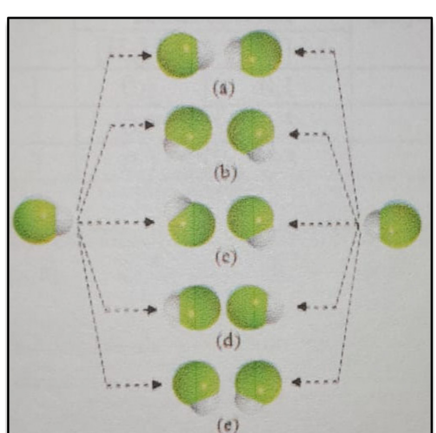

Figure 2. Example of CLO question

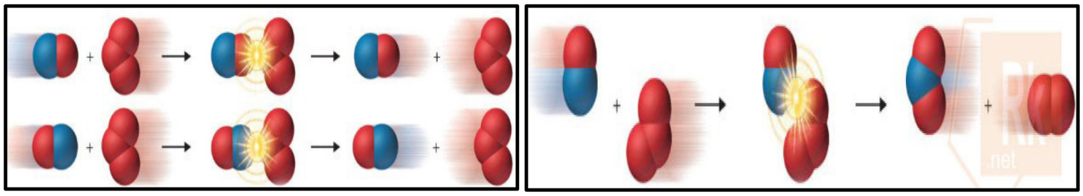

Figure 3. Example of CTS question

particularly how the orientation of collisions could lead to acquiring enough energy for a chemical reaction. However, the question in Figure 3 demands a higher level of thinking compared to the earlier question due to the increased complexity of the molecules involved. For this reason, Figure 2 was designed to measure CLO, while the other targeted CTS.

3.3. Data analysis

Data analysis of students' CLO and CLS was conducted using an Independent Samples t-test, N-gain score calculations, and Cohen's effect size. The t-test was applied only if both normality and homogeneity tests were satisfied, indicating that the data were normally distributed and homogeneous. The normality test was performed using the Shapiro-Wilk test, while homogeneity was assessed through Levene's test, both carried out via IBM SPSS for Windows. The Independent Samples t-test was conducted on post-test scores for critical thinking skills and cognitive learning outcomes at a 5% significance level (α = 0.05). The N-gain test aimed to evaluate the effectiveness of the teaching model by comparing the overall improvement in scores before and after the treatment, using IBM SPSS for analysis. Finally, Cohen's effect size was employed to ascertain the magnitude of the treatment's impact on the measured variables.

3.4. Ethical clearance

This study has been reviewed by the appointed panel within the department to ensure that the study meets the criteria for studies involving humans. In addition, the school committee has also reviewed and granted permission for the authors to carry out this study. All participants have also provided their consent before participating in data collection.

4. Results and Discussion

The analysis of the normality test results for the pretest data on students' CTS in both the experimental and control classes yielded p-values of 0.089 and 0.053, respectively, indicating that the data were normally distributed. The homogeneity test result was 0.383, demonstrating that the data were homogeneous. Furthermore, the mean equality test revealed no significant difference in initial abilities between the two classes, with a significance value of 0.512, indicating that they were suitable for sampling in the study. Similarly, the normality test results for the CLO pretest in the experimental and control classes were 0.051 and 0.061, respectively, also indicating normal distribution. The homogeneity test, with a value of 0.368, confirmed that the data were homogeneous. The mean equality test for CLO further revealed no significant difference in initial abilities, with a significance value of 0.314, allowing both groups to be included as samples. The pretest data analysis, conducted before the treatment, was performed using IBM SPSS 26 for Windows, with a significance level set at $p < 0.05$.

The normality test results for post-test data on CTS in both the experimental and control groups, analyzed using IBM SPSS 26 for Windows, indicated significance values of 0.101 and 0.054, respectively, confirming a normal distribution. The homogeneity test showed a significance value of 0.691, demonstrating that the data were homogeneous. In assessing CTS achievement, based on Facione,[23] the assessment utilized indicators of interpretation, analysis, and inference. In the experimental group, the achievement percentages were as follows: interpretation at 64.13% (good), analysis at 82.07% (excellent), and inference at 66.30% (good), resulting in an average score of 70.83%. Conversely, in the control group, the percentages were "interpretation" at 40.22% (moderate), "analysis" at 59.78% (moderate), and "inference" at 45.11% (moderate), resulting in an average score of 48.37%.

Table 1. Hypothesis test for critical thinking skills and learning outcomes

Variable	Significance Value	α
Critical Thinking	0.001	0.05
Learning Outcomes	0.002	

Table 1 presents the hypothesis test results using the Independent Sample t-test for the post-test data on CTS and CLO in both the experimental and control groups. The Table demonstrates a significance value of less than 0.05, indicating a statistically significant difference in CTS and CLO between students taught using Pictorial-Based Learning and those taught using Direct Instruction.

Table 2. N-Gain score test

Variable	N-Gain	Category
Critical Thinking	0.540	Medium
Learning Outcomes	0.560	Medium

The effectiveness of PcBL on CTS and CLO was evaluated using N-gain calculations and Cohen's effect size test. The results from the N-gain and Cohen's effect size tests are presented in Tables 2 and 3, respectively. Based on the data in Table 2, there was an increase in CTS and CLO in the PcBL class. Meanwhile, Table 3 shows that the effect of PcBL on CTS and CLO is substantial.

Table 3. Cohen's effect size test

Variable	Effect Size Cohen's *(d)*	Category
Critical Thinking	1.080	Very Large
Learning Outcomes	0.950	Very Large

This research implemented different teaching models in both classes, where the experimental class engaged in PcBL focused on reaction rates, while the control class employed DI for the same subject. The learning sequence began with a pretest to determine the initial skill levels of the experimental and control groups. Following this, instruction was carried out over six sessions, utilizing worksheets to facilitate the learning process, and concluded with a post-test. The purpose of the post-test was to evaluate whether implementing the two teaching models enhanced students' CTS in both the experimental and control classes.

Data analysis was performed using the Independent Sample t-test to evaluate the equality of means, and no significant difference in student abilities was observed. Following instructions with each of the different models in both the experimental and control classes, the average pretest and post-test scores for CTS were acquired, as illustrated in Figure 4.

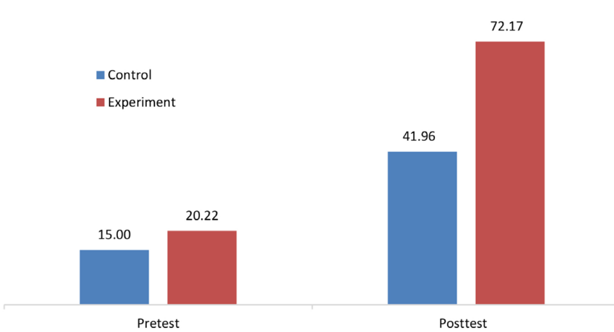

Figure 4. Average CTS scores

Figure 4 shows the graph comparing the pretest and post-test scores for the control and experimental classes. In the experimental class, there was a 10.39-point increase in CTS after being taught using PcBL. In the control class, the increase was 6.48 after being taught with DI. This indicates that both the PcBL and DI models resulted in improvements. However, the PcBL class exhibited higher CTS than the DI one. Thus, it can be concluded that implementing the PcBL model more effectively enhances students' critical thinking skills in chemistry learning about reaction rates than the control class, which only employed the DI model. The CTS advantage of PcBL students can be illustrated using Figure 5.

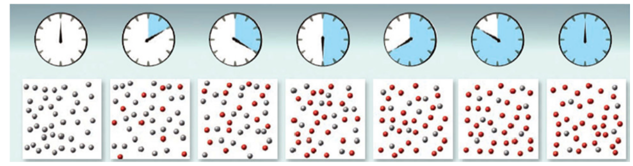

Figure 5. Pictorial representation of reaction progress A (grey spheres) → B (red spheres)

From the pictorial representation in Figure 5, PcBL students were able to create an accurate table and graph of the reaction rate, showing the decrease in A molecules and the increase in B molecules over time. This phenomenon illustrates an active process of knowledge construction within the students' cognitive domain, leading them to understand the nature of the law of reaction rate. This indicates the development of CTS skills, such as interpretation, analysis, and inference, among PcBL students. Their ability to extract information from pictorial cues helps foster CTS behaviors.[11]

The difference in CTS can also be substantiated through the results of hypothesis testing, N-gain tests, and Cohen's effect size. The disparity in critical thinking skills among students lies in their ability to understand the concept and in the syntax of the PcBL learning model, which incorporates stages that utilize pictorial triggers or visual representations. Learning based on visual representations can emphasize students' observational skills and prompt them to view phenomena from different perspectives. This type of learning activity directs students to analyze a problem, leading to solutions derived from pictorial triggers.[11]

Engaging in visual representation-based learning effectively enhances students' CTS. Activities centered around visual representations invite students to grasp the material on reaction rates from macroscopic, submicroscopic, and symbolic levels. Furthermore, it allows students to formulate and comprehend the material based on these three levels of representation, thereby improving their understanding of reaction rates. Figure 4 shows the percentage of critical thinking skill levels in the experimental and control classes.

Figure 6 illustrates an increase in the CTS of PcBL students compared to those of DI students. It can be concluded that the analysis indicator was more dominantly mastered by students when completing the critical thinking skills test, with a percentage of 82.07%, followed by the inference indicator at 66.3%, and then the interpretation indicator at 64.13%. The dominant indicator was also analyzed in the control class taught with the DI model, with a percentage of 59.78%, followed by the inference indicator at 45.11% and the interpretation indicator at 40.22%. In all three indicators, there was an improvement in students' critical thinking skills, as students observed and analyzed

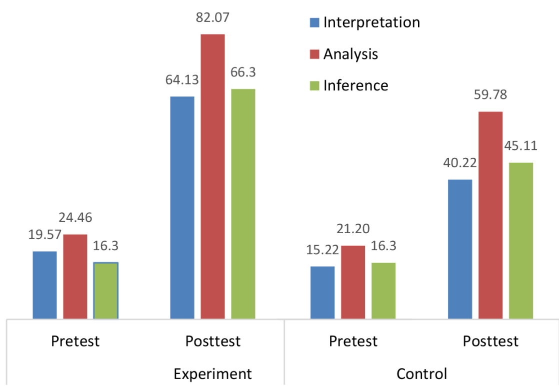

Figure 6. Critical thinking skills for the experimental class and the control class

pictorial triggers presented to stimulate their observation and analysis of images or visual representations during learning.

The measurement of CLO was also conducted similarly to assessing CTS. The learning process began with a pretest to identify the initial abilities of the experimental and control classes. Following this, it consisted of six meetings using worksheets (LKS) and ended with a post-test aimed at assessing whether the implementation of both models resulted in improved cognitive learning outcomes for students in both the experimental and control classes. Data analysis was conducted using the Independent Samples t-test to examine the equality of means, which confirmed that there was no difference in students' abilities. After being taught using different models in experimental and control groups, the average pretest and post-test scores for students' cognitive learning outcomes were obtained, as shown in Figure 7.

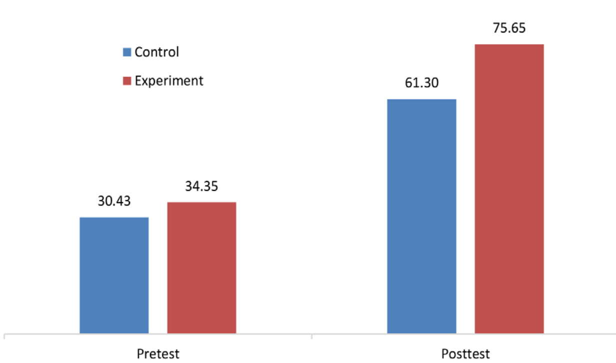

Figure 7. Scores of students' CLO

Figure 7 compares the pretest and post-test scores for the control and experimental classes. In the experimental class, there was a 75.65% increase in CLO after being taught using the PcBL model. In the control class, there was a 61.30% increase after being taught using Direct Instruction (DI). This indicates that the PcBL and DI models led to improvements. However, the class taught with PcBL achieved higher CLO compared to the class taught with DI. The difference in CLO is also supported by the results of hypothesis testing, N-gain, and Cohen's effect size.

The PcBL positively improves students' CLO by effectively guiding them in problem-solving related to the macroscopic, submicroscopic, and symbolic dimensions of reaction rate topics. Addressing issues within the concept of reaction rates necessitates the ability to integrate these three levels of representation. Chemistry generally encompasses three tiers: macroscopic, submicroscopic, and symbolic representations, collectively enhancing the understanding of chemical concepts.[4,24] Moreover, this study's findings are consistent with the research by Baptista,[25] which indicates that utilizing visual representations across these three domains significantly improves cognitive structures from pretest to post-test. Conceptual understanding can improve because visual representations serve as a bridge for students to comprehend abstract chemical concepts that require pictorial depiction.

5. Conclusion and Suggestions

Implementing the Pictorial-Based Learning (PcBL) model has significantly enhanced students' critical thinking skills (CTS) and learning outcomes (CLO). The findings reveal a marked increase in students' critical thinking abilities, characterized by an enormous effect size and a moderate N-gain. Similarly, there was a notable improvement in students' learning outcomes, as indicated by a considerable effect size and a moderate N-gain. Our findings highlight the pivotal role of using pictorial triggers for tackling students' difficulty in extracting valuable information from a visual representation, as mentioned in previous studies.[9,10] Therefore, utilizing this approach is a reasonable suggestion for helping chemistry students in this regard. However, this research is limited to evaluating critical thinking skills in the context of reaction rates. Future studies should consider similar characteristics when exploring other 21st-century competencies, such as Higher-Order Thinking Skills (HOTS) and scientific literacy, involving a more extensive and diverse sample to yield more representative findings.

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Declaration of AI-Assisted Technology

While preparing this paper, we used Grammarly to correct spelling and grammatical errors. Meanwhile, the content is entirely the responsibility of the authors. Additionally, we used ChatGPT to create the graphical abstract with detailed prompts to ensure that the picture accurately reflects the essence of this study.

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