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Development of STEAM-Based Learning Tools Integrated with the Techno-Analogy Inquiry Model to Enhance Elementary Students' Scientific Thinking Skills

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Abstract: This study aims to develop STEAM-based learning tools integrated with the Techno-Analogy Inquiry (TAI) model to enhance elementary school students' scientific thinking skills. The novelty of the TAI model lies in its integration of inquiry processes with technology-supported analogical reasoning, which serves as a cognitive bridge to help students connect abstract scientific concepts with familiar real-life experiences. The study employed a Research and Development (R&D) method using the ADDIE model. The participants consisted of 29 fifth-grade students. Data were collected through expert validation of the content, language, and media aspects conducted by four experts using a 4-point Likert scale, as well as through pretest–posttest assessments, observations, and student response questionnaires. The data were analyzed using descriptive statistics, N-gain analysis, and paired-sample t-tests. The results indicate that the developed learning tools are highly feasible, with an average validation score of 87.5%. Students' scientific thinking skills improved significantly, as reflected in the increase in the mean score from 47 on the pretest to 84 on the posttest. The N-gain score of 0.68 falls within the moderate-to-high category. Furthermore, the paired-sample t-test results revealed a statistically significant difference between the pretest and posttest scores ($p < 0.001$). These findings suggest that the integration of STEAM, inquiry-based learning, and technology-supported analogical reasoning through the TAI model is effective in enhancing students' scientific thinking skills and in providing a more meaningful and conceptually accessible learning experience.

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Introduction

The rapid advancement of digital technology in the 21st century has driven fundamental changes in how education is understood and implemented across the globe. Education is no longer viewed merely as a one-way process of knowledge transmission but rather as a systematic effort to develop higher-order thinking skills. Sheffield et al. (2018) emphasize that contemporary education systems must integrate scientific literacy with critical thinking skills in a comprehensive manner. This perspective aligns with Hidayat and Firmanti (2024), who argue that the effective use of technology in learning depends on pedagogical approaches that actively engage students' higher-order cognitive processes.

Within this framework, scientific thinking skills emerge as a key competency that must be developed from the elementary level. These skills extend beyond conceptual understanding to include the ability to engage in systematic and logical reasoning. Alé et al. (2025) explain that scientific practices involve activities such as observation, questioning, and hypothesis testing based on empirical evidence. Similarly, Papadakis (2025) highlights that inquiry-based approaches are effective in training students to construct arguments grounded in data and evidence. Therefore, science learning should be designed to promote students' active involvement in scientific investigation.

From a theoretical perspective, elementary education plays a crucial role in establishing the foundation of scientific thinking. At this stage, students are transitioning cognitively and require concrete learning experiences as a bridge toward abstract understanding. Florina (2022) stresses the importance of connecting concepts to real-life experiences to enhance comprehension. In this context, the STEAM (Science, Technology, Engineering, Arts, and Mathematics) approach offers a relevant alternative. Studies indicate that STEAM-based learning fosters critical thinking through contextual and interactive activities (Perastiati & Andayani, 2026), while also enhancing scientific literacy and creativity through project-based learning (Redhana, 2023).

In addition to STEAM, the use of analogy plays a significant role in helping students understand abstract concepts. Analogies enable learners to connect new knowledge with prior experiences, making learning more meaningful. Chen and She (2020) argue that analogy-based instruction strengthens conceptual understanding by systematically linking similarities across domains. Furthermore, Adúriz-Bravo (2024) notes that analogical reasoning supports students in constructing mental representations and understanding the structure of scientific concepts more deeply. These findings are supported by Handee and Thammaprateep (2025), who demonstrate that analogy-based learning enhances both metacognitive skills and scientific reasoning, particularly in understanding complex scientific phenomena. Additionally, Dai et al. (2024) reveal that integrating analogies with technology effectively reduces misconceptions and improves conceptual understanding of abstract scientific ideas.

Despite the growing implementation of innovative learning approaches, several studies indicate that such advancements have not yet been fully aligned with improvements in students' scientific literacy. This issue reflects not only a national concern but also a broader global challenge in elementary science education, particularly related to students' difficulties in understanding abstract concepts. In Indonesia, the OECD (2023) reported that students' science performance remains below the international average, indicating fundamental issues in literacy and reasoning competencies. Husamah et al. (2026) identify low reading literacy as a major factor hindering students' understanding of scientific information, while Siregar (2025) highlights that weak numeracy skills limit students' ability to analyze data and draw logical conclusions.

This gap between ideal expectations and classroom realities is also evident in instructional practices. Winarni et al. (2025) report that science learning in Indonesia is still largely teacher-centered, limiting students' opportunities to develop inquiry skills. Similarly, Nabila and Rosjanuardi (2025) note that lecture-based methods remain dominant, reducing student engagement in scientific exploration. As a result, students often struggle to formulate questions, develop hypotheses, and draw evidence-based conclusions.

Although research on STEAM and inquiry-based learning continues to evolve, most studies focus primarily on general learning outcomes without explicitly addressing how students construct conceptual understanding through appropriate cognitive support. Conventional inquiry approaches tend to emphasize procedural investigation but often lack structured strategies to bridge students' prior knowledge with abstract scientific concepts.

In this context, the Techno-Analogy Inquiry (TAI) model offers a complementary and innovative approach. Unlike conventional inquiry models, TAI integrates inquiry processes with technology-supported analogical reasoning as a cognitive bridge to facilitate students in connecting abstract scientific concepts with familiar real-life experiences. This integration not only strengthens conceptual understanding but also enhances students' engagement through interactive and contextual learning experiences.

Based on these challenges, this study focuses on developing STEAM-based learning tools integrated with the Techno-Analogy Inquiry (TAI) model. Through this approach, students are expected not only to understand concepts theoretically but also to relate them to real-life phenomena. Accordingly, this study aims to develop and examine the effectiveness of STEAM-based learning tools integrated with the Techno-Analogy Inquiry model in improving elementary students' scientific thinking skills. This study is expected to contribute both theoretically and practically. Theoretically, it enriches the discourse on integrating STEAM, inquiry, and analogy in science education. Practically, the findings may serve as a reference for teachers and policymakers in designing more innovative, contextual, and student-centered learning to support the development of 21st-century skills.

Research Method

This study employed a Research and Development (R&D) approach systematically designed based on the ADDIE model, which consists of five main stages: Analysis, Design, Development, Implementation, and Evaluation. This model was utilized to both develop and evaluate STEAM-based learning tools integrated with the Techno-Analogy Inquiry (TAI) model. The approach not only focuses on producing instructional products but also emphasizes continuous refinement through systematic validation and feedback at each stage of development. The ADDIE model is widely recognized as an instructional design framework with a clear yet flexible structure, allowing adjustments based on contextual learning needs. Dousay and Logan (2017) state that this model supports continuous formative evaluation to improve instructional design quality. Furthermore, recent studies indicate that design-based approaches such as ADDIE can produce learning products that are not only theoretically grounded but also contextually relevant and empirically validated (McKenney & Reeves, 2019). Therefore, this model was selected to ensure that the developed learning tools including lesson plans, student worksheets, and learning media meet the criteria of validity, practicality, and effectiveness, particularly in enhancing students' scientific thinking skills.

The participants in this study were 29 fifth-grade students, consisting of 15 male and 14 female students from SDN Sentul 1, Tangerang Regency, Indonesia. Participants were selected using purposive sampling, considering students' cognitive readiness to engage in inquiry-based learning and interdisciplinary approaches such as STEAM.

At the elementary level, students begin to demonstrate more structured reasoning abilities, making them relatively prepared to participate in learning that integrates inquiry processes with real-world contexts and technology. Creswell and Creswell (2018) emphasize that participant selection in educational research should align with the study's objectives. Additionally, the OECD (2023) highlights the importance of developing thinking competencies from an early stage as a foundation for sustainable scientific literacy.

Instruments

This study employed multiple instrument. The validation instrument used a 4-point Likert scale, with criteria ranging from 1 (not feasible) to 4 (highly feasible) to obtain comprehensive data, including expert validation sheets, observation sheets, student response questionnaires, and scientific thinking skills tests. All instruments were developed based on the theoretical framework of scientific inquiry and STEAM learning principles, ensuring alignment with the research objectives.

The learning tools were produced and subsequently validated by four experts, consisting of experts in content, language, and instructional media. The validation process

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aimed to determine the feasibility and quality of the developed products in terms of content accuracy, linguistic clarity, and media. Instrument reliability was tested through preliminary trials and internal consistency analysis. The use of multiple instruments in development research is highly recommended to ensure data triangulation, thereby enhancing the credibility and trustworthiness of findings (van den Akker et al., 2019). Moreover, a multi-instrument approach enables researchers to capture both learning processes and outcomes more comprehensively (McKenney & Reeves, 2019).

Data collection was conducted over approximately six months, covering all stages of the ADDIE model. The initial stage involved a needs analysis carried out through classroom observations, teacher interviews, and document analysis to identify instructional gaps and challenges. Subsequently, during the design and development stages, the learning tools were created, validated by experts, and revised based on feedback received. The implementation stage involved a limited classroom trial to assess the practicality and preliminary effectiveness of the product. The final stage, evaluation, was conducted both formatively and summatively to assess the overall quality of the developed learning tools. Throughout the research process, ethical considerations were strictly maintained, including obtaining informed consent from participants and ensuring data confidentiality.

This study combined quantitative and qualitative data analysis to provide a comprehensive understanding of the findings. Quantitative data were analyzed using descriptive statistics, percentage analysis, normalized gain (N-Gain), and paired sample t-tests to measure improvements in students' scientific thinking skills. Recent studies indicate that the N-Gain method is effective in measuring learning improvement by considering initial scores and the maximum achievable scores (Hake, 2017). Additionally, the paired sample t-test was used to determine whether the difference between pretest and posttest scores was statistically significant in the context of the instructional intervention (Fraenkel et al., 2019).

Meanwhile, qualitative data obtained from observations and expert feedback were analyzed using descriptive and thematic approaches. This analysis aimed to gain deeper insights into the learning process and to provide a basis for revising and refining the product. The integration of quantitative and qualitative analyses aligns with modern educational design research, which emphasizes a balance between measuring effectiveness and understanding the learning context comprehensively (McKenney & Reeves, 2019).

Results and Discussion

Feasibility Test Results of the Learning Tools

The first stage conducted prior to implementation was the feasibility testing of the product through expert validation. This step is essential to ensure that the developed learning tools meet academic standards in terms of content, language, presentation, and instructional design construction. The evaluation was carried out comprehensively by considering the alignment of the material with the curriculum, the clarity of language use, the coherence of learning components, and the quality of presentation in supporting students' learning activities. The validation results indicated that the developed learning tools achieved an average score of 87.5%, which falls into the highly feasible category. More specifically, the presentation aspect received the highest score, indicating that the structure and learning flow were well designed and easy to follow. Meanwhile, the language aspect was categorized as feasible, suggesting that it is generally communicative, although minor refinements are still needed.

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Table 1. Validation Results of Learning Tools

Aspect	Percentage	Category
Content Feasibility	88%	Highly Feasible
Language Feasibility	85%	Feasible
Presentation Feasibility	90%	Highly Feasible
Construction Feasibility	87%	Highly Feasible
Average	**87.5%**	**Highly Feasible**

These findings indicate that the learning tools meet the criteria for use in instructional activities. Nevertheless, feedback from validators was still utilized as a basis for limited revisions to further optimize the product quality before classroom implementation.

Description of Students' Learning Outcomes

After the learning tools were declared feasible, the next stage involved implementation in an actual classroom setting to observe changes in students' scientific thinking skills. Measurements were conducted using pretests administered before instruction and posttests after instruction, involving 29 students. The descriptive analysis showed that the initial scores (pretest) ranged from 30 to 80, reflecting varied baseline abilities, generally categorized as low to moderate. After the learning intervention, a notable improvement was observed, with posttest scores ranging from 70 to 100.

The average pretest score was 47, which increased to approximately 84 in the posttest. The score differences ranged from 20 to 40 points, indicating a substantial improvement in learning outcomes. In terms of improvement patterns, most students experienced gains between 30 and 40 points, suggesting that the improvement was relatively evenly distributed across the class. Meanwhile, smaller gains (around 20 points) were typically observed among students who already had higher initial scores. To provide a clearer overview of the distribution of improvement, a summary is presented in Table 2.

Table 2. Summary of Pretest and Posttest Results

Category	Pretest Range	Posttest Range	Gain
Low	30–40	70–80	40
Medium	40–50	70–90	30–40
High	60–80	90–100	20–30

An interesting pattern can be observed in Table 2, where students in the low category showed higher gains compared to those in the high category. Students with initial low scores improved by up to 40 points, while those in the high category showed smaller gains ranging from 20 to 30 points. This phenomenon is commonly referred to as the ceiling effect, where students with higher initial performance have limited room for further improvement due to the upper limit of the assessment scale.

This finding suggests that the implemented learning approach, particularly the TAI model, is highly effective in supporting lower-achieving students by providing structured guidance through inquiry processes and analogy-based learning. However, it may also indicate that the test instrument was not sufficiently challenging to capture more advanced improvements among higher-achieving students.

N-Gain Test Results

To obtain a more proportional measure of learning improvement, a normalized gain (N-Gain) analysis was conducted. This analysis determines the extent of improvement relative to the maximum possible achievement. The results showed that the average N-Gain ranged from 0.65 to 0.72, with an overall average of approximately 0.68. This value falls within the moderate to high category, indicating that the improvement achieved is fairly effective.

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Table 3. N-Gain Results

Category	Range	Description
Low	$g < 0.30$	Not observed
Medium	$0.30 \leq g < 0.70$	Some students
High	$g \geq 0.70$	Some students
Average	**≈ 0.68**	**Moderate–High**

The absence of the low category indicates that all students experienced meaningful improvement. The distribution of scores within the medium and high categories suggests that the enhancement of scientific thinking skills occurred consistently across different levels of student ability.

Effectiveness Test Results (Paired Sample t-test)

To determine whether the observed improvement was statistically significant, a hypothesis test using a paired sample t-test was conducted. This test compares the mean scores before and after instruction within the same group. The analysis revealed a mean difference of 33.79 with a standard deviation of 7.28. The calculated t-value was 25.00 with 28 degrees of freedom (df). Meanwhile, the critical t-value at a significance level of 0.05 was 2.048.

Table 4. Paired Sample t-test Results

Parameter	Value
Mean Difference	33.79
Standard Deviation	7.28
t-value	25.00
t-table	2.048
Decision	Significant

Since the calculated t-value is significantly higher than the critical t-value, it can be concluded that there is a statistically significant difference between the pretest and posttest results. In other words, the observed improvement is not due to chance but reflects a strong effect of the implemented learning intervention.

Discussion

The results of this study indicate that the developed STEAM-based learning tools integrated with the Techno-Analogy Inquiry (TAI) model are effective in improving students' scientific thinking skills. This can be seen from the increase in students' scores between the pretest and posttest, as well as the N-Gain results, which fall into the moderate category. This finding shows that learning activities involving inquiry processes and analogy can support students in understanding scientific concepts more meaningfully, particularly in elementary science learning contexts (OECD, 2023).

Further analysis shows that students in the low initial ability group experienced higher improvement compared to those in the high group. Students in the low category showed a significant increase in scores, while students in the high category tended to show smaller gains. This phenomenon can be explained by the ceiling effect, where students with higher initial scores have limited room for improvement due to the upper limit of the assessment scale. This indicates that the implemented learning approach is particularly effective in helping students with lower initial abilities, although it may be less sensitive in capturing improvements among high-achieving students.

The improvement in students' scientific thinking skills is also influenced by the integration of STEAM components in the learning process. The inquiry aspect encourages students to actively observe, ask questions, and draw conclusions, which are essential

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components of scientific thinking. In addition, the use of analogy helps students relate abstract concepts to more familiar contexts, making the learning process easier to understand. Previous studies have also shown that inquiry-based and context-based learning approaches can significantly enhance students' conceptual understanding and engagement (Lazonder & Harmsen, 2021).

In addition to inquiry and analogy, the Engineering and Arts components also play an important role. The Engineering aspect is reflected in activities where students construct simple models and solve contextual problems. In this study, students created replicas that illustrate the working process of the human digestive system in terms of input, process, and output using simple materials such as recycled cardboard. This type of design-based activity is known to support students' problem-solving skills and procedural understanding (English, 2020).

Meanwhile, the Arts component appears in the creative design and visual representation of the models. Students express their understanding through how they arrange and present their work, which helps make abstract concepts more concrete. This also increases students' engagement during the learning process. The integration of arts in STEM learning has been shown to enhance creativity and support deeper learning experiences (Henriksen, 2020).

More importantly, the effectiveness of this learning is not only influenced by the use of STEAM, but also by the integration of analogy within the inquiry process through the TAI model. The use of analogy functions as a bridge that connects students' prior knowledge with new concepts, so students do not only follow the inquiry steps but also understand the concepts more deeply. This is in line with recent studies emphasizing the importance of cognitive scaffolding in supporting meaningful learning (Zhang, 2022). Overall, the integration of STEAM and the TAI model creates a learning process that is more meaningful and supports the development of students' scientific thinking skills.

Interpretation of Feasibility Test Results

The findings reveal that the developed learning tools fall into the highly feasible category. This indicates that all components of the tools, including content, language, presentation, and construction, have been carefully designed in accordance with effective instructional principles. This high level of feasibility reflects that the tools not only meet technical standards but also support a structured and meaningful learning process.

This condition suggests that the integration of the STEAM approach with the TAI model is capable of producing a systematic, adaptive, and contextual instructional design. In other words, the developed tools function not merely as instructional aids but also as a pedagogical framework that facilitates deeper student thinking processes.

These findings are consistent with previous studies stating that STEAM-based learning tools have advantages in integrating multiple disciplines contextually, thereby improving learning quality (Hsiao et al., 2025). In addition, the use of the ADDIE model in instructional design has proven effective in producing valid and flexible products that meet users' needs (Dousay & Logan, 2017). Other studies emphasize that expert validation is a crucial step in ensuring alignment among objectives, materials, and instructional strategies (van den Akker et al., 2019). Thus, these results reinforce that the developed tools meet feasibility standards and are ready for implementation in real classroom settings.

Improvement in Learning Outcomes and Scientific Thinking Skills

The results demonstrate a clear improvement between students' pretest and posttest scores. This increase reflects that the implemented learning approach effectively promotes significant changes in students' understanding. The rise in average scores indicates that

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students not only improved quantitatively but also developed their scientific thinking processes. This improvement can be explained by the characteristics of STEAM learning, which emphasize active student engagement. This approach enables students to relate learned concepts to real-life situations, making learning more meaningful and less abstract (Nursalim et al., 2024). Furthermore, the inquiry-based approach integrated into the TAI model encourages students to explore, ask questions, and construct knowledge independently (Evagorou et al., 2024).

From a cognitive perspective, the use of analogy in the TAI model plays a crucial role in helping students understand complex concepts. Analogies serve as a bridge between prior knowledge and new concepts, facilitating the internalization of information (Chen & She, 2020). Moreover, the integration of technology in analogy-based learning has been shown to enhance higher-order thinking skills and conceptual understanding (Dai et al., 2024). Therefore, these findings indicate that the improvement in students' scientific thinking skills results from the combined application of STEAM, inquiry-based learning, and analogy strategies.

Effectiveness Analysis Based on N-Gain

The N-Gain values, which fall into the moderate to high category, indicate that the improvement in learning outcomes is not only absolute but also effective when viewed in relation to students' initial abilities. This suggests that the implemented learning approach optimally enhances students' learning potential proportionally.

These results support previous studies indicating that STEAM-based learning significantly improves critical and scientific thinking skills (Perastiati & Andayani, 2026). In addition, project-based and inquiry-based approaches within STEAM have been proven effective in enhancing scientific literacy and 21st-century skills (Oanh & Dang, 2025). Interestingly, no students were categorized as having low improvement. This indicates that the developed learning tools have broad applicability and can positively impact all students, regardless of their initial ability levels.

The results of the paired sample t-test indicate that the difference between pretest and posttest scores is statistically significant. The calculated t-value, which is much higher than the critical t-value, shows that the observed improvement is not due to chance but is a direct result of the implemented instructional intervention. These findings are consistent with studies stating that inquiry-based learning has a significant effect on improving students' learning outcomes (Siregar, 2025). Furthermore, the integration of STEAM in instruction has been shown to significantly enhance scientific thinking skills and other 21st-century competencies (Tijani & Adeduyigbe, 2026). Thus, the statistical analysis provides strong empirical evidence that the developed learning tools are effective in improving students' scientific thinking skills.

The findings of this study contribute to the development of learning theory, particularly in the context of integrating STEAM, inquiry, and analogy. The TAI model demonstrates its role in bridging conceptual understanding through analogical reasoning, which is a key component in science learning (Adúriz-Bravo, 2024). In addition, this study reinforces the design-based research approach, which emphasizes the importance of developing instructional tools through iterative processes involving continuous validation and evaluation (McKenney & Reeves, 2019). This suggests that the quality of learning is determined not only by instructional methods but also by the design of the learning tools used. From a practical perspective, the results of this study indicate that STEAM-based learning tools integrated with the TAI model can be applied as an alternative instructional

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strategy in elementary schools. This approach is capable of creating a more active, contextual, and student-centered learning environment.

Teachers can utilize this model to encourage students to think scientifically through activities such as exploration, discussion, and problem-solving. Furthermore, the integration of technology and the use of analogies can help explain complex concepts in a more accessible manner (Hidayat & Firmanti, 2024). Therefore, the implementation of these learning tools not only improves learning outcomes but also has the potential to enhance the overall quality of the learning process.

Conclusion

This study concludes that the development and implementation of STEAM-based learning materials integrated with the Techno-Analogy Inquiry (TAI) model were effective in improving the scientific thinking skills of elementary school students. The findings indicate that the integration of the STEAM approach, inquiry processes, and analogy-based learning strategies was able to create a meaningful learning environment. This condition significantly enhanced students' cognitive engagement and strengthened their conceptual understanding. These findings also emphasize the importance of integrative and student-centered instructional design within the context of science education at the elementary level. More specifically, the developed learning materials demonstrated excellent quality based on expert validation results. The aspects of content, language, presentation, and construction fulfilled the standards of effective learning materials. This suggests that instructional designs combining interdisciplinary approaches with cognitive strategies can produce materials that are not only theoretically sound, but also relevant and practical for classroom implementation.

In addition, the significant improvement between pretest and posttest scores indicates that the implemented learning process successfully promoted the development of students' scientific thinking skills. This finding was further supported by the N-Gain scores, which were categorized as moderate to high, indicating that the improvement was proportional and relatively consistent among students with varying levels of prior ability. Furthermore, the results of the paired sample *t*-test revealed that the improvement was statistically significant. Therefore, it can be confirmed that the observed changes were a direct impact of the designed instructional intervention.

Overall, this study confirms that integratively designed instruction through the combination of STEAM, inquiry, and technology-based analogy has strong potential to develop the scientific thinking skills of elementary school students. This approach not only helps students understand concepts more deeply, but also trains them to think logically, systematically, and based on evidence.

Recommendation

Based on the findings of this study, several recommendations can be proposed for different stakeholders. For teachers, it is recommended to implement STEAM-based learning integrated with the TAI model as an alternative instructional approach to enhance students' scientific thinking skills. Teachers are encouraged to incorporate inquiry activities, analogy-based explanations, and technology-supported media to facilitate students' understanding of abstract concepts.

For policymakers, this study suggests the need to support the development and dissemination of innovative learning models that integrate interdisciplinary approaches such as STEAM with cognitive strategies like analogy. Providing training programs for teachers

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on the implementation of such models would be beneficial in improving the overall quality of science education.

For future researchers, it is recommended to expand this study by involving a larger sample size and different educational contexts. Further research may also explore the effectiveness of the TAI model in other subject areas or investigate the development of more advanced assessment instruments to better capture higher-order thinking skills.

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