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ANALYSIS OF GRADE X STUDENTS' CONCEPTUAL UNDERSTANDING IN SOLVING PROBLEMS ON EXPONENTIAL AND LOGARITHMIC COMPETENCY TESTS BASED ON APOS THEORY

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ABSTRACT

Understanding mathematical concepts in exponents and logarithms is essential for developing higher-order reasoning; however, many students still struggle to connect these inverse concepts conceptually. This study aimed to analyze students' levels of conceptual understanding in exponents and logarithms through the lens of APOS (Action, Process, Object, Schema) theory. A qualitative descriptive approach was employed with three Grade X students from SMAN 4 Binongko, selected purposively to represent high, medium, and low mathematical abilities. Data were collected through competency tests and semi-structured interviews, and analyzed thematically according to the four APOS stages: action, process, object, and schema. The findings revealed that high-ability students had reached the schema stage, demonstrating integrated conceptual understanding; medium-ability students were at the object stage, showing partial abstraction; and low-ability students remained at the process stage, indicating limited conceptualization. These results suggest a clear differentiation in students' cognitive construction of mathematical concepts according to ability levels. Furthermore, the application of the APOS framework proved effective in identifying students' understanding stages and mapping their conceptual development in exponents and logarithms. The study implies that APOS theory can serve as a theoretical foundation for designing instructional strategies that enhance students' conceptual comprehension and promote more meaningful learning in mathematics.

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1. INTRODUCTION

Mathematics plays a crucial role in fostering students' logical, systematic, and analytical thinking abilities. Through mathematics learning, students are expected not only to master procedural computations but also to comprehend the meaning and relationships underlying each concept. At the secondary education level, this conceptual comprehension forms the foundation for solving various problems related to real-life situations and other fields of study. The objectives of mathematics education emphasize the development of reasoning, problem-solving, and higher-order thinking skills that enable students to think critically, creatively, and reflectively(Anak et al., 2022.). Thus, mathematics learning is not merely about numbers and symbols but about cultivating the ability to reason systematically and apply concepts meaningfully.

However, numerous studies indicate that Indonesian students still struggle to achieve a deep conceptual understanding of mathematics. Evidence from international assessments such as (PISA 2022) and national reports from the Ministry of Education and Culture show that students' mathematical performance remains below the international average, particularly in items that require conceptual reasoning rather than procedural calculation. Siregar and Siregar (2020) also reported that many students tend to rely heavily on memorized formulas without understanding the underlying concepts. This situation reveals that conceptual understanding—a crucial component of mathematical literacy—remains a major challenge in mathematics education in Indonesia.

One of the fundamental topics taught in the Grade X mathematics curriculum is **exponents and logarithms**, which are interrelated and form the basis for more advanced mathematical concepts such as exponential functions, logarithmic transformations, and models of growth and decay. According to Khodijah, Mailizar, and Eva (2023), understanding exponents and logarithms requires not only the ability to manipulate formulas but also the ability to recognize the inverse relationship between them. Since exponential and logarithmic functions are inverse in nature, misconceptions in one often lead to errors in understanding the other. Therefore, mastery of these topics demands a solid conceptual understanding that enables students to explain why a particular procedure is valid and how it can be applied across different contexts (Ilhan & Akin, 2022).

Despite their importance, many students continue to find exponents and logarithms challenging. Research findings show that errors frequently occur when students are asked to interpret logarithmic equations conceptually or relate them to exponential forms. This indicates that students' understanding often remains at the procedural level—knowing how to calculate—rather than the conceptual level—understanding why those procedures work. A sound conceptual understanding allows students to connect representations, reason through problem contexts, and transfer knowledge to new situations. Consequently, it becomes essential to analyze students' conceptual understanding in these areas to identify how far learning objectives in mathematics have been achieved and what misconceptions may still persist.

One theoretical framework that can be used to analyze students' thinking processes in understanding mathematical concepts is the **APOS theory**, developed by Dubinsky. APOS, which stands for *Action, Process, Object, and Schema*, explains how mathematical understanding develops progressively through cognitive constructions. The theory posits that learning begins with specific actions that are later internalized into processes; these processes are then encapsulated into mental objects and finally organized into coherent schemas (Mulyono, 2011). These stages describe cognitive development from concrete activities to abstract representations, which aligns well with how students construct understanding of exponential and logarithmic relationships. Applying APOS theory in educational research helps teachers and researchers identify where students experience cognitive obstacles and how instruction can be designed to support their conceptual development.

Several studies (e.g., Ilhan & Akin, 2022); (Nafiah et al., 2024) highlight the usefulness of APOS theory in explaining conceptual construction processes of mathematical topics. Ratnawati (2022) investigated students' comprehension of exponential functions based on APOS theory and found that most students were still at the *action* and *process* stages, indicating incomplete formation of *object* and *schema* levels. This finding highlights the cognitive complexity involved in developing a full understanding of exponential relationships. Although several studies have analyzed students' understanding of exponential functions using the APOS theory, research integrating both exponential and logarithmic concepts remains limited, even though the two concepts are intrinsically related and should be understood as a unified structure. Furthermore, few studies have analyzed students' conceptual understanding of these topics within the context of **competency tests**, which demand the ability to connect conceptual reasoning with problem-solving.

Given these research gaps, it is essential to conduct a study that examines students' conceptual understanding of exponential and logarithmic problems through the lens of APOS theory. Such a study will provide a more comprehensive view of how students construct mathematical knowledge and where conceptual difficulties emerge. The findings are expected to contribute both **theoretically** and **practically**. Theoretically, this study will enrich the literature on the application of APOS theory in secondary mathematics, particularly by integrating two related but often separately studied topics—exponents and logarithms. Practically, the study will offer valuable insights for mathematics teachers in designing learning activities that promote meaningful understanding rather than rote memorization. By identifying students' cognitive stages within the APOS framework, educators can better tailor instructional strategies to guide students from procedural manipulation toward deeper conceptual comprehension. Ultimately, this research seeks to support the improvement of mathematics learning that nurtures critical, reflective, and adaptive thinkers prepared to apply mathematical reasoning in diverse real-world contexts.

2. METHOD

This study employed a **descriptive qualitative design** to explore students' conceptual understanding of exponential and logarithmic concepts through the framework of the APOS (Action, Process, Object, Schema) theory. The qualitative approach was selected because it allows for an in-depth examination of students' thought processes and reasoning rather than focusing solely on quantitative performance outcomes. Through descriptive analysis, this study aimed to capture detailed patterns of students' understanding and difficulties across the APOS stages.

The research was conducted at **SMAN 4 Binongko**, a senior high school located in the Wakatobi Regency, Southeast Sulawesi, during the **2025/2026 academic year**. The subjects consisted of **26 Grade X students** who had completed lessons on exponents and logarithms. The selection of this school was based on its implementation of competency-based assessments and the diverse mathematical achievement levels of its students. The participants were chosen using **purposive sampling**, ensuring representation across various levels of mathematical ability—high, medium, and low. The classification of students into these categories was based on the results of a preliminary **mathematical competency test**, which was analyzed using the categorization (Widhiarso, 2019) criteria shown in Table 1.

Table 1. Categorization of Mathematical Abilities

Category	Value Range
High	$x \geq Mean + SD$
Medium	$Mean - SD < x < Mean + SD$
Low	$x \leq Mean - SD$

This categorization method followed Widhiasro (2019), who classified students' mathematical abilities based on their performance distribution.

Research Instruments

Two primary instruments were used in this study:

1. **Competency Test** — consisting of four open-ended problems on exponents and logarithms. The test was designed to reveal students' reasoning and conceptual connections rather than procedural skills.
2. **Semi-Structured Interview Guide** — used to explore students' thought processes in more depth, particularly how they represented each concept across the four APOS stages (Action, Process, Object, and Schema).

Data Collection Techniques

Data were collected through three main procedures:

1. **Written test administration**, to obtain initial data on students' conceptual understanding levels;
2. **Individual interviews**, conducted with selected students from each ability group to gain insight into their cognitive reasoning and conceptual transitions; and
3. **Documentation**, including students' written responses and teacher lesson plans, to support data triangulation.

All interviews were audio-recorded and transcribed verbatim for analysis.

Data Analysis Techniques

The data were analyzed using the **Miles and Huberman (1994)** model, which consists of three stages:

1. **Data reduction**, by coding students' test responses and interview transcripts according to APOS stages;
2. **Data display**, by organizing coded data into descriptive tables and diagrams to identify recurring conceptual patterns; and
3. **Conclusion drawing and verification**, by interpreting patterns to describe students' conceptual development and common difficulties.

The analysis focused on mapping students' reasoning to the four cognitive constructions of APOS theory to determine their dominant stage of understanding.

Data Credibility

To ensure the credibility and reliability of the findings, **methodological and time triangulation** were employed. Methodological triangulation was achieved by comparing data from written tests, interviews, and documentation, while time triangulation involved verifying consistency in students' responses during different sessions. Additionally, peer debriefing with fellow researchers was conducted to reduce subjectivity in the interpretation of qualitative data.

3. RESULT AND DISCUSSION

3.1. Result

Data collection was obtained from student scores on questions in the exponent and logarithm competency test. The competency test results provide an overview of students' initial conceptual mastery of exponents and logarithms before deeper analysis through APOS stages. Based on the results of the study of student answers, data was obtained on the number of students who took the competency test, the average student score, the maximum score, the minimum score, and the standard deviation in the following table:

Table 3.1 Competency Test Results Data

N	Min	Max	Mean	Standard Deviation
26	10,00	95,00	39,42	25,05

Description:
N : Number of students

The low mean score (39.42) with a wide standard deviation (25.05) indicates significant variation in students' mathematical proficiency, suggesting differing levels of conceptual understanding. While a few students achieved high scores close to 95, several others scored far below the passing standard, implying that conceptual understanding was unevenly distributed across the class.

To facilitate further qualitative analysis, students were grouped into **three ability categories**—high, medium, and low—based on their scores relative to the mean (M) and standard deviation (SD). This categorization aimed to select representative participants from each ability level to explore their conceptual understanding qualitatively.

Table 3.2 Categorization of Students

Category	Value Range	N	Percentage
High	$x \geq 64{,}47$	6	23,08
Medium	$14{,}37 < x < 64{,}47$	12	46,15
Low	$x \leq 14{,}37$	8	30,77

The largest group consisted of students with **medium ability** (46.15%), followed by those in the **low ability** group (30.77%) and the **high ability** group (23.08%). This distribution reflects a typical learning situation in which only a small portion of students demonstrate complete conceptual mastery, while the majority exhibit partial or limited understanding. The samples taken in this study were representative of each category for data collection through interviews.

The classification of students into these categories was essential for selecting **representative participants** for the qualitative phase of the study. One student from each category was chosen using purposive sampling to participate in in-depth interviews exploring their conceptual understanding through the **four stages of APOS theory**—Action, Process, Object, and Schema.

This selection allowed the researchers to capture the **variation in students' cognitive structures** across different ability levels. The high-ability student (S13) represented a learner with strong conceptual reasoning, the medium-ability student (S28) reflected transitional understanding, and the low-ability student (S12) represented procedural or incomplete understanding.

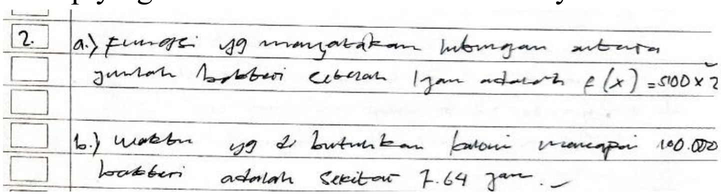
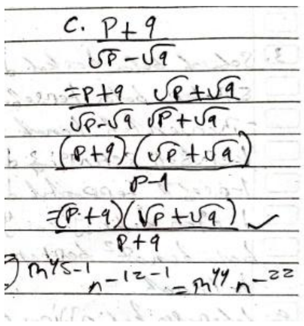
Overall, the descriptive results of the competency test reveal that **students' conceptual understanding of exponents and logarithms varies widely**, and most students have not yet reached full conceptual mastery. These findings provided the empirical foundation for conducting a deeper qualitative analysis using the APOS framework to trace students' cognitive development in solving problems related to exponents and logarithms

3.2. Discussion

The results of students' conceptual understanding were analyzed according to the four stages of APOS theory: action, process, object, and schema. Data were obtained through written tests and in-depth interviews with three representative students: S13 (high ability), S28 (medium ability), and S12 (low ability). The analysis focused on how each student constructed mathematical understanding according to their cognitive stage.

3.2.1. Action Stage

Table 3.3 Action Phase Interview Transcript

	Transcript	Code
P	Please explain the steps you took to solve the problem!	
S	First, I understand the question and check what is known in the question. As in question number 2, I express it in the form of a function by multiplying the initial number of bacteria by two.  2. a.) fungsi yg menyatakan hubungan antara jumlah bakteri setelah 1 jam adalah $f(x) = 500 \times 2$ b.) waktu yg di butuhkan koloni mencapai 100.000 bakteri adalah sekitar 7.64 jam.	S13
S	In question number 1 part c, there is a fraction with a denominator in the form of a root, so I multiply it by a conjugate root to convert it into an integer, no longer in the form of a root, then solve it by multiplying each numerator and denominator.  c. $\frac{p+9}{\sqrt{p}-\sqrt{9}}$ $= \frac{p+9}{\sqrt{p}-\sqrt{9}} \cdot \frac{\sqrt{p}+\sqrt{9}}{\sqrt{p}+\sqrt{9}}$ $\frac{(p+9)(\sqrt{p}+\sqrt{9})}{p-9}$ $= \frac{(p+9)(\sqrt{p}+\sqrt{9})}{p+9}$ $m^{45-1} n^{-12-1} = m^{44} n^{-22}$	S28
S	First, I worked on the question that I thought was the easiest, which was number 2. For question number 2, I created a table showing bacterial growth at one-hour intervals, then I detailed it with x representing the duration of bacterial growth in hour.	S12

2. Fase x	0	1	2	3	4	5
Banyak Bakteri	500	1000	1500	2000	2500	3000

untuk $x = 0 \rightarrow 500 \times 2^0 = 500$
$x = 1 \rightarrow 500 \times 2^1 = 1000$
$x = 2 \rightarrow 500 \times 2^2 = 1500$
$x = 3 \rightarrow 500 \times 2^3 = 2000$
$x = 4 \rightarrow 500 \times 2^4 = 2500$
$x = 5 \rightarrow 500 \times 2^5 = 3000$

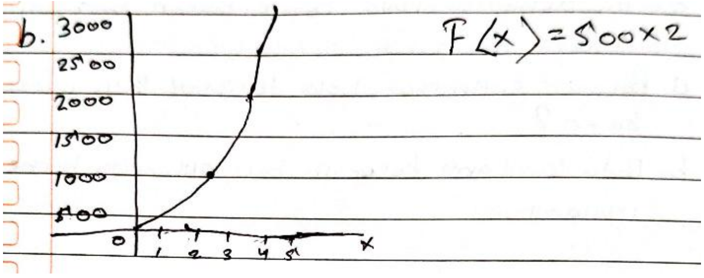
At the **Action stage**, students perform concrete manipulations following given instructions without yet developing a deeper conceptual understanding. All three subjects—S13, S28, and S12—were able to identify what was asked in the problem and carry out the necessary computational steps correctly. For instance, S13 expressed exponential growth in a bacterial problem by forming a function $N = N_0 \times 2^t$, showing that he could operationalize procedures fluently. Similarly, S28 rationalized denominators containing roots using conjugate multiplication, and S12 constructed a value table to determine patterns before forming a function.

According to Dubinsky and McDonald (2001) students at the action stage rely heavily on external cues and physical manipulation of symbols. This was evident as the subjects followed known procedures rather than reasoning conceptually. While all participants successfully passed the action stage, their explanations revealed procedural reliance rather than internalized understanding. This finding aligns with Ratnawati (2022), who observed that many high school students could perform algorithmic operations correctly yet struggled to articulate the meaning behind them.

3.2.2. Process

Table 3.4 Process Phase Interview Transcript

	Transcript	Code
P	Now, explain why you took those steps!	
S	I created a function according to the question's requirements. The multiplication by two is because the bacteria in the colony divide themselves into two every hour. Sebuah bakteri terdiri atas 500 bakteri yang akan membelah diri menjadi dua setiap 1 jam	S13
S	In order to simplify fractions with root denominators, I first rationalize the denominator $\sqrt{p} - \sqrt{q} \Longrightarrow p - q$	S28

S	The reason is so that I can easily draw the function graph, then I can determine the requested function 	S12

At the **Process stage**, students begin to internalize actions and understand the reasons behind them. All three subjects demonstrated partial internalization of concepts. S13 explained that multiplying by two was due to bacterial division every hour, linking symbolic manipulation to real-world meaning. S28 rationalized roots "to simplify fractions," while S12 justified constructing a value table "to make the function graph easier to draw."

These explanations indicate that students had begun to connect procedures with conceptual reasoning. However, the depth of understanding varied. S13 exhibited awareness of the mathematical relationship between variables, while S28 and S12 still relied on visual or concrete representations. This finding supports Ilhan and Akin (2022), who emphasized that students in this phase show emerging abstraction but still need guidance to make connections between concepts.

The transition from action to process reflects cognitive development where external actions become mental operations. Students who can explain "why" they perform a step are developing mental representations—an essential bridge toward higher conceptual understanding.

3.2.3. Object

Table 3.5 Object Phase Interview Transcript

	Transcript	Code
P	From the concept you used to explain the steps you took earlier, can you view it as an object that you can use for other problems? Give an example!	
S	Yes, the concept I used in solving the problem can be applied to solving other problems, such as calculating the trajectory of a ball (the height and distance the ball travels) when it bounces until it stops.	S13
S	In my opinion, I can use this form of conjugate multiplication to factor negative exponents, such as $a^2 - b^2$ factored into $(a + b)(a - b)$	S28
S	Yes, you can. Later, you can create a table like before to find the function P: If the question is different, such as the amount of money we have after 5 years in the bank with an interest rate of 10% per year, can it be solved using the steps you used earlier? S: I don't know, sir. Maybe it's possible.	S12

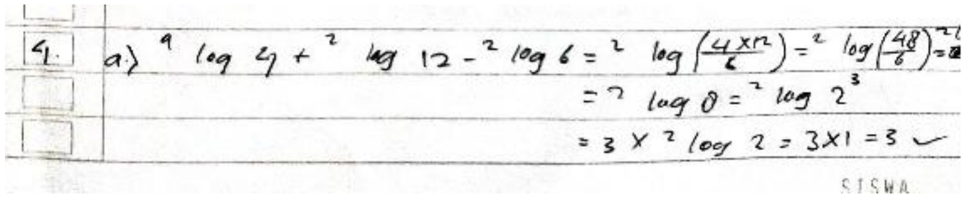
In the **Object stage**, students are expected to encapsulate processes into coherent mental objects that can be manipulated as single entities. S13 and S28 demonstrated characteristics of this stage, while S12 did not fully reach it. S13 showed the ability to apply the concept of exponential functions to other real-world contexts, such as modeling a bouncing ball's trajectory. This indicates that he viewed the function as an abstract object that could be used flexibly.

S28 explained that conjugate multiplication could also be used in factoring negative exponents, revealing an emerging ability to generalize and connect different mathematical structures. Meanwhile, S12 could not confidently transfer the concept of functions to a new context (e.g., bank interest problems), suggesting that her understanding remained procedural.

According to Dubinsky's APOS model, this encapsulation process is critical for conceptual flexibility. The findings correspond with Nafiah et al. (2024), who found that students who reached the object stage were able to use learned concepts to solve unfamiliar problems. The varying levels of encapsulation among students highlight the influence of prior knowledge and reasoning ability in achieving abstraction.

3.2.4. Schema

Table 3.6 Schema Phase Interview Transcript

	Transcript	Code
P	From the steps you have used in the four questions, do you see any connection between the concepts that appear in each question?	
S	The connection that I know of is the use of exponents in solving logarithm problems. In solving problem number 4, two methods can be used. The first is as I wrote in the answer sheet, and the second is by converting it into an exponential form with two powers, the result of which is 4 ($2^x = 4$) that is 2  4. a) ${}^{9}\log 4 + {}^{2}\log 12 - {}^{2}\log 6 = {}^{2}\log\left(\frac{4 \times 12}{6}\right) = {}^{2}\log\left(\frac{48}{6}\right) =$ $= {}^{2}\log 8 = {}^{2}\log 2^{3}$ $= 3 \times {}^{2}\log 2 = 3 \times 1 = 3$ SISWA	S13
S	Excuse me, sir. I mean, from questions 1 to 4, which ones use logarithms or exponents? P: No, what I mean is, problems in the form of a are solved using method b, such as logarithmic problems are solved using exponential methods. S: Oh, I don't know, sir.	S28
S	Yes, sir. I see the connection, because everything is still related to logarithms and exponents.	S12

The **Schema stage** represents the highest level of cognitive construction in APOS theory, where students can integrate multiple concepts into a unified mental structure. Only S13 reached this stage. He was able to recognize the relationship between exponential and logarithmic forms, explaining that logarithmic equations can be solved by converting them into exponential form (e.g., $\log_2 4 = 2 \Rightarrow 2^2 = 4$).

This shows that S13 possessed a coherent understanding that allowed him to move flexibly between representations and apply inverse relationships conceptually. In contrast, S28 failed to perceive the interconnection between the two concepts, while S12 only noted that "both involve exponents and logarithms" without articulating the structural link.

This pattern supports findings by Ratnawati (2022) and Khodijah et al. (2023), which indicate that only a small number of students develop fully integrated schemas linking exponential and logarithmic reasoning. Reaching this stage requires extensive exposure to problem contexts that emphasize conceptual relationships rather than isolated procedures

3.2.5. Summary and Implications

The analysis across the four APOS stages demonstrates clear differentiation in students' conceptual understanding based on ability level. **High-ability students (S13)** showed integration across all stages and reached schema-level understanding. **Medium-ability students (S28)** achieved partial abstraction at the object stage, while **low-ability students (S12)** remained at the process stage, relying primarily on procedural reasoning:

Table 3.7 Summary of Students' APOS Stages

Subject	APOS Framework			
	A	P	O	S
S13	✓	✓	✓	✓
S28	✓	✓	✓	×
S12	✓	✓	×	×

Note:

✓ = Passed the stage

× = Ongoing or incomplete understanding

These findings confirm that **students' conceptual development is gradual and hierarchical**, moving from procedural execution toward conceptual integration, as proposed by Dubinsky. They also indicate that instructional design must facilitate transitions between these stages through guided reflection, exploration, and contextual application.

The implications of this study are both **theoretical** and **practical**. Theoretically, the findings reinforce the validity of APOS theory in explaining the progression of students' mathematical cognition, particularly in topics involving inverse relationships such as exponents and logarithms. Practically, the study suggests that teachers can utilize the APOS framework to design learning trajectories that guide students from procedural operations toward integrated conceptual structures.

In summary, the discussion reveals that the **APOS framework is effective in mapping the diversity of students' conceptual understanding** and provides valuable insights for designing mathematics instruction that prioritizes reasoning, connection, and conceptual growth over procedural memorization.

4. CONCLUSION

This study concludes that the application of the APOS (Action, Process, Object, Schema) framework is effective for analyzing students' conceptual understanding of exponents and logarithms. The findings revealed that all students reached the action and process stages, some achieved the object stage, and only one student attained the schema stage, indicating complete conceptual integration between exponential and logarithmic ideas. These results demonstrate that students' understanding remains largely procedural and requires further development in connecting related mathematical concepts.

The findings are consistent with previous studies (Nurajijah et al., 2023; Purnama Sari et al., 2021) confirming that APOS theory facilitates gradual cognitive development from concrete actions to abstract representations. Theoretically, this study extends the application of APOS theory to the combined context of exponents and logarithms, emphasizing its relevance for mapping interconnected conceptual domains. Practically, the APOS framework can be used as a diagnostic and pedagogical guide for teachers to design learning strategies that promote deeper conceptual comprehension rather than procedural mastery. These findings suggest that students' conceptual understanding remains largely procedural and fragmented, highlighting the need for instructional strategies that promote relational thinking and conceptual linkage.

Future research may explore APOS-based interventions across broader mathematical topics to strengthen students' transition from procedural knowledge toward holistic conceptual understanding applicable in real-life contexts.

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