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Are you assessing learning goals or prior knowledge? A critical approach in constructing calculus exam questions

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ABSTRACT

The quality of exam questions is one of several factors that are essential for students' success. In this study we analyzed two exam questions of a calculus exam of students at the Anton de Kom universiteit van Suriname. We conducted a thorough analysis of the two questions and students' solutions to ascertain whether the questions are suitable for assessing the related learning goals. We found that one of the questions required modification due to the fact that prior knowledge obstructed the assessment of the learning goal. We constructed an alternative question that required less specific prior knowledge to address this issue. We also calculated the difficulty level and discrimination level of both the questions and the findings supported our recommendations. We concluded that the examiner should be thoughtful when constructing exam questions, particularly regarding specific prior knowledge at the beginning of a question.

Keywords: prior knowledge, error analysis, calculus, learning goal, difficulty index, discrimination index

INTRODUCTION

At the engineering faculty of mathematics and natural sciences many incoming students have a weak background in mathematics and fail their calculus exams. Our previous research revealed that many students lack adequate prior knowledge of some topics (Mahadewsing et al., 2024).

Mathematics is hierarchical by nature and students must have a strong foundation in high school mathematics to perform well in class and on exams.

Many studies have been conducted to investigate and overcome the mathematics gap between high school to university (Ancheta & Subia, 2020; Rach & Ufer, 2020). Various suggestions have been made to bridge the gap, including crash courses, tests, pre-courses, etc. (Basitere & Ivala, 2015). Most of these suggestions emphasize preparing students for the college Calculus course while also helping them recognize their own capabilities.

Our study focuses on the exam questions and the influence that prior knowledge has on solutions. More specifically, is the learning goal sufficiently assessable or inhibited by the level of prior knowledge? By this, we refer to the situation that students who does not possess a particular prior knowledge are unable to solve the problem, which prevents the instructor from determining whether the learning goal has been achieved.

The aim of this study is to evaluate whether the prior knowledge on exam questions inhibits the learning goal. Whenever possible we will offer recommendations for modifying exam questions without compromising the quality of the exam. We emphasize the importance of assessing learning goals rather than focusing on specific prior knowledge.

We address the following main research question:

What factors should an examiner definitely consider when creating Calculus exam questions ?

THEORETICAL FRAMEWORK

Much research has been conducted that involves calculus courses. Part of which focused on error analysis and error classification (Ancheta, 2022; Khairani et al., 2019; Villavicencio, 2023).

In this section, we will discuss some studies concerning calculus learning, such as the level of difficulty in calculus exams, the effectiveness of written exams and the different paths that students follow prior to enrolling in college calculus courses.

Table 1. Interpreting item difficulty and item discriminating indices (Padua & Santos, 1997)

IDI	**Interpretation**	**DI**	**Interpretation**
0.00 → 0.20	Very difficult	-1.00 → -0.60	Questionable
0.21 → 0.40	Difficult	-0.59 → -0.20	Not discriminating
0.41 → 0.60	Moderately difficult	-0.19 → 0.20	Moderately discriminating
0.61 → 0.80	Easy	0.21 → 0.60	Discriminating
0.81 → 1.00	Very easy	0.61 → 1.00	Very discriminating
Difficulty level	**Discriminating level**		**Action**
Difficult	Not discriminating		Discard
	Moderately discriminating		Revise
	Discriminating		Include
Moderately difficult	Not discriminating		Revise
	Moderately discriminating		Revise
	Discriminating		Include
Easy	Not discriminating		Discard
	Moderately discriminating		Revise
	Discriminating		Revise

Machisi (2024) analyzed the application question of calculus exams of three consecutive years from several high schools to investigate the quality of the questions. For these exam questions he calculated the item difficulty index (IDI) and the item discrimination index (DI) to formulate an action. To interpret these two indices a specific table can be used (Padua & Santos, 1997, as cited in Machisi, 2024). For each question the difficulty and the discrimination indices were calculated based on responses from the top 27% and bottom 27% of students, classified according to their overall performance on the exam.

For the IDI he used the following formula:

$$IDI = \frac{Average\ score\ per\ item}{Total\ marks\ allocated\ to\ the\ item}, \tag{1}$$

where the IDI lies between 0 and 1.

For the DI he applied the following formula:

$$DI = \frac{H-L}{N}, \tag{2}$$

where *H* is the number of students in the top group that answered the question correctly, *L* is the number of students in the bottom group that answered the question correctly, and *N* is the total number of students in both groups.

Table 1 illustrates the interpretation of the difficulty and the DI. Furthermore, suggested actions were designed for different levels of difficulty and discrimination.

According to Machisi (2024) very difficult questions should be avoided in an exam since they fail to give a clear picture of students' performance. He also found that lecturers should not rely on their intuition when determining the level of difficulty. They should also analyze students' performance on previous exam questions. He argued that it is necessary that exam results differentiate between students who are strong and those who are weak. Strong students are expected to do better than weak students, however if an exam question is poorly formulated, that is no longer evident. He ultimately concluded that it is important for lecturers to reflect on their own exams as one of the many strategies to improve the quality of exam questions.

Mahadewsing et al. (2024) investigated the role of prior knowledge in a calculus exam to gain insights into students' poor results. They defined low, medium and high impact of prior knowledge on exam questions. Low impact refers to prior knowledge required near the end of the solution, while high impact indicates that the prior knowledge is required near the beginning of the solution. Medium impact falls in the middle of these two extremes. They stated that it is essential for a student to possess the necessary prior knowledge that is required at the beginning of the solution; without that knowledge the student will be unable to start the solution and ultimately fail the entire question.

In their study, Sadler and Sonnert (2018) examined the impact of two different paths to college calculus on student performance in college. The path where students took high school calculus before entering college and the path where students took only the preparatory mathematics courses (algebra 1, geometry, algebra 2, precalculus). How to prepare students for success in college mathematics has been a topic of discussion among mathematics education researchers, high school teachers, college professors, and students themselves. In their paper, they also discussed two learning approaches, namely Gagné's theory of hierarchical learning and Bruner's spiral learning approach. The hierarchical learning theory of Gagné states that learning is optimized when all prerequisite skills and knowledge have been acquired. However, Bruner claims that repetition of the material at various levels and times maximizes learning. Considering the two perspectives, taking calculus for the first time in college can be seen as a more hierarchical approach, whereas taking it in high school as a spiral approach. Sadler and Sonnert (2018) extensively discussed the conflicting opinions of college professors and high school teachers on the readiness for college calculus. High-school teachers believe that their students are well-prepared, particularly if they have taken calculus. On the other hand, college professors stated that students perform better in college calculus when they master the preparatory mathematics courses in high school. There is no simple answer to this debate. This study found support for both their opinions and that both paths to college calculus are good predictors for success in college calculus.

Table 2. MATH taxonomy

Descriptors	Topic				
	Topic 1	Topic 2	Topic 3	Topic 4	Topic 5
Factual knowledge					
Comprehension					
Routine use of procedures					
Information transfer					
Application in new situations					
Justifying and interpreting					
Implications, conjectures and comparisons					
Evaluation					

In his paper Ortega-Sanchez(2016) discussed and presented the effectiveness of assessments particularly written exams. He emphasized the importance of well-designed exams. According to him a written exam must meet the following standards: the exam must be reasonable so that all students can show their abilities, discriminate against weak from strong students, test different levels of thinking, and identify students who should fail and who should pass. He stated that simple questions should be included first and the level of difficulty should be increased gradually. He distinguished five types of knowledge: essential knowledge, basic knowledge, intermediate knowledge, advanced knowledge and transfer knowledge. In his paper he also indicates types of questions that are suitable for each level of knowledge. The examiner must also be aware of the level of difficulty of the exam, for example not too many easy or too many hard questions. He recommends the following percentages: 10% for essential knowledge, 20% for basic knowledge, 40% for intermediate knowledge, 20% for advanced knowledge and 10% for transfer knowledge.

Smith et al. (1996) defined a modification of Blooms taxonomy especially for mathematics, named mathematics assessment task hierarchy (MATH). They suggested this taxonomy to categorize assessment tasks based on the type of activity instead of their level of difficulty. They emphasized that assessments in mathematics primarily consist of written exams and that students tend to remember the material for only a brief duration. Research has shown that students only learn what they need to pass the exams. The taxonomy consists of eight descriptors, as shown in **Table 2**. The first three descriptors, factual knowledge, comprehension and routine use of procedures are referred to as category A. Category B consists of the following descriptors: information transfer and application in new situations and finally category C include the following three descriptors: justifying and interpreting, implications, conjectures and comparisons and evaluation. The aim of the descriptors is to help examiners construct well-balanced written exams.

We discussed several studies related to calculus learning and our research focused on a different aspect. When constructing exam questions, some instructors do not consider the stage of specific prior knowledge in the solution. In some cases, prior knowledge is required at the beginning of the solution. As a result, students who lack that prior knowledge may be unable to solve the problem. This prevents the instructor from determining whether the learning goal has been achieved. Our study aims to evaluate if prior knowledge required for exam questions inhibits the learning goal. Whenever possible, we provide suggestions for adjusting exam questions without compromising the quality of the question. We emphasize the significance of evaluating learning goals instead of focusing on particular prior knowledge.

MATERIALS AND METHODS

Research has been conducted on various aspects, such as the quality of exams questions and the importance of well-designed exams.

In this study we investigated two exam questions and solutions of 82 engineering students of the 2019 calculus exam. We selected both the questions based on the following criteria: poor students' performance and high impact of prior knowledge. The requirement of prior knowledge near the beginning of the solution of an exam question is considered one with a high impact. The first selected question was to determine whether the limit of a piecewise function existed or not. The impact of prior knowledge on this question was 100% and only 29% had the correct solution. The other question concerned logarithmic differentiation and had an impact of prior knowledge of 83% and only 24% solved the question correctly (Mahadewsing et al., 2024).

A question with a high impact of prior knowledge can be overwhelming to students who lack or cannot recall that prior knowledge. These students mostly adopt a wrong approach from the start or make erroneous calculations, which results in an incorrect solution. Exam questions with a high impact of prior knowledge are not always suitable, because they can make it more difficult to determine whether or not the learning goal is achieved. We analyzed the two questions and students' solutions thoroughly, in order to determine whether the learning goals are assessable. Based on the findings, we modified the first question to make the learning goal assessable. In the second question, a modification was not recommended because the required prior knowledge was essential.

In addition, we calculated the difficulty and discriminating index for these questions as done by Machisi (2024). To calculate these indices, we first ranked the 82 students based on their total exam score from highest to lowest. Next, we selected the top 27% and bottom 27% of these students and calculated these values.

RESULTS AND DISCUSSION

In this section, we will present and discuss two exam questions thoroughly. We will determine whether these exam questions are suitable for assessing the learning goals of the topics. The difficulty and discriminating levels of these two questions will also be discussed.

In addition, we will examine students' solutions and errors. Since various students committed similar errors, we identified and analyzed three different types of errors. We will provide modifications, if possible, to lessen the impact of prior knowledge. We selected the following 2019 exam questions.

Analysis of Exam Question 1

Exam question: calculate the $\lim\limits_{x \to 1} \frac{x^2+|x-1|-1}{|x-1|}$ if it exists, if it does not exist, explain why.

From our previous research it appeared that 29% of the students committed prior knowledge errors in this exam question (Mahadewsing et al., 2024). The learning goal of this question was to evaluate whether students understand the concept of the existence of a limit of a piecewise function.

The function is piecewise and, therefore, this limit exists only if both the left and right limits exist and have the same value. The required prior knowledge of this question is absolute valued functions. Students who lacked that prior knowledge failed to recognize that it was a piecewise function. If the exam question clearly indicated that it was a piecewise function, students would likely assess both the left and right limits. The complexity was compounded by the inclusion of an absolute valued function in both the denominator and the numerator, which in our perception was unnecessary. Another point to consider is that the need for prior knowledge at the start of a solution is not ideal because a student who lacks that knowledge starts off incorrectly. From most of the proposed solutions, it was no longer visible whether the student grasped the concept of the existence of a limit.

As mentioned above, 29% of the students committed errors with absolute values, which led to many incorrect solutions to the problem. Since various students committed similar errors with this exam question, we analyzed three different types of errors from students in order to demonstrate the influence of the absolute value in the solution.

Some students used an incorrect definition, while others did not recognize and ignored the notation of an absolute valued function. Examples of these errors are presented in figures.

In **Figure 1**, the student recognized the notation of an absolute valued function, but the expression was not entirely correct. The bigger issue is that the functions were not used in the solution, resulting in a simplified limit that no longer represents the limit of a piecewise function.

$$\lim_{x \to 1} \frac{x^2+|x-1|-1}{|x-1|}$$

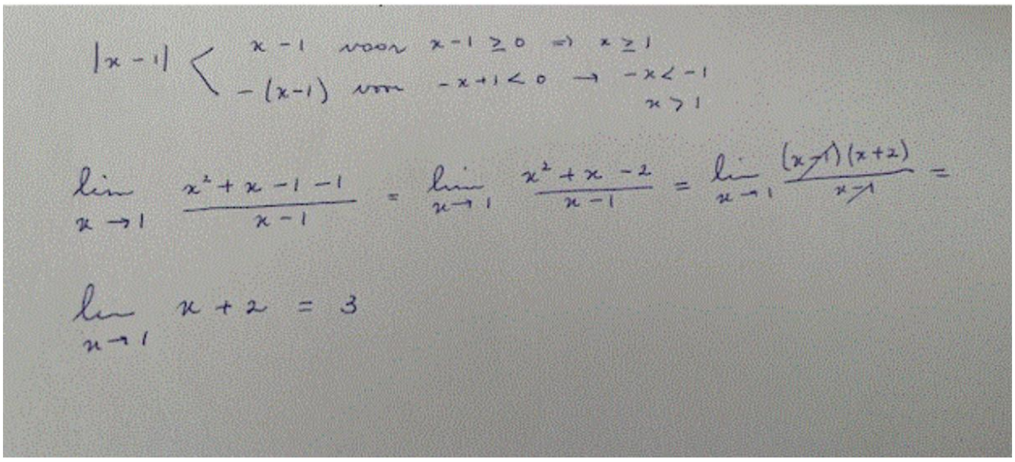

Figure 1. Exam question 1, solution of student 1 (Source: Field study)

In **Figure 2**, the student completely ignored or failed to recognize the notation of absolute valued functions. He considered the notation as brackets and therefore simplified the exam question to a straightforward limit. It is no longer visible whether the student understood the concept of the existence of a limit. Due to the lack of prior knowledge, the student totally changed the exam problem.

$$\lim_{x \to 1} \frac{x^2 + |x-1| - 1}{|x-1|}$$

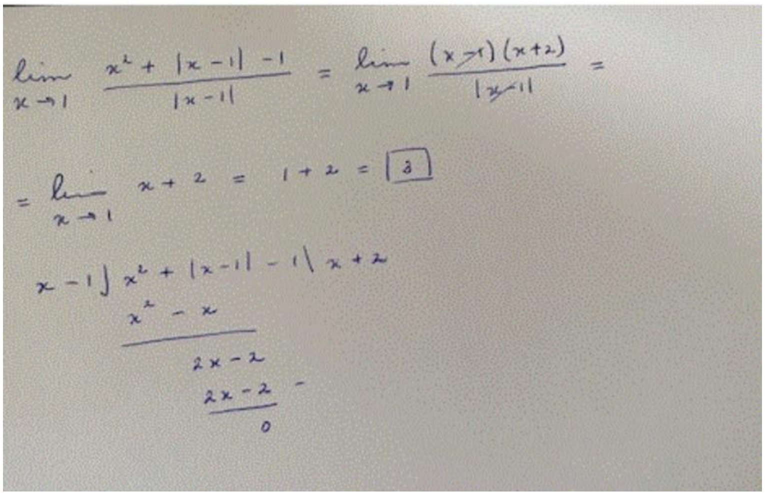

Figure 2. Exam question 1, solution of student 2 (Source: Field study)

It is evident that the student did not apply the definition of absolute valued functions correctly. In **Figure 3**, the intervals are incorrect (encircled in red). The student recalled the necessary prior knowledge but did not use the correct notation for the left and right limit. This kind of error is not caused by insufficient prior knowledge. Instead, it has to do with mistakes related to the new material. Although the limit does not exist, it is clear from the student's solution that he did not understand the concept of the existence of a limit.

$$\lim_{x \to 1} \frac{x^2 + |x-1| - 1}{|x-1|}$$

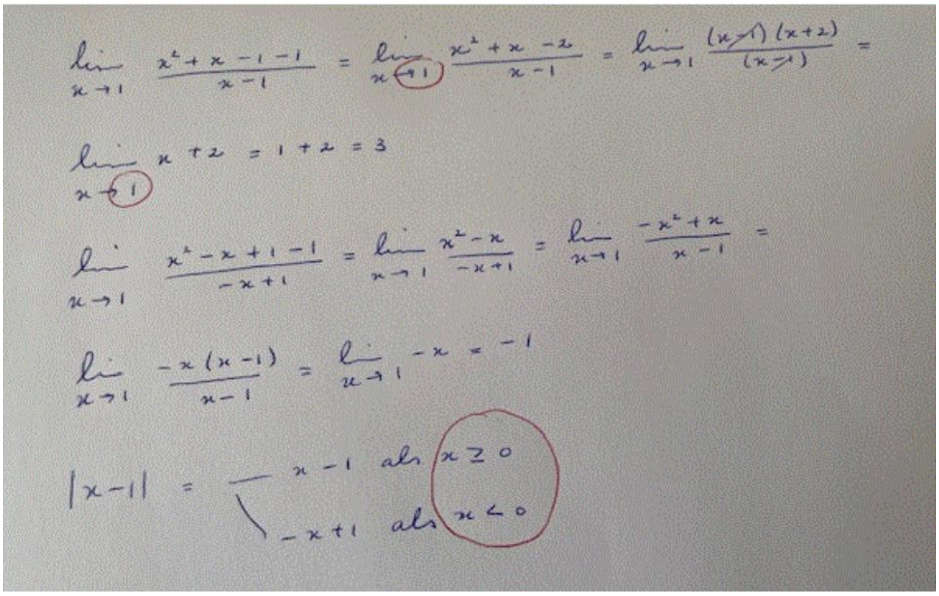

Figure 3. Exam question 1, solution of student 3 (Source: Field study)

Upon examining the errors committed by the students, we observed in most cases that it was almost impossible to determine the students' actual comprehension of the subject matter. It is worth noting that in all three cases the students failed to calculate the left and the right limit. Due to the lack of prior knowledge students did not notice that a piecewise function was involved. If the exam question clearly indicated that it was a piecewise function, students would have likely assessed both the left and right limit.

Our recommendation is to rephrase this question using a piecewise function, so that it is assessable whether a student understands the concept of the existence of a limit. The exam question can be modified by the following question: Given $f(x) = \begin{cases} \frac{x^2-x}{-x+1} \; if \; x \leq 1 \\ \frac{x^2+x-2}{x-1} \; if \; x > 1 \end{cases}$. Calculate the limit $\lim_{x \to 1} f(x)$ if it exists. If it does not exist, explain why.

The instructor should realize that the exam question and the suggested question are of different difficulty levels. The suggested question is less complex because the student does not need prior knowledge of absolute valued functions.

Analysis of Exam Question 2

Exam question: Calculate y'using logarithmic differentiation if $xe^y = y - 1$.

The learning goal of this question was to assess students' proficiency with logarithmic differentiation. Students needed the following prior knowledge of logarithms in order to start solving the exam question correctly.

1. $ln(ab) = ln(a) + ln(b)$
2. $ln(a)^b = b \cdot ln(a)$
3. $ln\, e = 1$

From our previous research it is evident that 52% of the students committed prior knowledge errors in this exam question (Mahadewsing et al., 2024).

Knowledge of logarithmic rules and concepts is crucial to solve this exam problem. Without it, students cannot even start the solution. To solve this exam question successfully, students must apply the logarithmic rules and then differentiate implicitly. To complete the solution, they had to perform a number of arithmetic calculations.

We found several types of errors and will discuss three of them. Some students used incorrect rules, some misinterpreted the number "*e*", while others had a completely wrong approach. Examples of these errors are presented in figures.

During the analysis, it was found that many students committed this error. In **Figure 4**, the student committed the following error: $ln(y - 1) = ln\, y - ln\, 1$.

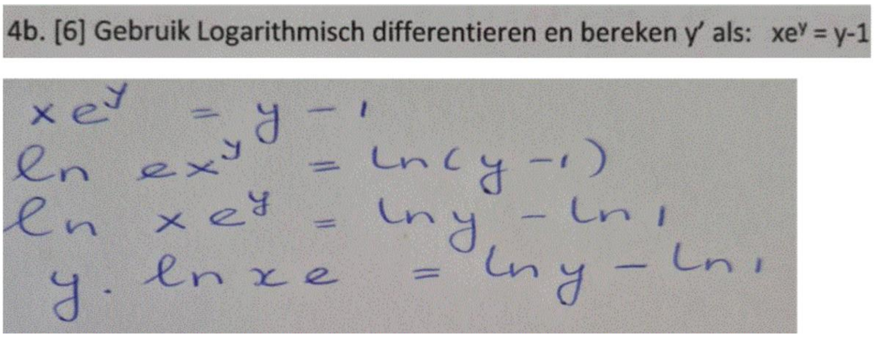

Figure 4. Exam question 2, solution of student 1 (Source: Field study)

In our perception students tried to use the distributive property or thought that they could use the rule "$ln(ab) = ln(a) + ln(b)$" as $ln(a - b) = ln(a) - ln(b)$.

Figure 5 shows a serious mistake.

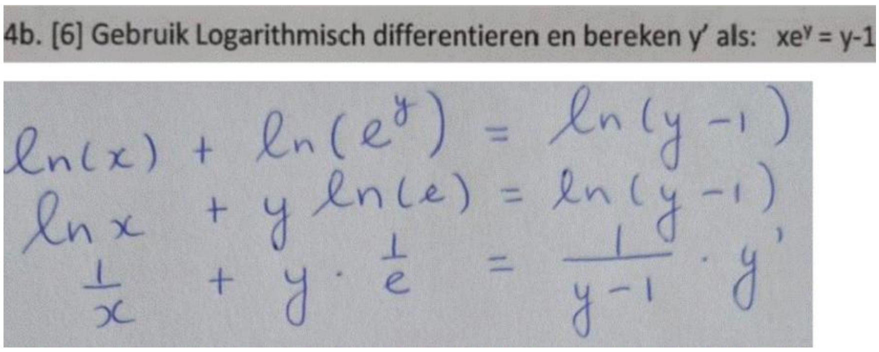

Figure 5. Exam question 2, solution of student 2 (Source: Field study)

The student apparently considered "$ln\, e$" as a function with the variable *e*. Students who committed this error failed to recognize the fact that "*e*" is a number and not a variable. They accordingly calculated the derivative as "$\frac{1}{e}$".

Figure 6 presents a serious but rare error. Evidently, the student had no clue of logarithms.

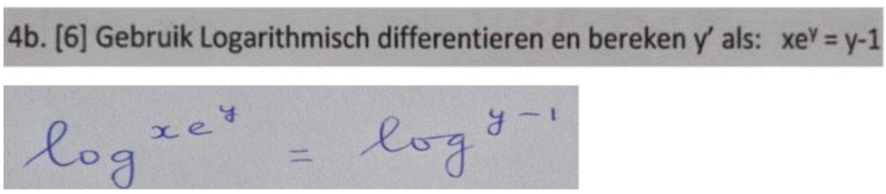

Figure 6. Exam question 2, solution of student 3 (Source: Field study)

The above errors allow the conclusion that the students did not understand the concept of logarithmic functions and their rules.

We do not recommend reformulating this particular question, because knowledge of logarithmic functions and their rules are indispensable for logarithmic differentiation. At the most, the number "*e*" could be replaced by an integer to minimize the possibility of misinterpreting the number as a variable. However, instructors must be aware of the "*logarithm gap*" of students and come up with strategies to solve this problem.

DISCUSSION

Written exams are commonly used in mathematics (Smith et al., 1996) and this also applies to our university. Exams are primarily intended to assess whether students have achieved learning goals and to evaluate the efficacy of instructors' teaching methods employed. Exam questions must be formulated clearly and preferably with the help of a test matrix, for example using Smith et al.'s (1996) MATH taxonomy.

It is important to note that all students who are admitted to our university have taken a similar route. Every student is required to possess a high-school diploma with calculus in their curriculum. According to Sadler and Sonnert (2018) this path is known as the spiral approach.

Smith et al. (1996) stated that students typically retain information for only a short period of time and primarily focus on studying material solely to pass examinations. Our investigation into students' prior knowledge, which indicated a significant deficiency in this area, supports this finding, as it pertains to the essential knowledge that students are expected to possess and acquired at an earlier stage.

We recommend reformulating the first exam question because, in this case, the prior knowledge is required at the beginning of the solution, which inhibits the assessment of the learning goal. In our opinion, exam questions should not be obstructed by too much specific prior knowledge.

Although the modified question and the original exam question are of different difficulty levels, they both fall within the same category A (comprehension) of Smith et al.'s (1996) taxonomy. It is essential for an examiner to recognize this. The questions can also be classified as intermediate knowledge based on the categorization of knowledge types by Ortega-Sanchez (2016).

In his paper Machisi (2024) emphasized that lecturers should not rely on their intuition when determining the level of difficulty. He calculated the difficulty and the discrimination indices for an exam question and used a table to recommend an action. In a similar way, we calculated these indices for both exam questions.

The difficulty and discrimination indices of the question about the existence of a limit were 0.51 and 0.16, respectively, as can be seen in **Table 3**. According to the table used by Machisi (2024), this question is considered difficult and moderately discriminating, which indicates that the question should be revised.

Table 3. IDI and DI

Exam question	IDI	DI	Action
1	$IDI = \frac{Average\ score\ per\ item}{Total\ marks\ allocated\ to\ the\ item} = \frac{3.08}{6} \approx 0.51$	DI = $\frac{9-2}{44} \approx 0.16$	Revise
2	$IDI = \frac{Average\ score\ per\ item}{Total\ marks\ allocated\ to\ the\ item} = \frac{2.11}{6} \approx 0.35$	DI = $\frac{10-0}{44} \approx 0.23$	Include

Calculation of the difficulty and the discrimination indices of the question about logarithmic differentiation indicated that this question does not need revision. The difficulty and discrimination indices of this question were 0.35 and 0.23, respectively. The question was considered difficult and discriminating.

These findings support our suggestions that the first question should be reformulated while the second could be included.

Although prior knowledge is of great importance to effective learning, specific prior knowledge should not be a prerequisite for every question, but only for those in which the examiner intentionally aims to present a more complex question.

The challenge is to create an exam that is well-balanced, so that not all questions are too easy or overly difficult but rather belong to different levels of Smith et al.'s (1996) taxonomy.

Examiners should also take into consideration that Calculus is a complementary first-semester course for engineering students. Ortega-Sanchez (2016) recommends percentages for different types of knowledge and, according to us, the position of the course within the curriculum should also be considered. The percentages used when constructing a first-year calculus exam should be different from those of a second or third-year course exam.

Limitations

In this study, we disregarded the overall difficulty level of the exam. The purpose of this paper is to highlight the importance of careful preparation for the calculus exam.

CONCLUSION

We found that the exam question about the existence of a limit was obstructed by prior knowledge. We modified this question to avoid the specific prior knowledge. We suggested no modification of the exam question regarding logarithms, as the necessary prior knowledge is indispensable.

Based on existing literature and our own findings, we would make the following recommendations for improving the construction of calculus exams:

- Avoid specific prior knowledge at the beginning of a question.
- Avoid overly difficult questions, given that calculus is a complementary first-year course. Difficult questions may be examined formatively, for example in home assignments. The examiner may choose the questions from category A and at most B of Smith et al.'s (1996) taxonomy.
- The examiner should consider percentages for the different types of knowledge for the whole exam, before creating exam questions.
- Exam questions should be formulated with the help of a test matrix to ensure evaluation of the learning goals.

It is also important that examiners conduct a thorough error analysis to improve the quality of future exams.

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AI statement: The authors stated that no AI-based tools were used for the study design, data analysis or preparation of this paper.

Declaration of interest: No conflict of interest is declared by the authors.

Data sharing statement: Data supporting the findings and conclusions are available upon request from the corresponding author.

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