



AN ANALYSIS OF STUDENTS' MISCONCEPTIONS AND CONCEPTUAL UNDERSTANDING OF GRADIENT, DIVERGENCE AND CURL

Sumargiyani*

Department of Mathematics Education, Universitas Ahmad Dahlan, Yogyakarta, Indonesia

*Correspondence author, Email: sumargiyani@pmat.uad.ac.id

Abstract

Understanding the concepts of gradient, divergence, and curl is fundamental in science and engineering. However, students often experience misconceptions about these materials. This study aims to identify and map the profile of conceptual errors made by students when solving problems on gradient, divergence, and curl. This study uses a descriptive qualitative approach by analyzing student answer sheets from the Vector Analysis exam. Seven indicators of conceptual understanding are used to diagnose errors in student work. The analysis reveals two main profiles of misconceptions: (1) fundamental conceptual failures, characterized by the inability to distinguish definitions and procedures between different operations (e.g., curl and dot product) and classify the results as scalar or vector; and (2) application-level failures, where students can correctly identify procedures and problem representations (e.g., constructing the determinant for curl), but fail to apply prerequisite algorithmic skills, especially partial derivatives.

Keywords: Conceptual Understanding; Curl; Error Analysis; Gradient; Vector Calculus

Abstrak

Pemahaman konsep materi gradien, divergensi, dan curl, merupakan hal yang fundamental di bidang sains dan teknik. Namun, mahasiswa sering kali mengalami miskonsepsi pada materi ini. Penelitian ini bertujuan untuk mengidentifikasi dan memetakan profil kesalahan konseptual yang dilakukan mahasiswa saat menyelesaikan soal materi gradien, divergensi, dan curl. Penelitian ini menggunakan pendekatan kualitatif deskriptif dengan menganalisis lembar jawaban mahasiswa dari ujian Analisis Vektor. Tujuh indikator pemahaman konsep digunakan untuk mendiagnosis kesalahan hasil pekerjaan mahasiswa. Hasil analisis mengungkap dua profil utama miskonsepsi: (1) kegagalan konseptual fundamental, yang ditandai oleh ketidakmampuan membedakan definisi dan prosedur antara operasi yang berbeda (misalnya, curl dan dot product) serta mengklasifikasikan hasilnya sebagai skalar atau vektor; dan (2) kegagalan pada tingkat aplikasi, di mana mahasiswa mampu mengidentifikasi prosedur dan representasi masalah secara benar (misalnya, menyusun determinan untuk curl), namun gagal dalam menerapkan keterampilan algoritma prasyarat, terutama pada turunan parsial.

Kata kunci: Analisis Kesalahan; Curl; Gradien; Kalkulus Vektor; Pemahaman Konsep

INTRODUCTION

Vector analysis is one of the key topics in advanced mathematics that plays a significant role in various applied fields such as physics (Lubis 2025; Kurniawan et al., 2019), engineering, and computer science (Narpila, Aulia, et al., 2025). Vector analysis is a course that occupies a strategic position in developing critical thinking skills (Anisa, 2018). In the context of mathematics education at the university level, vector analysis serves as the foundation for understanding various phenomena related to scalar and vector fields. Divergence examines the rate of expansion or contraction of a vector field from a point, curl examines the rate and direction of rotation of a vector field, and gradient examines changes in space, contours, and potential fields (Curl et al., 2025).

Real-world observations indicate that many students struggle to understand the concepts of gradient, divergence, curl, and integrals of vector functions compared to other topics in vector analysis,

particularly regarding conceptual understanding. This is evident from the average grade of 62.53 achieved by students in the vector analysis course, as shown in Figure 1 below.

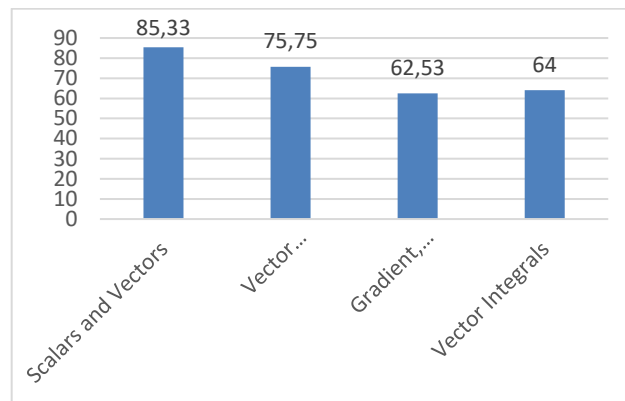


Figure 1. Average Results of Vector Analysis

Understanding mathematical concepts is important because it serves as the foundation for mastering other mathematical skills (Sofiatunnisa & Adirakasiwi, 2025). With a solid understanding of a concept, it becomes easier to grasp subsequent, more complex content (Erawati et al., 2025). Conceptual understanding is a person's ability to restate what has been learned, both orally and in writing (Rohmah et al., 2024). According to Zulkardi (Rohmah et al., 2024), mathematical conceptual understanding is a student's ability to solve mathematical problems or questions based on the knowledge they have acquired. Hani et al. (2024) add that conceptual understanding reflects an individual's readiness or ability to articulate the results of their thinking, whether concrete or abstract, in mathematics learning materials using various forms of representation. Good conceptual understanding is characterized by students' ability to rephrase learned concepts using their own words (Wahyuni et al., 2024). Based on previous research findings, many errors in students' conceptual understanding are still observed. A study (Dirgantoro et al., 2019) found that students still make many errors stemming from a lack of conceptual understanding. Similar findings were reported by Fitriasari (2020), indicating that students' abilities are still considered adequate.

METHOD

This study is a descriptive qualitative research aimed at examining conceptual errors and understanding. The study was conducted during the even semester of the 2024/2025 academic year, specifically from May to July 2025, at the Mathematics Education Study Program, Ahmad Dahlan University (UAD), Yogyakarta. The target of this study was all sixth-semester students in the Mathematics Education Study Program at Ahmad Dahlan University who were taking the Vector Analysis course, with a total of 14 students. All of these students were involved as research subjects to obtain a comprehensive picture of the profile of errors in solving vector analysis problems. By including all students, this study provides a comprehensive picture of the various learning difficulties that arise. The research instrument used was an essay-type test consisting of questions from the final exam for the vector analysis course. The selection of these two questions was tailored to the 90-minute exam duration and the learning outcomes outlined in the Semester Learning Plan (SLP). Although the number of questions is limited, each item is designed in depth to assess students' understanding of the concepts of gradient, divergence, and curl. Additionally, in accordance with quality assurance procedures in the Mathematics Education Program at UAD, these questions were verified by an expert faculty member in the Analysis field and approved by the Program Chair to ensure the quality and appropriateness of the instrument. Another instrument is a rubric based on concept understanding indicators. Concept understanding indicators include: "restating concepts, classifying objects based on specific properties,

providing examples and non-examples of concepts, presenting concepts in various forms of mathematical representation, developing necessary or sufficient conditions for a concept, using and selecting specific procedures or operations, and applying concepts or algorithms in problem-solving” (Khodijah et al., 2023; T. N. Rohmah et al., 2024). Each student’s work was classified by type of error based on the indicators of conceptual understanding. To facilitate the grading of student work, the researcher used a rubric with the stipulation that if a student did not provide an answer or provided. Based on the scores obtained, the error percentage for each indicator per item is calculated using a formula modified from (Amelia & Yulia, 2023):

$$\text{error percentage} = \frac{\text{total error score}}{\text{maximum score}} \times 100\%$$

Data collection was conducted by documenting final exam results, which were then analyzed using Miles and Huberman’s interactive model through three systematic stages: data reduction by selecting and categorizing students’ errors based on their types; data presentation by organizing the results of the reduction into a matrix to map patterns; and drawing conclusions by repeatedly verifying these findings against the theoretical framework of conceptual understanding.

RESULTS AND DISCUSSION

The data from the conceptual understanding test obtained in this study were analyzed by assigning scores based on a rubric of mathematical conceptual understanding indicators, and then the percentage of each student’s score was calculated. The data on the scoring results of the conceptual understanding test for the 14 research subjects are presented in Figure 2 below.

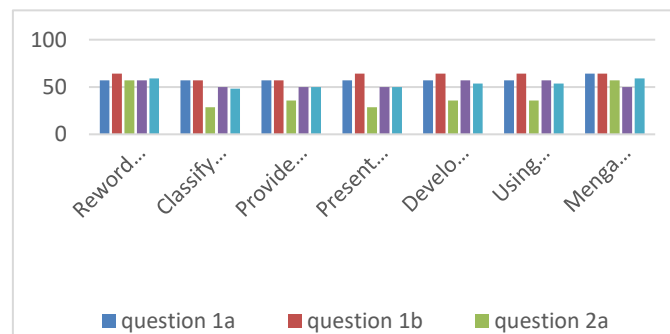


Figure 2. Percentage of Conceptual Misunderstandings per Question

Based on the analysis results, the average achievement of the concept comprehension indicator for students ranged from 48.21% to 58.93%. The indicators with the highest scores were restating concepts and applying concepts or algorithms to problem-solving, each at 58.93%. Meanwhile, the lowest score was on the indicator of classifying objects based on specific properties, at 48.21%.

Error Analysis for Question 1a

The question given in Question 1a is:

Given the vector fields $\vec{A} = 2x^2\vec{i} - 3yz\vec{j} + xz^2\vec{k}$ and $\psi = 2x - x^2y$
Find: a. The dot product $\vec{A} \cdot (\nabla\psi)$

Figure 3. Problem 1a. Dot Product of Vectors $\vec{A}$ with a gradient ψ

One of the students' solutions to Problem 1a is shown in Figure 4 below.

$$\nabla \psi = \left(\frac{\partial \psi}{\partial x}, \frac{\partial \psi}{\partial y}, \frac{\partial \psi}{\partial z} \right) = (4x + z^2, -3z, -3y + 2xz)$$

$$1.) \vec{A} \cdot (\nabla \psi) = ((2x^2)(4x + z^2))\vec{i} + ((-3yz)(-3z))\vec{j} + ((xz^2)(-3y + 2xz))\vec{k}$$

$$= (8x^3 + 2x^2z^2)\vec{i} + 9yz^2\vec{j} + (-3xy z^2 + 2x^2z^2)\vec{k}$$

Figure 4. Solution to Problem 1a. Student AN

The problem presented in Problem 1a (Figure 3) involves gradient and dot product operations, specifically, finding the result of $\vec{A} \cdot (\nabla \psi)$. As shown in Figure 4, the most fundamental errors identified were student AN's failure to restate concepts and select the appropriate procedures. Student AN demonstrated a misunderstanding of three distinct concepts: gradient, divergence, and dot product. In the initial step, student AN made an error that led to subsequent errors, namely in calculating the gradient of the scalar field ($\nabla \psi$). The student incorrectly applied the partial derivative operation to the components of the vector field. This indicates an inability to define and distinguish between the fact that the gradient operates on scalars, while the divergence operates on vectors. As a result, the procedure chosen for this first step is completely irrelevant to the given problem.

Furthermore, AN students struggled to classify the fundamental properties of mathematical objects, particularly the difference between scalars and vectors. This misclassification resulted in a vector being provided as the final answer to the operation *dot product*, which should definitely result in a scalar. By presenting the answer in component form $\vec{i}, \vec{j}, \vec{k}$ explicitly indicates that AN students do not understand the most basic concepts of operations, the *dot product*. This initial conceptual error led to a series of failures in the application of algorithms and mathematical representations. Although AN students structurally understood the prerequisites for performing calculations $\nabla \psi$ first failed in the final step. An error in selecting the input for the gradient operation, but also an error in choosing the mathematical representation for the *dot product*. Instead of using the formula for the sum of the products of the components, student AN applied a component multiplication algorithm that produced a new vector. The errors made by student AN were not merely arithmetic mistakes but stemmed from a series of interrelated conceptual failures. These ranged from an inability to distinguish the definitions of basic operations to misclassifying scalar and vector properties to the selection of incorrect procedures and representations.

Error Analysis of Problem 1b

The task given in Problem 1b is stated as follows:

Given the vector fields $\vec{A} = 2x^2\vec{i} - 3yz\vec{j} + xz^2\vec{k}$ and $\psi = 2x - x^2y$
Find : a. The cross product $\vec{A} \times (\nabla \psi)$

Figure 5. Problem 1b. The cross product of a vector $\vec{A}$ with the gradient ψ

One solution to problem 1b is shown in Figure 6 below.

$$\begin{vmatrix} \vec{i} & \vec{j} & \vec{k} \\ 2x^2 & -3yz & xz^2 \\ 4x & -3yz & 0 \end{vmatrix} = (x^2 - 3yz)\vec{i} + (2x^2 + 2xz^2)\vec{j} + (12yz - 16xyz)\vec{k}$$

$$= (2x - 3yz)\vec{i} + (16x^2)\vec{j} + (-4xz)\vec{k}$$

$\therefore$ Jadi Hasil cross product $\vec{A} \times (\nabla \psi)$ adalah
 $(2x - 3yz)\vec{i} + (16x^2)\vec{j} + (-4xz)\vec{k}$

Figure 6. Solutions to Problem 1a. RF Students

Question 1b (Figure 5) involves the cross product of a vector field and the gradient of a scalar field. In Figure 6, the primary conceptual error in this work lies in the failure to meet a necessary condition for the concept, even though the RF student successfully selected the correct main procedure. The RF student correctly identified that to solve $\vec{A} \times (\nabla\psi)$, The procedure used is the cross product, which the RF students correctly represented as the determinant of a 3x3. matrix. However, the RF students failed in the prerequisite step of calculating the vector $\nabla\psi$. RF students do not take partial derivatives of scalar fields $\psi = 2x - x^2y$, but instead filling the third row of the determinant with the wrong vector, namely $(4x^2, -3yz, 0)$. This vector lacks a clear computational basis for ψ , indicating that RF students are unable to correctly reformulate or apply the concept of the gradient.

Furthermore, RF students were able to present the concept of the cross product in the form of a determinant representation; however, this representational ability was not matched by computational skills. The calculations performed were inconsistent and did not follow Sarrus's rule, resulting in errors in the obtained results. These errors made by RF students indicate that their understanding of determinant calculations remains weak. In terms of conceptual understanding, RF students perform better; specifically, they demonstrate the ability to classify objects and consistently treat the final result as a vector, as evidenced by the inclusion of the components $\vec{i}, \vec{j}, \vec{k}$ in their answers. This indicates that RF students possess a correct understanding that the cross product of two vectors yields a new vector.

Error Analysis for Question 2a

The question given in question 2a is :

Given the vector fields $\vec{A} = xz^3\vec{i} - 4x^2y\vec{j} + 2yz^4\vec{k}$ and $\vec{B} = (x + 2y)\vec{i} + 5xz\vec{j} - y^2\vec{k}$
compute the curl of their sum, $\nabla \times (\vec{A} + \vec{B})$

Figure 7. Problem 2a: Curl of a Vector $(\vec{A} + \vec{B})$

One of the solution results for Problem 2a is presented in Figure 3

The image shows a handwritten solution for Problem 2a. The student starts by identifying the vector fields $\vec{A}$ and $\vec{B}$. They then calculate the curl of their sum, $\nabla \times (\vec{A} + \vec{B})$, using the determinant method. The solution is as follows:

$$\nabla \times (\vec{A} + \vec{B}) = \begin{vmatrix} \vec{i} & \vec{j} & \vec{k} \\ \frac{\partial}{\partial x} & \frac{\partial}{\partial y} & \frac{\partial}{\partial z} \\ xz^3 + x + 2y & -4x^2y + 5xz & 2yz^4 - y^2 \end{vmatrix}$$

Then, the student calculates the components of the curl:

$$\vec{i}: \frac{\partial}{\partial y}(2yz^4 - y^2) - \frac{\partial}{\partial z}(-4x^2y + 5xz) = 2z - 2y + 4x^2y - 5x$$

$$\vec{j}: \frac{\partial}{\partial x}(2yz^4 - y^2) - \frac{\partial}{\partial z}(xz^3 + x + 2y) = 0 - 3xz^2 + x + 2y - 3xz^2 + x + 2y$$

$$\vec{k}: \frac{\partial}{\partial x}(-4x^2y + 5xz) - \frac{\partial}{\partial y}(xz^3 + x + 2y) = -8xy + 5z - xz^3 + x + 2 - xz^3 + x + 2$$

Finally, the student writes the result:

$$\text{Jadi } \nabla \times (\vec{A} + \vec{B}) = (2z - 2y + 4x^2y - 5x)\vec{i} + (3xz^2 - x - 2y)\vec{j} - (8xy + 5z - xz^3 + x + 2)\vec{k}$$

Figure 8. Student KL's Solution to Problem 2a

Figure 7 presents a problem with the curl of a vector. $(\vec{A} + \vec{B})$, Figure 7 presents a problem involving the curl of a vector, with the corresponding solution by student KL shown in Figure 8. The solution produced by student KL demonstrates a significantly higher level of structural and procedural understanding. A detailed analysis of the student's work indicates the ability to identify and organize appropriate procedures, as well as to execute the required computational steps accurately. Furthermore, student KL exhibits a strong conceptual understanding, as evidenced by the correct application of several indicators of understanding. First, the student can develop the necessary conditions of a concept by identifying the correct prerequisite step, namely by summing the vector fields $\vec{A}$ and $\vec{B}$ namely by

summing the vector fields without making any errors. Second, student KL appropriately selected and applied the curl operation. Third, the student was able to represent the concept in multiple mathematical forms by expressing the curl operation in the form of a determinant 3x3 by expressing the curl operation in the form of a determinant correctly, including the partial derivative operators and the components of the resulting vector sum.

Mistakes made by KL students when calculating partial derivatives, which form the core of the curl operation. In the calculation of each component of the resultant vector $(\vec{i}, \vec{j}, \vec{k})$, Nevertheless, student KL made errors in computing the partial derivatives, which constitute the core of the curl operation, especially in determining each component of the resulting vector $\vec{i}$, the partial derivative of $\frac{\partial(2yz^4)}{\partial z}$ was incorrectly computed as $2z$, ignoring the exponent rule for the variable z^4 . A similar pattern of errors is observed across other components. Student KL appears to experience difficulty in applying the power rule and frequently misidentifies which variables should be treated as constants, indicating a weak understanding of differentiation. Although the final result is incorrect, the student correctly demonstrates the conceptual understanding that the sum of two vectors yields a vector and that the curl of a vector produces another vector.

Error Analysis of Problem 2b

The task provided in Problem 2b is stated as follows:

Given the vector field $\vec{A} = xz^3\vec{i} - 4x^2y\vec{j} + 2yz^4\vec{k}$ and $\psi = x^2yz$
and the scalar field $\nabla \times (\psi \vec{A})$

Figure 8. Problem 2b. $\nabla \times (\psi \vec{A})$

Handwritten student work for Problem 2b. The student calculates the curl of the product of a scalar field $\psi = x^2yz$ and a vector field $\vec{A} = xz^3\vec{i} - 4x^2y\vec{j} + 2yz^4\vec{k}$. The student uses the determinant method for the curl operation. The final result is marked with a blue 'X'.

Figure 10. Student RD's Work on Problem 2b

Figure 10 presents Problem 2b, which asks for the curl of $(\psi \vec{A})$, with one of the students' responses presented in Figure 10. Student RD's solution initially appears to demonstrate an understanding of the structure of the problem; however, it ultimately reveals a fundamental conceptual failure in the application of the operator. The student shows initial success in both procedural execution and representation. Student RD correctly identifies the necessary condition of the problem by beginning with the multiplication of the scalar field ψ and the vector field $\vec{A}$. Student RD exhibited carelessness by using the dot product symbol $(\cdot)$ for this operation; nevertheless, the computational result was correct, suggesting an implicit understanding of scalar–vector multiplication. Moreover, the student was

able to select the appropriate procedure and represent the concept of curl accurately in mathematical form by expressing it in the form of a determinant 3×3 accurately, incorporating the required operator $\partial/\partial x$ and the vector components $\psi \vec{A}$ that have been computed. This result indicates that student RD has correctly carried out the procedural stage. However, a conceptual error occurs when computing the determinant. The conceptual understanding of partial derivatives is not properly demonstrated, as indicated by the incorrect use of symbols $\partial/\partial y$ and $\partial/\partial z$ are no longer treated as operators for performing differentiation. This indicates that student RD is unable to restate the concept of partial derivatives in terms of computational procedures. The student's work reflects an understanding of the formula, but without a proper grasp of the operational meaning of the symbols involved. Although student RD correctly classifies the objects and understands that the final result of the curl must be a vector, errors are still evident in the computational steps.

Based on the results of the analysis, students' errors in solving vector analysis problems can be categorized into four main points. First, conceptual understanding errors that directly lead to procedural mistakes. This finding is consistent with the studies of Hajerina et al. (2022) and Laila et al. (2025), which emphasize that failure to understand concepts correctly becomes the root cause of inaccurate solution procedures. Second, procedural errors are characterized by students' inability to construct systematic solution steps. This phenomenon is supported by the studies of Lusiana (2017), Rahmawati and Permata (2018), and Laila et al. (2025), which indicate that students often do not know the appropriate steps to solve problems, particularly those with a field-dependent cognitive learning style. Third, errors in applying formulas stem from misconceptions or insufficient mastery of prerequisite knowledge. Findings by Aini et al. (2025), Sari (2025), and Hidayat et al. (2022) suggest that errors in selecting formulas are often caused by weak prior understanding. Furthermore, Putri and Jupri (2025) found that weaknesses in mastering theorems and proof skills further exacerbate this issue. Fourth, errors in classification and mathematical representation. Students were found to be unable to distinguish between fundamental mathematical objects, such as scalars and vectors (Maifa, 2019; Setiawan, 2017). This is further reinforced by representational errors, in which students express the final result as a vector in operations that should yield a scalar. According to Inganah et al. (2021), this occurs because students tend to rely solely on formulas without understanding the underlying conceptual meaning.

CONCLUSION

Based on the analysis of the students' responses, it can be concluded that students' misconceptions in solving vector analysis problems can be categorized into two fundamentally distinct profiles of failure. The first profile is a basic conceptual failure, characterized by students' inability to distinguish definitions, select appropriate procedures for fundamental operations such as the dot product and curl, and classify whether the result of an operation is a scalar or a vector. The second profile is a failure at the application level, in which students demonstrate a good structural understanding by being able to construct correct procedures, but make errors during execution due to weak mastery of prerequisite computations, such as partial derivatives. These findings logically suggest that errors in advanced topics often stem from insufficient understanding of fundamental concepts. Therefore, the main implication is the need for a diagnostic approach to teaching, in which educators are encouraged not only to focus on new material but also to actively identify and reinforce students' understanding of prerequisite concepts to support their academic success.

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