Development of a Three-Dimensional Geometry Instrument to Measure Mathematics Students' Problem-Solving Ability

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DOI: https://dx.doi.org/10.47772/IJRISS.2026.1026EDU0111

Received: 07 February 2025; Accepted:15 February 2026; Published: 06 March 2026

ABSTRACT

The ability to solve three-dimensional (3D) geometry problems is an essential competence for mathematics education students, particularly because geometry requires skills in representation, reasoning, and spatial visualization. However, instruments specifically designed to measure students' problem-solving ability in 3D geometry are still limited. This study aimed to develop a test instrument to measure the problem-solving ability of prospective mathematics teachers in solving 3D geometry problems. The developed instrument was an essay-type test based on geometric concepts, focusing on three-dimensional geometry and consisting of four items. The instrument was developed using the ADDIE R&D model (Analysis, Design, Development, Implementation, and Evaluation). The validation process included expert validation and empirical validation. The results of expert validation indicated that the instrument had high validity, as shown by a Gregory index of 1. The results of empirical validation showed that all test items were valid and reliable, with a reliability coefficient of 0.666. The validated instrument was then implemented to measure students' problem-solving ability. The findings revealed that the average score of students' problem-solving ability was 40 (SD = 20.37), with the highest score of 85 and the lowest score of 6 on a scale of 0–100. Therefore, it can be concluded that the developed test instrument is valid and can be used to measure students' problem-solving ability in solving 3D geometry problems.

Keywords: Three-dimensional geometry, Instrument, Problem-solving

INTRODUCTION

Problem-solving is an essential skill at all levels of education because it involves various cognitive processes, including analysing, interpreting, reasoning, predicting, evaluating, and reflecting (M. M. Rahman, 2019). Problem-solving refers to the process in which learners use previously acquired knowledge and skills to find solutions and adapt to the demands of a given situation (Shi et al., 2023). In mathematics, problem-solving, based on the nature of mathematics itself, is a process of overcoming problems by using relevant information and procedures through mental processes or reasoning (Tachie, 2019); (A. Rahman & Ahmar, 2016).

Mathematical problem-solving is a form of higher-order thinking. It is one of the essential higher-order thinking skills in learning mathematical concepts and procedures (Tambunan, 2019); (Tajudin & Chinnappan, 2016). The scope of problem-solving is broad.

According to (Türkoğlu & Yalçınalp, 2024) Problem-solving is a vital skill at almost all levels of education for several reasons. During the problem-solving process, students: (a) construct new mathematical knowledge, (b) reflect on their thinking processes, (c) apply and adapt strategies, and (d) solve problems in various contexts.

Therefore, continuous efforts to improve problem-solving ability have become an important focus of research among mathematics educators and scholars (Olivares et al., 2020); (Montague et al., 2014).

The ability to solve 3D geometry problems is an important competence for mathematics education students. However, instruments specifically designed to measure students' problem-solving abilities in 3D geometry are still limited. Problem-solving in 3D geometry requires representational skills, reasoning, and spatial visualization. It also involves the application of various mathematical concepts, such as ratios, theorems, and measurement, within more complex spatial contexts (Maqoqa, 2024); (Silitonga et al., 2023). Two important variables that influence the effectiveness and strategies of problem-solving are cognitive style, which describes how individuals process information, and mathematical ability (Sudjana, 2014); (Bendall et al., 2016).

Geometry is one of the most important branches of mathematics and is a fundamental topic because it deals with the properties and relationships among points, lines, shapes, and space. Geometry encompasses mathematical knowledge related to shapes and space, measurement, magnitude, and the relationships among points, lines, angles, and planes (Abdul Hanid et al., 2022); (Abd Rahim et al., 2018). Many studies have shown that geometry is often perceived as overly formal, complex, and difficult to understand (Adelabu et al., 2019); (Alex & Mammen, 2016). Students frequently experience difficulties in reasoning about geometric representations, and such representations are sometimes difficult for students to interpret (İbili et al., 2019); (Adelabu et al., 2019). Nevertheless, geometry has strong potential to develop important and transferable skills, including visualization, critical thinking, intuition, perspective-taking, problem-solving, conjecturing, deductive reasoning, logical argumentation, and proof (Hourigan & Leavy, 2017); (Jones & Tzekaki, 2016).

Previous studies have also shown that geometry is one of the most challenging topics to teach and to learn. Geometric objects are generally divided into two major categories: two-dimensional (2D) geometry and three-dimensional (3D) geometry. To date, research on 3D geometry has primarily focused on students' abilities to perform curriculum-related tasks and procedures (Sudirman et al., 2023). In learning 3D geometry, students experience varying levels of difficulty and possess different learning experiences (Sudirman et al., 2024); (İbili et al., 2019). Success in solving geometry problems is strongly correlated with students' mathematical achievement both in school and at higher levels of education (Krawec & Huang, 2017); (Shi et al., 2023). Previous research on 3D geometry problem-solving has largely focused on school students. Therefore, this study aims to develop an instrument to measure university students' problem-solving abilities in solving 3D geometry problems.

METHOD

This study employed a Research and Development (R&D) approach. The instrument developed in this study was a test designed to measure students' ability to solve 3D geometry problems, using the ADDIE development model proposed by Branch. The ADDIE model consists of five stages: (1) analysis, (2) design, (3) development, (4) implementation, and (5) evaluation.

The development procedure in this study was carried out through the following steps. First, an analysis was conducted on how problem-solving ability is assessed. Second, the development of the test instrument was planned by determining indicators of problem-solving ability. Third, the problem-solving test instrument was developed based on the selected indicators. Fourth, the developed test instrument was implemented.

During the development stage, the instrument underwent validation before being implemented. The validation process consisted of expert validation and empirical validation. Expert validation aimed to obtain evaluations on four aspects: (1) the alignment of test items with the indicators, (2) the level of item difficulty, (3) language use, and (4) the correctness of the concepts used. In addition, expert validation was intended to obtain suggestions for improving the instrument. Instruments that were declared feasible by the experts were then subjected to empirical validation to determine their validity and reliability.

The test instrument that had passed both expert and empirical validation was subsequently implemented to measure the problem-solving ability of mathematics education students. The implementation was carried out with 36 respondents, namely students of the Mathematics Education Program at Universitas Negeri Surabaya.

The data obtained from expert validation, empirical validation, and implementation consisted of two types: qualitative and quantitative data. Qualitative data were in the form of experts' suggestions, which were used as considerations for improving the problem-solving test instrument. Quantitative data consisted of the instrument assessment scores from expert validation; validity and reliability coefficients obtained from empirical validation; and students' problem-solving scores obtained from the implementation of the test instrument.

Furthermore, the expert agreement index was calculated using the Gregory index formula, which compares the number of items rated as highly relevant by both experts to the total number of items. This index was used to indicate the level of agreement between experts regarding the validity of the instrument items (Retnawati, 2016). Since two experts were involved as validators, the Gregory index formula was applied using a contingency table with 2 × 2 = 4 cells, as shown in Table 1. The Gregory index formula is presented in Equation (1) below.

$$\text{Content Validity Coefficient (Cv)} = \frac{D}{(A+B+C+D)} \quad (1)$$

Table 1. Contingency Table for Calculating the Gregory Index

		Rater 1 (SN)	
		Weak	Strong
Rater 2 (RK)	Weak	A	C
	Strong	B	D

The expert agreement index can be described using the validity criteria presented in Table 2.

Table 2. Content Validity Criteria (Cv)

Expert Agreement Index	Description
0,0 ≤ Cv < 0,4	Low validity
0,4 ≤ Cv < 0,8	Moderate validity
0,8 ≤ Cv ≤ 1,0	High validity

The instrument that had been declared valid and revised based on the validators' suggestions was then administered to three students to test the readability of the test items. After that, an empirical trial was conducted to determine the validity, level of difficulty, discriminating power, and reliability of the test instrument.

Validity

An exploratory factor analysis (EFA) procedure was conducted to determine the construct validity of the PMG3D instrument. The EFA procedures were conducted using IBM SPSS version 24.

Item Difficulty Level

The formula used to calculate the item difficulty index is as follows:

$$P = \frac{\bar{S}}{S_{max}} \quad (2)$$

P = item difficulty index

$\bar{S}$ = mean score of each item

S_{max} = maximum possible score for each item

ISSN No. 2454-6186 | DOI: 10.47772/IJRISS | Volume X Issue XXVI February 2026 | Special Issue on Education

The criteria for item difficulty levels are presented in Table 3.

Table 3. Criteria for Item Difficulty Level

Score Range	Category
0,00 ≤ P ≤ 0,30	Difficult
0,30 < P ≤ 0,70	Maderate
0,70 < P ≤ 1,00	Easy

(Sudjana, 2014)

Discriminating Power

$$D = \bar{S}_A - \bar{S}_B \quad (3)$$

D = item discrimination index

$\bar{S}_A$ = mean score of the upper group

$\bar{S}_B$ = mean score of the lower group

The criteria for item discrimination are presented in Table 4.

Table 4. Criteria for Item Discrimination

Rentang Nilai	Kategori
0,00 ≤ D ≤ 0,20	Poor
0,20 < D ≤ 0,40	Fair
0,40 < D ≤ 0,70	Good
0,70 < D ≤ 1,00	Very Good
Negative	Not Acceptable

(Arikunto, 2012)

Reliability

In the present study, the reliability of PMG3D instrument was measured using the Cronbach's Alpha coefficient, The calculation of the reliability coefficient was performed with SPSS.

RESULTS

This study developed a test instrument consisting of four essay-type items designed to measure students' ability to solve 3D geometry problems and to obtain a description of students' reasoning processes in solving such problems.

The research procedure applied five stages of the ADDIE model, namely analysis, design, development, implementation, and evaluation. These five stages are described in detail as follows.

Analysis

At this stage, an analysis was conducted of materials related to 3D geometry, components of reasoning involved in solving 3D geometry problems, and indicators that reflect reasoning ability in solving such problems. The results of this analysis served as the foundation for developing the 3D geometry problem-solving test instrument.

Design

Determining the Objectives of the Test Instrument

The first objective of the test was to measure students' ability to solve 3D geometry problems. The second objective was to obtain data on students' reasoning processes in solving 3D geometry problems. The test developed in this study was in the form of essay questions. In addition, the scope of the material, the time allocation for completing the test, and the target group of students were also determined.

Developing the Test Blueprint

The blueprint was constructed in the form of a matrix table containing specifications of the test items to be developed. The blueprint served as a guideline for writing the items, ensuring that different item writers would produce questions with relatively similar content and difficulty levels. In developing the blueprint, both content indicators and indicators of reasoning in solving 3D geometry problems were specified. The instrument developed in this study consisted of written essay questions oriented toward reasoning in solving 3D geometry problems, namely 1) representation of 3D objects, 2) spatial structuring, 3) conceptualization of properties of 3D shapes, and 4) measurement. The content scope of the instrument included the volume of 3D objects, surface area, nets, and orthographic views. The indicators specified in the test included: calculating the volume of cubes and rectangular prisms, comparing the volumes of cubes and rectangular prisms, drawing three-dimensional objects composed of unit cubes, drawing front, top, and side views of 3D objects, drawing nets of 3D shapes, and calculating the surface area of 3D objects. Based on the predetermined indicators, four PMG3D test items were developed: the first item concerns the volume of cubes and rectangular prisms, the second focuses on orthographic views, the third involves drawing nets of three-dimensional objects, and the fourth addresses the calculation of surface area.

Development

Item Writing

The construction of the test items was based on the indicators specified in the test blueprint. The development of the 3D geometry problem-solving test instrument was carried out in accordance with the previously selected indicators. Based on these indicators, four test items were developed. Each item was designed to obtain data on students' reasoning in solving problems.

The first item required students to (1) determine the volume of a cube based on the arrangement of unit cubes, (2) determine the number of rectangular prisms that can be formed from the unit cubes composing the cube, and (3) draw the resulting rectangular prism. The second item required students to draw the front view, top view, and side view of a 3D object composed of several cubes.

The third item required students to draw the net of a 3D object consisting of stacked cubes and a regular square pyramid. The fourth item required students to determine the surface area of a 3D object composed of stacked rectangular prisms, cubes, and a regular square pyramid.

Preparation of Answer Keys and Scoring Guidelines

Each test item was accompanied by an answer key and a scoring guideline. The scoring guidelines were developed specifically for essay-type questions to ensure objectivity and consistency in scoring. These guidelines served as a reference to minimize subjectivity in assessing students' responses.

ISSN No. 2454-6186 | DOI: 10.47772/IJRISS | Volume X Issue XXVI February 2026 | Special Issue on Education

Expert Validation

The developed test items were subsequently validated by experts. Expert validation was conducted by two individuals with expertise in mathematics education and geometry. The validation aimed to evaluate four aspects (1) the alignment of the test items with the indicators, (2) the level of difficulty of the items, (3) the appropriateness of language use, and (4) the accuracy of the mathematical concepts applied. The results of the expert evaluations were analysed using the Gregory formula to determine the content validity of each item.

Table 5. Results of the Evaluation by Validators SN and RK

Item No.	Validator SN	Validator RK
1	4	4
2	4	4
3	4	4
4	4	4

Next, the first category, namely not relevant (score 1) and less relevant (score 2), was reclassified into the weak relevance category. The second category, namely quite relevant (score3) and very relevant (score4), was reclassified into the strong relevance category. Thus, the results of validation by the two experts were reclassified as presented in Table 6.

Table 6. Recategorized Results of Validation by SN and RK

Item No.	Validator SN	Validator RK
1	Strong	Strong
2	Strong	Strong
3	Strong	Strong
4	Strong	Strong

The results shown in Table 6 were then arranged into a contingency table with 2 × 2 = 4 cells, as presented in Table 7.

Table7.Contingency Table of the Recategorized Validator Assessments

		Rater 1 (SN)	
		Weak	Strong
Rater 2 (RK)	Weak	0	0
	Strong	0	4

Next, the content validity coefficient was calculated using Gregory's formula as follows:

Content Validity Coefficient (Cv):

$$(Cv) = \frac{D}{(A+B+C+D)}$$

$$= \frac{4}{(0+0+0+4)}$$

ISSN No. 2454-6186 | DOI: 10.47772/IJRISS | Volume X Issue XXVI February 2026 | Special Issue on Education

$$= \frac{4}{4}$$

$$= 1$$

Based on the calculation of the content validity coefficient, the Gregory index for the 3D geometry problem-solving instrument is 1, which indicates that the instrument meets the criteria for high validity.

Readability Test

The readability test was administered to three Mathematics Education students who were not included as research subjects. The purpose of this test was to obtain feedback regarding the clarity and comprehensibility of the test items. The aspects evaluated in the readability test included the formulation of questions, clarity of meaning, ease of understanding, appropriateness of language use, and clarity of figures. The results of the readability test indicated that all three respondents stated that the questions and illustrations were very clear and easy to understand. The results of the readability assessment can be summarized as follows:

Table 8. Results of the Readability Analysis of the TPMG3D Instrument

Respondent	Analysis Results	Comments/Suggestions	Conclusion
KA	For Questions 1 and 4, KA strongly agreed with aspects 1, 2, and 5. KA For Question 2, KA agreed with all assessment aspects. For Question 3, KA strongly agreed with aspects 1 and 5, and agreed with aspects 2, 3, and 4.	Difficulty in determining the cube arrangement and the length of lines that were not clearly indicated in Question 3.	All four questions have good readability.
LM	For Questions 1–4, LM strongly agreed with all five assessment aspects.	The questions and figures are very clear and easy to understand.	All four questions have good readability.
RA	For Question 1, RA strongly agreed with aspects 1, 3, and 4, and agreed with aspects 2 and 5. For Question 2, RA strongly agreed with all aspects. RA For Question 3, RA strongly agreed with aspects 2 and 5 and agreed with aspect 1. For Question 4, RA strongly agreed with aspects 1 and 4 and agreed with aspects 2, 3, and 5.	It is suggested that in Question 4, additional clarification be provided regarding the base section, which is also covered by wallpaper.	All four questions have good readability.

Notes on Assessment Aspects: (1) Clarity of question formulation; (2) Meaningfulness of the question; (3) Ease of understanding; (4) Use of standard language; (5) Clarity of figures

Field Trial

The field trial involved 67 students who had completed the geometry course. The construct validity of the PMG3D instrument in this study was examined using exploratory factor analysis (EFA) with the assistance of IBM SPSS 24. Data obtained from the trial were analyzed using SPSS software. The main components examined in the factor analysis included sample adequacy, item feasibility, communality, eigenvalues, and factor loadings. The stages of data analysis are described as follows.

ISSN No. 2454-6186 | DOI: 10.47772/IJRISS | Volume X Issue XXVI February 2026 | Special Issue on Education

Sample Adequacy

Based on the analysis results, the Kaiser–Meyer–Olkin (KMO) value was 0.692, indicating that the KMO value exceeded the minimum requirement of 0.50. In addition, the Bartlett's Test of Sphericity yielded a significance value of 0.000, which is less than 0.05.

These results indicate that the sample size was adequate and that the data were suitable for factor analysis. Therefore, the analysis could be continued to the next stage.

Item Feasibility

The Measure of Sampling Adequacy (MSA) indicates how well each individual item can be predicted by other items in the dataset. This value is used to determine whether an item is appropriate for inclusion in factor analysis. Items with an MSA value below 0.50 are considered unsuitable and should be excluded.

An analysis of the four items was conducted to determine their feasibility for factor analysis. The results showed that all four items had MSA values greater than 0.50, indicating that they were suitable for inclusion. The results are presented in Table 9.

Table 9. MSA Values for Each Item

No	Item	MSA Value
1	S1	0,721
2	S2	0,656
3	S3	0,653
4	S4	0,778

Communality

Communality represents the proportion of variance in each item that can be explained by the extracted factors. The results of the communality analysis are presented in Table 10.

Table 10. Communalities

Item	Initial	Extraction
S1	1,000	0,562
S2	1,000	0,538
S3	1,000	0,733
S4	1,000	0,511

Based on Table 10, item S1 has a value of 0.562, which means that 56.2% of the variance in item S1 can be explained by the extracted factor. The same applies to the other items; all of them have values greater than 50%.

ISSN No. 2454-6186 | DOI: 10.47772/IJRISS | Volume X Issue XXVI February 2026 | Special Issue on Education

Therefore, it can be concluded that all items can be adequately explained by the formed factor.

The higher the communality value, the stronger the relationship between the item and the factor, and the greater the extent to which the original characteristics of the item are represented by the extracted factor.

Eigenvalues

Table 11 below presents the eigenvalues used to determine the number of factors that can be formed.

Table 11. Eigenvalues and Variance Components from Factor Analysis

Factor	Eigenvalue	Percentage of Variance	Cumulative
1	2,344	58,595	58,595
2	0,800	20,008	78,603
3	0,528	13,188	91,791
4	0,328	8,209	100,000

Table 11 shows that only one factor can be retained, as only one eigenvalue is greater than 1. This factor was named according to the content area, namely 3D geometry (Geo3D). Based on the cumulative eigenvalue column, it can be seen that the reduction of four items into one factor explains 58.595% of the total variance.

Factor Loadings

Since only one factor was formed, each item correlates strongly with the same factor. This is shown in Table 12 below.

Table 12. Factor Loadings of Items

No	**Item**	**Geo3D**
1	S1	0,750
2	S2	0,734
3	S3	0,856
4	S4	0,715

Based on the exploratory factor analysis described above, it can be concluded that the 3D geometry problem-solving instrument is valid. After obtaining a valid instrument, further analyses were conducted, including item difficulty, discriminating power, and reliability testing.

Item Difficulty Level

The results of the item difficulty analysis are presented in Table 13.

Table 13. Item Difficulty Level

No	Item	P	Category
1	S1	0,201	Difficult
2	S2	0,356	Moderate
3	S3	0,409	Moderate
4	S4	0,339	Moderate

Based on the results shown in Table 13, of the four test items analysed, one item falls into the difficult category, while the remaining three items fall into the moderate category. Therefore, all four items are considered suitable for use as instruments for collecting research data.

Item Discrimination Index

The results of the item discrimination analysis are presented in Table 14.

Table 14. Discrimination Index of PMG3D Items

No	Item	D	Category
1	S1	0,328	Fair
2	S2	0,412	Good
3	S3	0,529	Good
4	S4	0,520	Good

Based on Table 14, item S1 falls into the fair category, while items S2, S3, and S4 fall into the good category. Referring to these criteria, all four items are considered acceptable and can be used as instruments for data collection in this study.

Instrument Reliability

The reliability of the PMG3D instrument was tested using Cronbach's alpha. The reliability analysis conducted using SPSS software produced a Cronbach's alpha coefficient of 0.666. Since this value exceeds the minimum acceptable threshold of 0.60, it can be concluded that the PMG3D instrument is reliable and suitable for use in measuring students' problem-solving ability in 3D geometry.

Implementation

The implementation of the 3D geometry problem-solving test instrument was conducted with 36 students of the Mathematics Education program who had completed the geometry course. The results of the implementation showed that the highest score was 85, the lowest score was 6, and the average score was 40 on a scale of 0–100, with a standard deviation of 20.37. These results indicate that students' problem-solving ability in 3D geometry is still relatively low.

Evaluation

Based on the results of the instrument implementation, the average score of 40 indicates a low level of problem-solving ability. Furthermore, the item difficulty analysis showed that one item (Item 1) was categorized as difficult, while three items (Items 2, 3, and 4) were categorized as moderate. These results suggest that the four test items have not yet reached an ideal level of difficulty distribution. Ideally, the test should consist of a balanced composition of easy, moderate, and difficult items. Therefore, further trials of the instrument are required to obtain a more ideal set of test items before wider implementation. In addition, for Item 4, clearer information regarding the surface in contact with the ground needs to be provided, as many students were confused by this aspect and consequently calculated surface areas that should not have been included.

DISCUSSION

Several previous researchers have developed assessment instruments in the field of geometry. For example, (Komala et al., 2021) designed a geometry test instrument grounded in van Hiele's theory. Their study resulted in a valid and reliable instrument for measuring students' levels of spatial reasoning ability. The test instrument has a reliability of 0.89, fall into the very high category. The results of the difficulty level of the developed test are 12.5% items have a very easy, 25% easy, 37.5% moderate, and 25% difficult. Meanwhile the present study indicate that the distribution of item difficulty levels consisted of 0% easy items, 75% moderate, and 25% difficult. This suggests that the spread of item difficulty was not evenly balanced. Furthermore, the test yielded a reliability coefficient of 0.67, which is classified within the high reliability category. This finding indicates that future research should ensure a more balanced distribution of item difficulty levels.

Moreover, (Widodo et al., 2021) developed a mathematical problem-solving test focusing specifically on triangles and rectangles for junior secondary school students. Their study produced an instrument that was both valid and practical for assessing students' abilities to solve mathematical problems, particularly in two-dimensional geometry involving triangles and rectangles. Meanwhile, (Pittalis & Christou, 2010) designed an assessment instrument aimed at measuring 3D geometric thinking. Their research resulted in a valid and reliable instrument for evaluating students' 3D geometric reasoning skills.

Based on the foregoing discussion, it can be concluded that most prior studies have focused on developing assessment instruments for school students. In contrast, the present study develops a 3D geometry instrument intended to measure the problem-solving abilities of mathematics undergraduates. By systematically applying the ADDIE framework, this research produced an instrument that demonstrates satisfactory validity and reliability for assessing students' competence in solving 3D geometry problems.

In addition, the instrument can be utilized to obtain data concerning students' reasoning processes when addressing 3D geometry tasks. It was deliberately designed to function as a practical tool for identifying the types of reasoning employed by students in solving 3D geometry problems. The reasoning types targeted include 3D object representation, spatial structuring, conceptualization of the properties of 3D objects, and measurement (Pittalis & Christou, 2010). These four categories of reasoning are closely associated with 3D geometric thinking and are therefore essential components in the teaching and learning of 3D geometry.

CONCLUSION

The results of the data analysis indicate that the four test items developed in this study are valid. These items also demonstrate a relatively high level of reliability, with a Cronbach's alpha coefficient of 0.666. This finding indicates that the four items are suitable for use as an instrument to measure students' problem-solving ability in 3D geometry. The validated instrument was then implemented with 36 students. The results showed an average problem-solving score of 40, with a maximum score of 85 and a minimum score of 6 (SD = 20.37).

Considering the outcomes of this research, various directions are suggested for further study. Subsequent development of 3D geometry problem-solving instruments could incorporate a wider range of 3D geometry topics to improve both the quality and utility of the instrument. Expand the number of assessment items to enhance content coverage and strengthen reliability indices. Carrying out the study with more extensive and varied samples from several universities would provide stronger support for generalizing the outcomes. In addition to exploratory factor analysis, subsequent research could apply confirmatory factor analysis (CFA) to strengthen evidence of construct validity.

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