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An Evaluation of The Relationship between Spatial Skills and Creating a Free Body Diagram

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Abstract
Spatial visualization is the ability to imagine what an object looks like from various viewpoints or after the object has been rotated in space or transformed in another way by some amount. Numerous studies have shown the link between spatial skills and success in engineering. But how do well-developed spatial skills contribute to engineering student success? In previous studies with elementary students, children with good spatial skills were able to create strategic sketches—sketches that accurately represented the problem and led to a correct answer. Poor visualizers drew non-strategic sketches—these were pictorial in style and did not lead to correct solutions. For example, when asked how many trees could be planted along a driveway that was 15 meters long if they were spaced every 5 meters, high visualizers drew a plan view of a line with an X spaced every 5 meters to arrive at the correct answer. Low visualizers drew a picture of a tree. In this paper, we report on a study to examine the link between spatial skills and the ability to solve problems from engineering mechanics. A total of 128 students from upper division engineering courses completed several tests of spatial skills and were also asked to solve 6 engineering mechanics problems. One of the six problems was merely to draw a free body diagram of a crane. In this paper, we examine the quality of the free body diagrams made by students to measure accuracy of the sketch, appropriateness of schematic representation and number and type of errors. How each of these factors relates to spatial ability will be reported along with examples of student work. This paper will illustrate the variation in approach to constructing free-body diagrams among students with low and high levels of spatial ability.

Background

Engineers are known problem-solvers. Through their rigorous education and subsequent practice, they learn to solve complex open-ended problems for the betterment of society. What is less well-known is that professional engineers are also great visualizers. In tests with more than 30,000 professionals [1], engineers demonstrated the highest level of spatial visualization skills, followed closely by architects and other STEM professionals. A more recent study shows a strong correlation between spatial visualization skills and creativity and technical innovation [2]. This leads to the hypothesis that undergraduate engineering degree programs should produce graduates with well-developed spatial skills if we are to produce engineers who are capable of solving the challenging and multidisciplinary problems our society faces.

In its recent report, *Preparing the Next Generation of STEM Innovators*, the National Science Board [3] makes the case for changing the way that we look for "STEM talent" going forward. After an exhaustive examination of available literature, they state that we have always looked for STEM talent among those who have high verbal and mathematics skills and that we should expand our search to include those with high spatial ability (see also Wai [4]), but they stop short of advocating for formal training in spatial thinking. The research cited by the NSB includes several correlational studies of the relation between STEM achievement and spatial skills—high STEM achievers tend to have high spatial skill levels.

It has been widely established that improving spatial skills among engineering education students has significant benefits for a variety of aspects of their study [5], [6]. A number of research studies have demonstrated significant gains in learning and higher retention and graduation rates among students within engineering following the implementation of a course designed to improve individuals' spatial competencies. In an extensive meta-analytic study, Uttal et al. [7] demonstrated that generally spatial skills training results in an improvement (equating to an effect size of 0.47) in spatial ability. This demonstrates that spatial skills can be effectively learned and have the potential to facilitate significant gains in learning within engineering [7].

A number of different spatial factors have been identified by various researchers such as Lohman [8] who proposed the existence of three different spatial factors, spatial visualization, spatial relations and spatial orientation. There have been a number of debates surrounding the specific nature of various spatial factors that have been proposed over the years. As a result, there is no agreement as to which specific factors constitute spatial ability [7]. However, there is general agreement that the factor of spatial visualization does constitute a significant component of spatial cognition [9], [10], [11]. A sub-factor of relevance to thinking in many scientific domains is *spatial visualization*, which is defined as the processes of apprehending, encoding, and mentally manipulating three- dimensional spatial forms [12]. Spatial visualization has also been found to correlate significantly with various other spatial factors such as spatial orientation [13]. Some spatial visualization tasks require the ability to predict the correspondence between three-dimensional forms and their two- dimensional representations. For example, inferring the shape and structure of a two- dimensional cross-section of a three-dimensional object requires spatial visualization skill. Focusing training efforts on the development of skills related to the spatial visualization factor has also been shown to transfer well to novel problems and other spatial processes [7]. Given that spatial visualization skills can be developed it is important to consider the various processes that can support spatial reasoning.

Research also links spatial skills to success in computer programming [14], [15]. Huang et al. [16] conducted functional Magnetic Resonance Imaging (fMRI) studies with computer science/software engineering students and found that data structure tasks share the same focal regions of the brain with mental rotation activities. More recently, Duffy et al [17] have found a link between spatial skills and success in solving mathematics word problems among engineering students. In this study, students were first given a test of spatial cognition and then asked to factor an equation to solve for x such as:

$$x^2 - 9x + 14 = 0$$

All students, regardless of spatial skill level, were able to solve this problem when presented in this format. Then students were given the following problem:

> You have a square lawn. You increase one side by 2 meters and the other side by 3 meters and you have doubled its area. What was the original size of the lawn?

When presented this way, the high visualizers could set up the equation ($2x^2=(x+3)*(x+2)$) and then solve for x. The low visualizers struggled to convert the words into an equation and thus were much less successful in solving this type of problem.

In statics education, the free body diagram (FBD) is recognized as an intermediate step for students to reduce cognitive load in the solution of problems [18]. With FBDs, students must isolate the body from its surroundings, replacing points of contact (supports) with forces and/or moments that are meant to represent the contribution of the support to the stability of the body.

This process of removing a body from its surroundings and replacing supports by reactions, is often viewed as the key kingpin in whether or not a student can solve the given problem correctly. In this study, we examined the link between a student's ability to correctly construct an FDB and his/her spatial skill levels, as measured by three different instruments.

Purpose/Research Questions

The purpose of this research was to examine the link between spatial skills and performance on a free body diagram problem for undergraduate engineering students. Specifically, this research aimed to answer the following:

Hypothesis 1: There is a statistically significant correlation between correctly drawing an FBD and high spatial skills.

Research Question 1: In what ways did undergraduate engineering students make errors when drawing FBDs?

Were these variations linked to spatial skills performance?

Methods

Setting and Participants

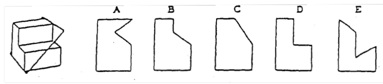
The research took place at the University of Cincinnati and the University of Nebraska-Lincoln. Participants were recruited through instructors who taught courses that required statics as a prerequisite. Students who had not passed their introductory statics course were excluded from the study. Over 140 students initially participated in the study. Demographics of the participants can be found in Table 1.

Table 1. Demographics of Participants (n = 143)

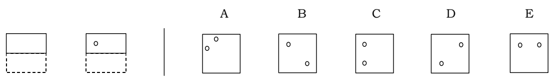
Variable	*n*
Male	92
Biomedical Engineering	15
Civil Engineering	26
Mechanical Engineering	59
Lower Classman (Year 1 & 2)	37

Data Collection

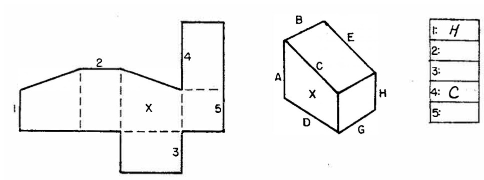
Data was collected over two phases during the Spring 2021 semester. During the first phase, an online survey was administered to participants via Qualtrics. The online survey consisted of three spatial tests (Mental Cutting Test (MCT), Folding Test (FT), and Surface Development Test (SDT)) and collection of demographic information (GPA, gender, degree program, etc). Figure 1 includes example problems from each of the spatial skills tests. [For the MCT, students were to identify the cross-section produced by slicing the object with the indicated plan. For the FT, students were presented with a series of pictures to the left of the vertical line showing a piece of paper as it is folded through subsequent folds. In a last step, a hole is punched in the paper and students are to identify what the paper would look like after it has been unfolded to its original shape. In the SDT, students are to fold up the given pattern and determine corresponding edges between the pattern and the object.]



MCT Example (Correct Answer D)



FT Example (Correct Answer C)



SDT Example (1:H, 2:B, 3:G, 4:C, 5:H)

Figure 1. Example Problems from Spatial Instruments

The second phase of data collection had a majority of the students completing an online survey while some students completed the survey in-person (this was done for purposes beyond the scope of this paper). Both groups of students were given the same survey. The second survey consisted of a fourth online spatial test, a verbal analogy test and six mechanics problems. The verbal analogy test was used as a proxy for general intelligence and consisted of 16 items. For example, one item from the verbal analogy test was:

Portion is to Dose as Food is to (a. rain, b. drug, c. dessert, d. amount)— correct answer is b. drug

The results reported here used data from the MCT, FT, SDT, demographics, and the FBD problem (one of the six mechanics problems students solved). Online participants were proctored on Zoom by the researchers where they were asked to leave their cameras on during the completion of the tests and surveys.

The FBD problem given to students is shown in Figure 2. This problem was deliberately selected since it is oriented vertically (compared to more standard horizontal beam problems). In selecting a unique orientation for the problem, we theorized that students who did not understand the fundamentals might have problems in orienting the load at the roller support.

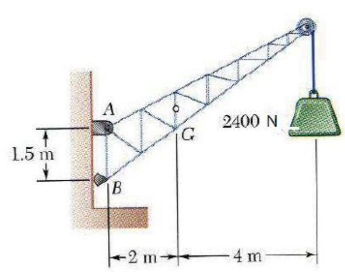


Figure 2. Crane Problem from Mechanics Test.
(Students were told the crane weighed 2000 N, located at G.)

Data Analysis

Descriptive statistics for each of the variables of interest were calculated. Spatial scores from the MCT, FT, and SDT were combined and a z score was calculated, since each of the tests had a varying number of points possible. The data for the three spatial ability measures were converted to z-scores before they were added together to create the Combined Spatial z score. Each spatial ability measure has a different range so adding them together as raw values would have brought an uneven weighting to each measure. Z score conversion was done in the standard way by first calculating the mean and standard deviation for each measure and using the following equation to convert each spatial ability score to a z score.

$$z = \frac{x - \mu}{\sigma}$$

where z = the z score

x = the raw spatial ability score

μ = the mean value for the spatial ability measure

σ = the standard deviation for the spatial ability measure

When converted to z scores, each new distribution has a mean of 0 and a standard deviation of 1. A participant with a z score of 0 is on the mean while a participant with a z score of 1 is 1 standard deviation above the mean and so on. By standardizing them first, the sum of the z-scores brought an equal weighting from each measure to the combined value along with the same mean and standard deviation.

Pearson correlations between the individual and combined spatial variables and verbal scores were calculated. Verbal scores were used to control for general intelligence. An independent-sample t-test was then used to determine if spatial scores between participants who got the FBD problem correct or incorrect differed.

In addition to marking the problems as either correct or incorrect (i.e., 1 or 0), the FBD problem solutions were all coded to determine common errors on the various features of the problem. The codes and their definitions can be found in Table 2. The codes were generated based on conventions in statics and mechanics that are vital characteristics of drawing a free body diagram. The codes were created to evaluate the question in consideration so that all possible methods of for FBD construction, correct or incorrect, were considered. For this particular problem, there were 12 individual codes identified by the researchers.

Table 2. Individual Codes Used in the Analysis

Code number	Description
1	Separate sketch created
2	Marks the supports as given
3	Pinned support marked correctly
4	Roller support marked correctly
5	Self-weight is clearly marked
6	Marked self-weight at C.O.G.
7	Vertical forces for load are labelled
8	Reaction forces for both supports are marked
9	Horizontal reaction at pinned support
10	Vertical reaction at pinned support
11	Horizontal reaction (perpendicular to roller support) at roller support (Correct)
12	Vertical reaction (parallel to roller support) at roller support (Incorrect)

Results

All statistical analyses of the data were performed using IBM SPSS Version 28.0.0.0. The sample size, minimum value, maximum value, mean, standard deviation and the result of the Shapiro-Wilk test for normality are presented in Table 3 for each of the variables for which data were collected or measured in this study.

Table 3. Descriptive statistics for each variable.

Variable	*n*	Min	*Max*	Mean	Std. Dev.	Normality[1]
GPA	139	2.50	4.00	3.6942	.31715	No
MCT	143	1	25	13.38	5.560	Yes
FT	143	3	20	14.97	3.326	No
SDT	143	9	60	46.50	12.789	No
Combined Spatial Z scores	143	-7.68	4.40	0	2.596	Yes
Verbal	128	0	16	10.29	2.575	Yes

[1] Shapiro Wilk test for normality

There was significant skew to the upper end of the range on the GPA, FT and SDT data and these distributions were found to be non-normal using the Shapiro-Wilk test. Data for the three spatial tests – MCT, FT and SDT – were converted to Z-scores and then added to create a combined Spatial Z-score. The MCT, Combined Spatial Z-score and Verbal data were found to be normally distributed using the Shapiro-Wilk test.

The magnitude and significance of the relationships between accuracy of the free-body diagram solutions and spatial ability and verbal ability were measured using the Pearson correlation with a two-tailed test of significance and these results are presented in Table 4. In this table, FBD Coded includes the correlations between the spatial/verbal tasks and a student's score out of 12 on the FBD problem and FBD Binary, signifies the correlations when student solutions were marked as either 0 or 1 (i.e., they scored a perfect 12 on the problem).

Table 4. Correlation Matrix Between Variables of Interest

	FT	SDT	Combined Spatial Z-scores	Verbal	FBD Coded	FBD Binary
MCT	.545**	.640**	.842**	.115	.061	.170*
FT		.686**	.859**	.152	.185*	.188*
SDT			.896**	.197*	.195*	.250**
Combined Spatial Z-scores				.179*	.170*	.234**
Verbal					.127	.165

**. Correlation is significant at the 0.01 level. *. Correlation is significant at the 0.05 level

The data were then grouped into those who correctly answered the FBD problem and those who did not and an independent samples t-test was conducted on the Combined Spatial Z-score and the Verbal measures. These results are presented in Table 5 along with a calculation of the effect size or magnitude of the difference between the two groups using Cohen's d. Effect size (Cohen's d) is a statistical analysis that is an indication of the magnitude of the difference between two groups. Statistical significance will only tell you if there is a difference; effect size (i.e., Cohen's d) will tell you how large the difference is. Generally, an effect size of 0.2 is considered to be small, 0.5 is considered to be medium, and 0.8 is considered to be large.

Table 5. Independent samples t-test grouped by FBD correct or incorrect

Test	FBD incorrect			FBD correct			t-test	Sig (2-tailed)	Cohen's d (Size)
	n	M	SD	n	M	SD			
Combined Spatial Z-scores	70	-.674	2.751	65	.555	2.358	-2.775	.006	.48
Verbal	60	9.83	2.631	64	10.69	2.525	-1.845	.068	.33

The results of these statistical analyses revealed performance on the FBD problem to be significantly correlated with spatial ability but not with verbal ability. The correlation with spatial ability is moderate – $r(141) = .170$, $p<.01$ for Combined Spatial Z-score to FBD Coded and $r(141) = .234$, $p<.01$ for Combined Spatial Z-score to FBD Binary. Of the three spatial tests, the SDT revealed the largest correlation with FBD Coded and FBD Binary.

The independent samples t-test is another way of looking at the same result, (Table 6) by dividing the sample into two independent groups – those who were correct and incorrect in solving the problem – and comparing the means and standard deviations of the spatial and verbal data for these two groups. No significant difference is found for the verbal data while a significant difference was found for the Combined Spatial Z-scores ($t(141)=-2.775$, $p<.01$) along with a moderate effect size.

Table 6. Sample grouped by FBD codes and means of Combined Spatial Z score compared using an independent samples t-test (n=113)

Code	Incorrect			Correct			t-test	Sig (2-tailed)	Cohen's d (Size)
	n	M	SD	n	M	SD			
Marks the supports as given	26	-0.896	2.429	89	0.325	2.571	-2.156	0.033	0.49
Pinned support	28	-0.770	2.587	87	0.313	2.537	-1.955	0.053	0.42
Marks self-weight at C.O.G.	21	-0.410	2.454	93	0.106	2.586	-0.833	0.407	0.20
Marks vertical forces for load	10	-0.827	2.182	104	0.091	2.588	-1.084	0.281	0.38
Horizontal reaction at pinned support	27	-0.523	2.586	87	0.177	2.543	-1.244	0.216	0.27
Vertical reaction at pinned support	29	-0.735	2.520	85	0.265	2.537	-1.835	0.069	0.40
Horizontal reaction (perpendicular to roller support) at roller support	26	-0.750	2.848	88	0.236	2.440	-1.740	0.085	0.37
No vertical reaction (parallel to roller support) at roller	9	-1.300	2.434	105	0.123	2.549	-1.613	0.110	0.57

Table 7 includes a list of the most common errors made by students in constructing their FBDs and Figures 3-6 show representative work from the student participants.

Table 7. Most frequent student errors

Description	Count
Incorrectly representing pinned support	30
Incorrectly representing roller support	33
Not marking self-weight at center of gravity	16
Not marking vertical load correctly	11
At least one reaction (vertical or horizontal) missing at pinned connection	30
Incorrectly marking a reaction at the roller support parallel to it	9
Missing normal reaction at roller support	27

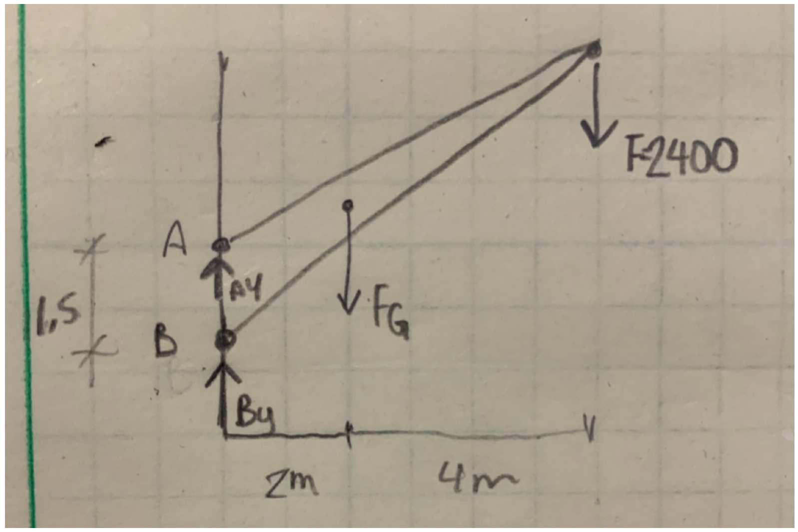


Figure 3. Example of Incorrect Reactions at Pin and Roller (Spatial Z score=1.55; Major=Civil Engineering; Year=Third)

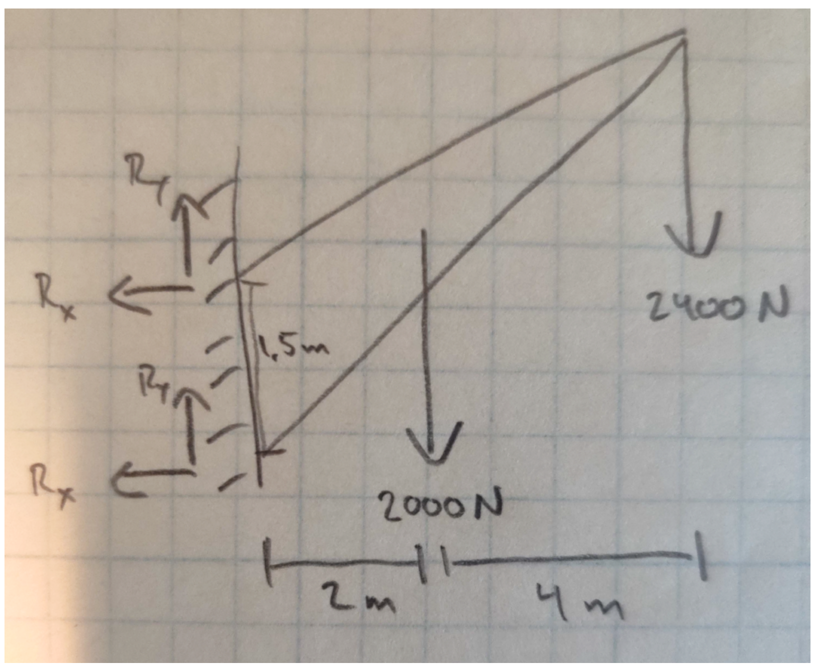


Figure 4. Example of Incorrect Reactions at the Roller only (Spatial Z score=2.18; Major=Aerospace; Year=Third)

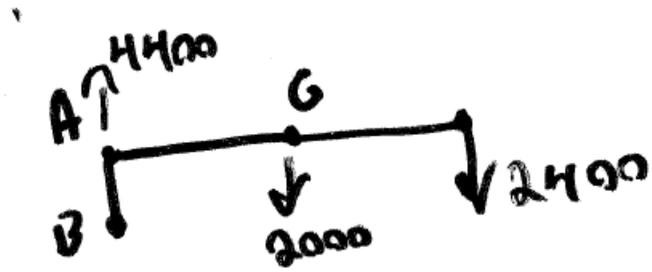


Figure 5. Example of Incorrect Representation by Idealizing the Crane as a Beam (Spatial Z score= -2.48; Major=Construction Management; Year=Third)

Discussion

From the data analyzed and presented in this paper, it appears that spatial skills play an important role in student production of FBDs (i.e., our hypothesis is validated). The significant correlations between the SDT and the spatial Z-score and whether or not a student got the FBD 100% correct (FBD Binary), demonstrate the strong relationship between spatial thinking and drawing FBDs. A correlation between verbal skills and skill in constructing an FBD was not found. If we use verbal scores as a proxy for general intelligence, then it appears that drawing correct FBDs are more closely related to spatial skill levels and not to general intelligence.

In response to our research questions, the most common errors students made in constructing the FBD was in correctly modeling the reactions at the two supports. Nearly one-third of the students did not correctly represent the reactions at the pin support and a full one-third did not represent the roller support correctly. In previous courses, in creating FBDs, students are most likely to have encountered a horizontal beam with pin and roller supports. In this “standard” beam configuration, the pin reaction might be understood to have X- and Y-components; however, in practice, the X-component is often zero (since all of the loads are typically in the vertical direction only), so students may be of the habit of thinking that a pin support only has one component of force. The tendency to view this problem as a beam, is best illustrated in Figure 5, where the crane was collapsed into a beam configuration by the student. For this problem, a solution would not be possible without two components of force at the pin connection.

Similarly, in the typical horizontal beam problem, the reaction at the roller is only in the vertical direction; for this problem, the reaction at the roller was in the horizontal direction. Figure 4 shows an example of student work where it appears that the student just put in X- and Y-components at both the pin and roller, not understanding the fundamental difference between the two types of reaction. Students who didn’t model the roller support correctly likely didn’t have a fundamental understanding that the reaction is always perpendicular to the member at the roller—it simply can’t support a force in the parallel direction. Thus, when the orientation of the problem is non-standard, students without a fundamental understanding of the concept of a roller support will likely get this incorrect. Figure 3, where the student represented the forces at each support as only vertical in direction, would tend to reinforce the notion that students are attempting to model this as if it were the “standard” horizontal beam they are familiar with from previous courses.

Although the correlation between spatial skills and a student's score on correctly drawing the FBD, when partial credit is given (FBD coded) is not as strong, it is still statistically significant. However, when each of the separate codes are analyzed individually, it does appear that there is a link between spatial skill levels and some of the aspects in drawing the FBD. Spatial skills appear to play a particularly strong role in whether or not a person is able to correctly model both reactions, but the roller reaction in particular. The largest effect size is in the difference between those who (correctly) did not include a vertical reaction at the roller and those who (incorrectly) included a vertical reaction there. The average Spatial Z-score for students who did this incorrectly was -1.3000, signifying that these students were nearly 1.5 standard deviations lower than the average Spatial Z-score for all students. The average Spatial Z-scores for students who got this correct was only slightly higher than average (Z-score average = 0.123).

Conclusions

Spatial skills appear to be a significant factor in students' ability to correctly draw FBDs in solving standard statics problems. In particular, it appears that spatial skills are critical in recognizing the orientation of reaction forces, in particular when the problem is presented in a non-standard vertical orientation. This work has implications in engineering education as we seek to improve student outcomes in basic problem-solving abilities. In engineering, we tend to stress mathematics and science understanding as the key to success for students. Spatial thinking skills are mostly overlooked when it comes to preparing students for success in engineering. This work reinforces the notion that spatial skills training may be a viable way to improve student success overall within their engineering programs. As an alternative to targeted spatial skills training, it may be necessary for faculty to scaffold learning in the creation of FBDs to help students visualize how bodies react in their surroundings, so that appropriate reaction forces are applied to the structure. Understanding that creating correct FBDs may be related to having well-developed spatial skills, faculty can tailor their instruction to include exercises that might improve spatial thinking as they are teaching their statics courses.

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