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# Exploring Innovative Methods for Dielectric Resonator Antenna Design with HFSS and Machine Learning Integration

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## ABSTRACT

The Dielectric Resonator Antenna (DRA) stands out as a distinctive antenna type, diverging from traditional metallic components by employing a dielectric resonator, which leverages the benefits of its high permittivity dielectric material. Functioning at precise frequencies, DRAs play diverse roles in microwave and millimeter-wave communication systems. Crafting and refining such antennas involves careful selection of dielectric materials, shaping the resonator, and fine-tuning for specific frequency characteristics. Central to the design and analysis of DRAs is the High-Frequency Structure Simulator (HFSS), which plays an essential role. Notably, the integration of machine learning-assisted optimization (MLAO) significantly streamlines this process. This study concentrates on designing cylindrical DRAs operating at 4 GHz using HFSS. Meticulously prepared datasets encompass output parameters like reflection coefficient, achieved by varying the height of CDRA from 5mm to 15mm. By employing various machine learning algorithms such as Support Vector Machine (SVM), Random Forest, Decision Tree Regression, and Gaussian Process Regression to enhance performance, the study conducts a comprehensive analysis to identify the most effective algorithm for accurately predicting antenna characteristics. Particularly noteworthy is the consistent 100% accuracy achieved by Decision Tree Regression, irrespective of variations in the antenna height. The study underscores the collaborative potential between electromagnetic simulation tools and advanced machine learning techniques in the realm of antenna engineering.

## Keywords

Antenna Engineering**,** Dielectric Resonator Antenna, High-Frequency Structure Simulator, Machine Learning-Assisted Optimization, Microwave Communication Systems.

## 1. INTRODUCTION

Integrating machine learning into antenna design [1] signifies a pioneering approach to enhance performance and streamline the process. By leveraging advanced algorithms, it enhances parameter optimization [2], pattern generation, automation, performance prediction, and anomaly detection. This fusion holds great potential for improving efficiency, accuracy, and innovation in crafting state-of-the-art antenna systems [3] across diverse applications.

The Cylindrical Dielectric Resonator Antenna (CDRA) stands out as a specialized type of dielectric resonator antennas (DRA), specifically designed for radio frequency applications [4]. Its cylindrical shape offers a compact and efficient solution, ideal for situations where space is limited. By utilizing a dielectric resonator with a high permittivity, the CDRA allows for precise tuning to specific frequency bands, making it well-suited for applications with targeted frequency requirements. Key characteristics of the CDRA include minimal radiation losses, potential Omni-directional radiation patterns, and resilience to environmental factors. The unique attributes of the CDRA make it a valuable component in various systems, including microwave, millimeter-wave communication, satellite communication, and radar systems.

Integrating machine learning with dielectric resonator antennas (DRAs) represents a significant advancement in antenna engineering. Through this integration, performance refinement, design process simplification, and efficiency enhancement across diverse applications are achieved. Optimizing parameters with machine learning algorithms [5] allows pinpointing optimal DRA configurations, resulting in improved efficiency, bandwidth, and radiation traits. Additionally, precise pattern generation empowered by machine learning enables tailored designs for specific needs such as beamforming or null steering.

Automation of tasks like geometry generation and simulation setup accelerates design iterations, facilitating tackling of intricate challenges. Moreover, machine learning assists in predicting performance and identifying anomalies, aiding in anticipating DRA behavior under varied conditions and detecting deviations from expected performance [6]. The fusion of machine learning with DRAs promises significant advancements in performance, efficiency, and reliability across multiple applications, from wireless communications to radar and sensing technologies. As machine learning progresses, it will play a pivotal role in driving innovation and shaping cutting-edge antenna systems.

The research approach aims to streamline the design process of the Dielectric Resonator Antenna (DRA), focusing on optimizing antenna parameters [7]. The objective is to develop an efficient system that enhances frequency response, broadens bandwidth, and maintains consistent performance for specific communication requirements, particularly at 4 GHz resonance. This involves exploring various resonator shapes, with a focus on the cylindrical design, to evaluate their impact on antenna efficiency and bandwidth.

The research goal is to identify the most accurate machine learning algorithms for predicting antenna parameters, reducing the need for multiple simulations and saving time and energy in creating high-quality antennas. By pinpointing the algorithm with the highest precision, the aim is to develop antennas with optimal dimensions in just one iteration, thereby enhancing efficiency and productivity in antenna design.

## 2. RELATED WORKS

Dielectric Resonator Antennas (DRAs) have gained attention for their compactness, efficiency, and frequency selectivity. With the increasing demand for high-performance antennas, researchers are turning to machine learning (ML) techniques to refine DRA design parameters.

In [8], Lin et al. (2021) utilized ML-assisted optimization to enhance DRA designs, showcasing how ML algorithms can improve antenna performance by effectively adjusting parameters like resonance frequency and bandwidth. Similarly, in [9], Wang et al. (2021) employed ML methods to optimize DRA designs, focusing on achieving broader frequency coverage. Their work demonstrated ML's ability to address design complexities and enhance antenna performance.

In [10], Pandey et al. (2020) explored ML's role in optimizing DRA parameters to meet specific communication requirements, resulting in improved efficiency and bandwidth. Additionally, in [11] Srinivasarao et al. (2019) investigated ML techniques for broadening the frequency range of DRAs, highlighting ML's effectiveness in enhancing antenna characteristics.

Furthermore, in [12] Nirmala et al. (2020) conducted research on optimizing DRA parameters using ML approaches such as neural networks and genetic algorithms, emphasizing ML's efficiency in navigating the design space and identifying optimal configurations.

These research endeavors highlight the increasing enthusiasm for utilizing ML techniques to improve DRA designs. They showcase the potential of ML-assisted optimization in enhancing DRA performance, expanding bandwidth, and boosting efficiency, thereby facilitating the advancement of sophisticated antenna systems across various communication domains.

The objective of this paper is to identify the most precise ML algorithms through the creation of dataset by designing a Cylindrical Dielectric Resonator Antenna (CDRA) using HFSS. This approach aims to surpass previous research efforts and achieve superior results in optimizing DRA designs.

## 3. METHODOLOGY

The typical structure of the Cylindrical Dielectric Resonator Antenna (CDRA) includes a cylindrical dielectric resonator situated above a ground plane. Constructed from a dielectric material possessing high permittivity, such as ceramics or polymers, the resonator is positioned vertically relative to the ground plane as shown in Figure 1. Excitation of the resonator can occur through either a feeding mechanism or direct coupling with a feeding structure [13]. The resonator's cylindrical form enables it to resonate at specific frequencies, rendering it suitable for a variety of communication applications. Moreover, the compact nature of the CDRA design allows for high efficiency and radiation performance, all within a minimal spatial footprint.

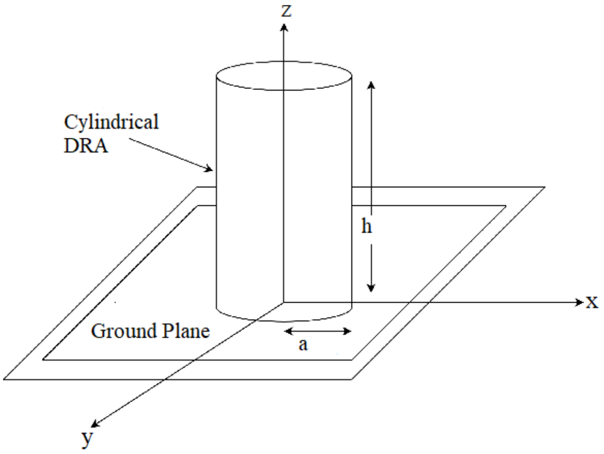

**Fig 1: Cylindrical Di-electric Resonator Antenna**

The resonance frequency of a cylindrical dielectric resonator antenna (CDRA) corresponds to the frequency at which the antenna effectively absorbs and emits electromagnetic waves [14]. This frequency is influenced by factors like the dimensions and material characteristics of the cylindrical dielectric resonator, including its radius, height, and relative permittivity. The resonant frequency of a CDRA in a hybrid mode of propagation can be determined using various mathematical expressions, which vary depending on the specific geometry and mode of resonance. One commonly used formula for calculating the resonant frequency of a CDRA in a hybrid mode of propagation is given by equation 1 as:

$$\mathrm{fr} = \frac{\mathrm{c}}{2\pi\,\mathrm{r}\,\sqrt{\varepsilon_{DRA}}}\left[1.71 + \left(\frac{\mathrm{r}}{\mathrm{h}}\right) + 0.1578\left(\frac{\mathrm{r}}{\mathrm{h}}\right)^2\right] \qquad (1)$$

where,

fr is Resonant frequency,

C is velocity of light,

$\varepsilon_{DRA}$ is permittivity of the dielectric material,

r is radius of resonator antenna,

h is height of resonator antenna.

When the antenna operates at its resonance frequency, the dielectric resonator responds most strongly to the electromagnetic field, resulting in optimal antenna performance. Therefore, precise adjustment of these parameters is essential to ensure resonance at the desired frequency, thus achieving optimal antenna functionality.

### 3.1 Antenna Design and Created Datasets

Designing a cylindrical dielectric resonator antenna (CDRA) using Ansoft HFSS software [15] demands meticulous attention to ensure optimal performance. The design process begins by defining the geometric properties of the cylindrical DRA, such as its dimensions and dielectric features, within the HFSS interface. These specific geometric parameters are outlined in the Table 1:

**Table 1. Geometric parameters of CDRA**

| Geometric Parameters | Values |
|---|---|
| Height of CDRA (h) | 10mm |
| Radius of CDRA (r) | 10mm |
| $\varepsilon_{DRA}$ | 9.9 |

Precise modeling of the dielectric resonator's shape and material attributes is essential to ensure the accuracy of the simulation. Additionally, defining boundary conditions and excitation sources is critical to capturing the antenna's real-world behavior accurately. The iterative process in HFSS permits engineers to refine the geometry and material properties of the dielectric resonator, allowing for optimization of antenna performance at targeted frequencies. By employing a systematic and thorough methodology in Ansoft HFSS, designers can effectively develop a custom cylindrical dielectric resonator antenna that meets specific requirements and performance standards.

The CDRA, which has been constructed based on the specified geometric parameters, is visually represented in Figure 2. The material employed is alumina ceramic, with a relative permittivity ($\varepsilon_r$) of 9.9. The CDRA is arranged in a compact manner, with both components positioned on a metallic ground [16] plane measuring 60 mm x 60 mm in height and width, respectively, reflecting the actual antenna dimensions.

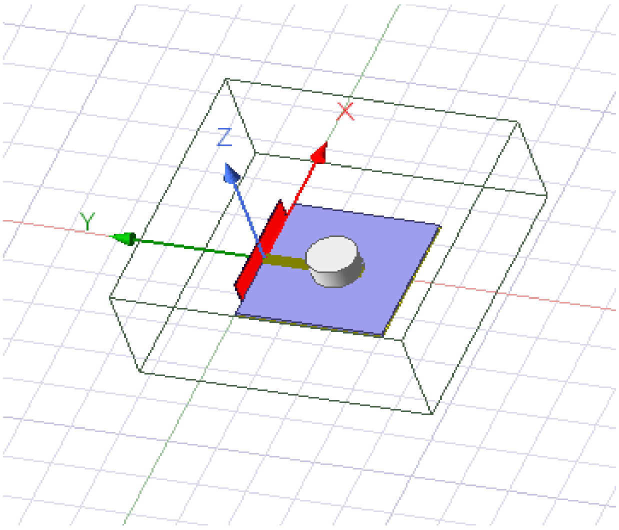

**Fig 2: Constructed Cylindrical Dielectric Resonator Antenna using Ansoft HFSS**

Following the configuration of the antenna with specified operating parameters such as frequency, height, length, and width, simulations are conducted using Ansys HFSS. Utilizing the sweep frequency technique, the antenna's performance is assessed by adjusting the height within the designated ranges. The resulting simulated data, including $S_{11}$ values, generates two distinct datasets corresponding to heights ranging from 5-10mm and 11-15mm. These datasets offer a comprehensive insight into the antenna's behavior across varied operational scenarios.

The dataset for the design of the cylindrical dielectric resonator antenna was meticulously compiled, accounting for two specific height ranges: 5-10mm and 11-15mm. Each set of $S_{11}$ values corresponds to different heights within these ranges, resulting in a comprehensive dataset comprising 456 rows. This dataset facilitates a thorough examination of $S_{11}$ values.

The sample dataset obtained by varying the height from 5mm to 10mm is presented in Table 2, while the sample dataset obtained by varying the height from 10mm to 15mm is presented in Table 3.

**Table 2. Sample Dataset of Dielectric Resonator Antenna with the height ranging from 5mm to 10mm**

| Operating frequency(GHz) | Height (mm) | Sweep frequency (GHz) | $S_{11}$ values (dB) |
|---|---|---|---|
| 4 | 5 | 3.5 | -0.7838 |
| 4 | 5 | 3.52 | -0.835293 |
| . | . | . | . |
| 4 | 6 | 3.6 | -1.128257 |
| 4 | 6 | 3.62 | -1.2322197 |
| . | . | . | . |
| 4 | 7 | 4.16 | -21.58735 |
| 4 | 7 | 4.18 | -19.24307 |
| . | . | . | . |
| 4 | 8 | 4.22 | -15.80444 |
| 4 | 8 | 4.24 | -14.55601 |
| . | . | . | . |
| 4 | 9 | 4.96 | -5.510006 |
| 4 | 9 | 4.98 | -5.427478 |
| . | . | . | . |
| 4 | 10 | 4.98 | -5.427478 |
| 4 | 10 | 5 | -5.344713 |

**Table 3. Sample Dataset of Dielectric Resonator Antenna with the height ranging from 10mm to 15mm**

| Operating frequency(GHz) | Height (mm) | Sweep frequency (GHz) | $S_{11}$ values (dB) |
|---|---|---|---|
| 4 | 11 | 3.56 | -0.961133 |
| 4 | 11 | 3.58 | -1.038614 |
| . | . | . | . |

| | | | |
|---|---|---|---|
| 4 | 12 | 4 | -11.38028 |
| 4 | 12 | 4.02 | -12.93709 |
| . | . | . | . |
| 4 | 13 | 4.26 | -13.52118 |
| 4 | 13 | 4.28 | -12.65032 |
| . | . | . | . |
| 4 | 14 | 4.3 | -11.90806 |
| 4 | 14 | 4.32 | -11.26869 |
| . | . | . | . |
| 4 | 15 | 4.94 | -5.592214 |
| 4 | 15 | 4.96 | -5.510006 |

These datasets are trained using various machine learning algorithms [17], such as Random Forest (RF), Decision Trees (DT), Support Vector Machines (SVM), and Gaussian Process Regression (GPR).

## 3.2 Machine Learning Algorithms

The optimization of Cylindrical Dielectric Resonator Antennas (CDRAs) in this research involves using multiple machine learning algorithms to improve their performance. These algorithms consist of the following:

### *3.2.1 Random Forest Regression*

Random Forest Regression (RFR), a machine learning algorithm, integrates principles from both random forests and regression techniques. It constructs multiple decision trees during training, and combines their predictions to enhance accuracy and reliability. Each tree is trained on a random subset of the data and features. Optimal utilization of Random Forest Regression involves adjusting parameters such as the number of trees, tree depth, and other hyperparameters to optimize model performance based on the dataset's unique attributes.

Random forest (RF) algorithms in antenna design use ensemble learning and regression tasks to build multiple decision trees during training and combine their predictions for accuracy and stability. In antenna design, RF predicts performance metrics like gain, efficiency, or impedance bandwidth by considering multiple input parameters simultaneously. RF models effectively address complex antenna optimization challenges by handling nonlinear relationships between antenna design parameters and performance metrics [18].

### *3.2.2 Support Vector Machine*

Support Vector Regression (SVR) is a machine learning approach derived from Support Vector Machines (SVM) and tailored for regression tasks. Unlike classification, where data points are categorized, SVR focuses on predicting continuous outputs. Its primary objective is to establish a hyperplane that effectively captures the relationship between input features and the continuous target variable. SVR proves advantageous in scenarios characterized by nonlinear relationships between features and the target variable, although achieving optimal performance requires careful selection of hyperparameters and kernel functions. SVM, commonly utilized in antenna design for pattern recognition and optimization, can classify different antenna types based on their radiation patterns or optimize antenna parameters [19] to meet specific performance criteria such as bandwidth or directivity.

### *3.2.3 Decision Tree Regression*

Decision Tree Regression, a supervised machine learning technique, is utilized for predicting continuous outcomes. It constructs a tree-like structure where internal nodes represent decisions based on specific features, while leaf nodes offer the predicted output. The algorithm strategically selects features to split the data at each node to maximize the reduction in variance or mean squared error. In Decision Tree Regression, predictions for new data points involve averaging the target values in the leaf node reached during traversal. This method is versatile, accommodating both simple and complex regression tasks, though careful parameter tuning is necessary to prevent overfitting and ensure optimal performance.

In antenna design, Decision Trees serve for both classification and regression tasks, aiding in decisions regarding antenna parameters like dimensions, materials, and configurations. These algorithms can analyze various antenna features and classify them based on performance characteristics [20] such as frequency response, gain, and impedance matching.

### *3.2.4 Gaussian Process Regression*

Gaussian Process Regression (GPR) is a Bayesian machine learning method designed for regression tasks, characterized by its non-parametric nature. Unlike traditional regression techniques, GPR defines a distribution over functions rather than relying on a single deterministic function, offering a versatile representation of functions. This flexibility proves beneficial in scenarios with intricate or unknown underlying relationships, where GPR excels in quantifying uncertainty, particularly in cases of limited data availability. However, its computational complexity poses challenges, especially when dealing with large datasets. In antenna design, GPR is employed to model complex relationships between antenna parameters and performance metrics, enabling prediction of antenna behavior [21] based on limited experimental data and facilitating efficient exploration and optimization of antenna configurations.

These algorithms examine the correlation between input parameters like antenna dimensions, materials, and configurations, and output metrics such as reflection coefficient to forecast the precision of CDRA performance. Through simultaneous consideration of multiple factors, these methods aid in refining CDRA designs to attain targeted performance attributes.

## 4. RESULTS AND DISCUSSIONS

The Cylindrical Dielectric Resonator Antenna is designed to operate at a frequency of 4GHz using HFSS software, and after configuring it with specific parameters such as height, length, and width, simulations were performed. The analysis involved varying the antenna height between 5-10mm and 11-15mm using sweep frequency techniques, resulting in two datasets of $S_{11}$ values shown in Tables 1 and 2. These datasets, totaling 456 rows, provide detailed insights into the antenna's behavior under different conditions.

Subsequently, these datasets were used to train several machine learning algorithms—Random Forest (RF), Decision Trees

(DT), Gaussian Process Regression (GPR), and Support Vector Machines (SVM). The objective was to assess the effectiveness of each algorithm in optimizing CDRA design across the 4GHz frequency range. The accuracy achieved by these algorithms, after training on the datasets, is summarized in Table 4. This evaluation helps to determine the most suitable approach for optimizing CDRA designs and achieving desired performance metrics.

**Table 4. predicted accuracy values of different algorithms for CDRA**

| **Machine learning algorithms** | **Accuracy (%)** | |
|---|---|---|
| | **CDRA height (5mm – 10mm)** | **CDRA height (10mm – 15mm)** |
| Random forest Regression | 100% | 99% |
| Support Vector Regression | 39% | 21% |
| Decision Tree Regression | 100% | 100% |
| Gaussian Process Regression | 14% | 99% |

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For antenna heights ranging from 5mm to 10mm, the machine learning algorithm accuracies are as follows: Random Forest Regression achieves 100% accuracy, Support Vector Regression yields 39%, Decision Tree Regression reaches 100%, and Gaussian Progression Regression results in 14%. Meanwhile, for antenna heights between 11mm and 15mm, the corresponding accuracies are: Random Forest Regression with 99% accuracy, Support Vector Regression at 21%, Decision Tree Regression scoring 100%, and Gaussian Progression Regression with 99% accuracy.

A decision tree regression graph visually represents the division of input parameters by a decision tree algorithm to predict S11 values for a CDRA design. It shows the algorithm's prediction process based on different parameters. Figure 3 and 4 display decision tree regression graphs for Dataset 1 and Dataset 2, respectively, demonstrating this process clearly.

From Figure 5 and 6 it is evident that the model exhibits perfect fit to the data, as each data point aligns precisely with the predicted values on the graph. This indicates that the decision tree has accurately captured all underlying patterns and relationships in the dataset. Achieving 100% accuracy means there are no prediction errors; every predicted value matches the actual value exactly. This suggests that the decision tree has segmented the data in a way that precisely reflects parameter values across the sweep frequency.

The graph from Figure 3 and 4 shows distinct, sharp transitions and clear separations at specific sweep frequency values, characteristic of decision tree models. These transitions indicate that the model has identified well-defined segments in the sweep frequency that correspond to specific parameter values.

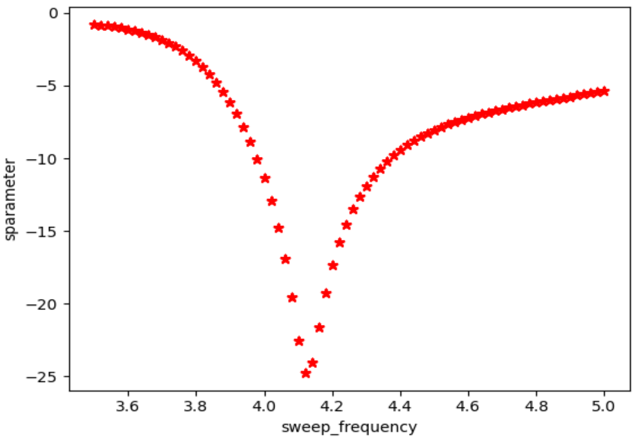

**Fig 3: Decision Tree Regression Analysis for Dataset 1 (5mm-10mm)**

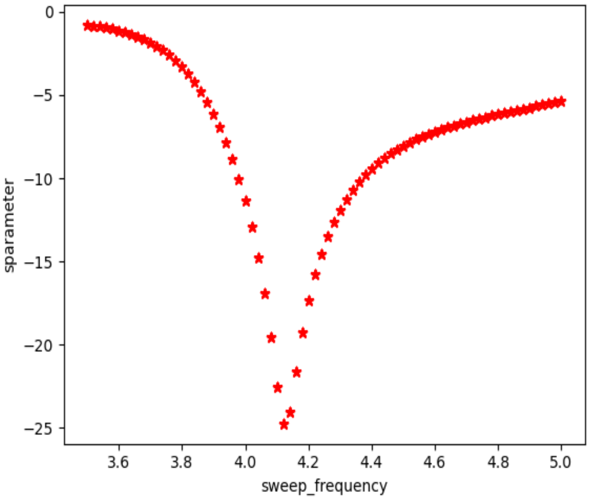

**Fig 4: Decision Tree Regression Analysis for Dataset 2 (10mm-15mm)**

The U-shaped pattern observed in the graph from Figure 3 and 4, especially with a pronounced minimum around 4.2 sweep frequency, illustrates that the model has effectively captured the complex, non-linear relationship between sweep frequency and the parameter.

The Decision Tree Regression model achieves 100% accuracy by fitting the dataset perfectly, as evidenced by the exact alignment of data points with the model's predictions in the graphs. This highlights the model's ability to discern intricate patterns in the data without inaccuracies.

Decision Tree Regression proves to be the most effective model for the designed CDRA, achieving the highest accuracy across various antenna height ranges with 100% accuracy in both instances. Its adaptability in handling complex regression tasks and analyzing diverse antenna features makes it the optimal choice for optimizing CDRA performance. Consequently, Decision Tree Regression emerges as the preferred model for accurately predicting and optimizing CDRA parameters.

## 5. CONCLUSION

In this research, exploration focused on various machine learning algorithms to optimize Cylindrical Dielectric Resonator Antennas (CDRAs). Through implementation of

Random Forest Regression, Support Vector Regression, Decision Tree Regression, and Gaussian Process Regression, effectiveness in predicting CDRA parameters across diverse antenna height ranges was evaluated. Findings reveal that Decision Tree Regression consistently attained highest accuracy, achieving 100% precision for both height intervals, namely 5mm to 10mm and 11mm to 15mm. This underscores suitability of Decision Tree Regression for accurately forecasting and enhancing CDRA performance. Nonetheless, future studies could delve into additional factors impacting CDRA optimization and explore alternative machine learning methodologies to further refine performance prediction and design optimization. In essence, investigation contributes to advancement of CDRA design approaches and underscores efficacy of machine learning algorithms in antenna engineering practices.

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