



# CURVE-FITTING-BASED FIR FILTER DESIGN FOR STOP-BAND ATTENUATION PERFORMANCE IMPROVEMENT

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## ABSTRACT

Finite impulse response (FIR) filters are widely used in signal processing due to their inherent stability, linear-phase property, and implementation robustness. However, achieving high stopband attenuation with a limited filter order and a steep attenuation slope remains challenging. This paper presents a curve-fitting-based FIR filter design method aimed at enhancing stopband attenuation performance. The proposed approach employs curve fitting to estimate the optimal parameters of a General Gauss1 model by fitting its functional form to a given impulse-response shape. The resulting mathematical model is then used to compute new FIR coefficients that enforce a smooth impulse-response profile, effectively suppressing oscillatory sidelobes. Consequently, the magnitude response exhibits a monotonic decay and an improved attenuation slope in the stopband. MATLAB simulation results confirm the effectiveness of the proposed method, demonstrating significant stopband attenuation enhancement without increasing the filter order.



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## I. INTRODUCTION

Finite Impulse Response (FIR) filters are fundamental components in modern signal processing, prized for their inherent stability, linear-phase characteristics, and straightforward implementation. They are extensively used in diverse applications, including communications, audio and speech processing, biomedical signal analysis, and control systems, where precise frequency shaping is essential [1-5]. FIR filters offer key advantages, including predictable phase response, robustness to coefficient quantization, and flexible design options [6],[7]. However, achieving high stopband attenuation with a limited filter order remains a persistent challenge, often requiring more coefficients and increasing computational complexity. Therefore, the design of FIR filters that effectively control the shape of the impulse response coefficients to minimize side lobe oscillations while maintaining the desired frequency response remains a critical research problem.

Numerous FIR filter design techniques have been suggested to address the trade-off between filter order, stopband attenuation, and side-lobe behavior. Classical window-based methods, including Hamming, Hanning, and Blackman windows [8], as well as the Kaiser window [9] and Gaussian basis representations [10], are widely adopted due to their simplicity and low computational cost; however, they offer limited flexibility in controlling stopband ripple and transition bandwidth. Frequency-sampling and Fourier-series-based approaches provide direct control over frequency characteristics but may introduce significant ripple effects [11]. Optimization-based techniques, including equiripple (Parks-McClellan) and least-squares methods [12], offer improved stopband attenuation and sharper transition bands, yet they often involve higher computational complexity and may still produce undesired oscillations in the impulse response.

More recently, advanced optimization frameworks have been developed to enhance FIR filter performance [13]. Among these, sparsity-promoting convex optimization techniques combine  $\ell_2$ -norm frequency-response error metrics with  $\ell_1$ -norm regularization to reduce filter order while preserving stringent passband ripple and transition-band specifications, enabling hardware-efficient implementations over classical window-based and Parks-McClellan designs [14]. In parallel, multi-objective evolutionary algorithms (MOEAs) have been applied to simultaneously optimize conflicting criteria such as side-lobe level and computational cost, yielding improved Pareto-optimal solutions compared to single-objective approaches [15].

Building on these developments, meta-heuristic and evolutionary algorithms have emerged as powerful tools for FIR filter design [16], with methods such as genetic algorithms (GA), particle swarm optimization (PSO), cuckoo search optimization (CSO), and Gray Wolf Optimization (GWO) demonstrating improved stopband attenuation, reduced passband ripple, and enhanced coefficient shaping. Notably, a hybrid sparse PSO (HSPSO) has achieved lower cost and execution time than conventional PSO variants while improving spectral performance for low-pass FIR filters [17]. GWO-based designs have shown faster convergence and superior performance compared to GA, PSO, and CSO [18], further enhanced through hybrid GWO–CSO schemes [19]. Additional improvements have been reported using CSA and Grasshopper Optimization (GOA) with LMS and  $\ell_1$ -norm error criteria for linear-phase FIR filters [20], as well as Brain Storm–Grey Wolf Optimizer (BSGWO) approaches that significantly improve stopband attenuation over conventional heuristic and analytical methods [21].

Machine learning-assisted FIR design has also emerged as a promising direction, in which filter coefficients are directly learned from noisy data, with effectiveness demonstrated through speech and music separation despite significant spectral overlap [22]. Another emerging trend is the use of fractional-order and adjustable window functions, such as the fractional Kaiser window, which has been shown to improve spectral performance and enhance stopband attenuation in FIR filter design compared with the conventional Kaiser window [23]. Although these recent approaches achieve notable improvements, challenges related to convergence reliability, computational complexity, and practical implementation persist.

All in all, despite these extensive efforts, achieving a well-controlled impulse-response shape with reduced side-lobe oscillations, high stopband attenuation, and a low computational burden remains an open challenge, motivating the pursuit of more effective FIR filter design methodologies.

In this regard, the present paper proposes a novel FIR filter design approach that enhances stopband attenuation by explicitly controlling the shape of the impulse-response coefficients while preserving linear-phase characteristics and a moderate filter order. The proposed approach incorporates a curve-fitting-based strategy to smooth and regulate the impulse-response coefficients, thereby suppressing side-lobe oscillations and improving frequency selectivity without increasing computational complexity. The main contributions of this paper are summarized as follows:

- A new FIR filter design framework is introduced that focuses on direct impulse-response coefficient shaping to achieve improved stopband attenuation.
- A curve-fitting-based technique is introduced to regulate the impulse-response coefficients, effectively reducing side-lobe oscillations while maintaining the desired frequency response.
- The proposed method achieves a steeper attenuation slope and enhanced stopband performance compared with conventional window-based and optimization-based FIR design approaches.
- Extensive simulation results demonstrate that the proposed design yields lower side-lobe levels, improved frequency selectivity, and competitive computational complexity.

The paper's remainder is structured as follows. Section 2 provides a description and mathematical formulation of the FIR filters. Section 3 describes the proposed approach for FIR filter design using curve fitting. Section 4 evaluates the performance of the proposed FIR design approach. Section 6 concludes the paper's findings.

## II. FIR FILTERS

FIR filters are stable digital filters that depend only on a finite number of input samples. They can achieve exact linear-phase characteristics by using symmetric coefficients and widely used due to their robustness and predictable behavior. According to the FIR filter's architecture illustrated in Figure 1, the transfer function for the  $N$ -tap FIR filter is given by:

$$H(z) = \sum_{n=0}^{N-1} h(n)z^{-n} \quad (1)$$

where  $h(n)$  denotes the filter impulse response coefficients, and  $N$  is the filter length.

Considering (1), the discrete-time frequency and magnitude responses of the  $N$ -tap FIR filter are obtained as:

$$H(e^{j\omega}) = \sum_{n=0}^{N-1} h(n) e^{-j\omega n} \quad (2)$$

$$|H(e^{j\omega})| = \sum_{n=0}^{N-1} |h(n) e^{-j\omega n}| \quad (3)$$

One of the key challenges in FIR filter design is controlling the shape of the impulse-response coefficients  $h(n)$  to reduce side lobe oscillations. When the coefficients are non-smooth or vary abruptly, stop-band ripples increase, attenuation is reduced, and the filter's ability to reject unwanted frequencies is compromised. These effects are especially pronounced when the filter order is limited, as oscillations in the transition band lead to a less predictable frequency response and degraded selectivity and spectral purity.

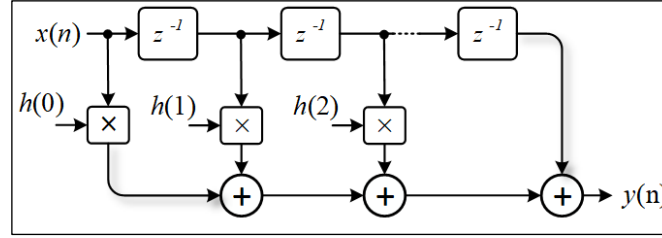


Figure 1: General architecture of a FIR filter.  
Source: Author, (2026).

In such an FIR filter, abrupt or non-smooth coefficients  $h(n)$  increase stop-band ripples and reduce attenuation, degrading the filter's ability to reject unwanted frequencies, particularly in low-order designs. This limitation motivates approximating  $h(n)$  with a smooth, symmetric General Gauss1 model using curve fitting, enabling controlled coefficient shaping and improved stopband performance without increasing the filter order.

### III. PROPOSED CURVE FITTING - BASED FIR FILTER DESIGN

The proposed method introduces a curve-fitting-based FIR filter design framework designed to enhance stop-band attenuation by shaping the impulse response. Instead of directly approximating a desired frequency response, the method defines a smooth target impulse response profile using a General Gauss1 model. The model parameters are then estimated by fitting its functional form to a given impulse-response shape, and the resulting representation is used to generate a new set of FIR coefficients with a smooth and symmetric profile, effectively suppressing oscillatory side lobes. This approach achieves monotonic decay and a steeper attenuation slope in the stop-band, improving stopband performance without increasing the filter order.

The overall design procedure is summarized as follows:

- Initial FIR coefficients: Start with selecting filter order ( $N = 21$  and  $N = 9$ ), and a preliminary set of low-order FIR coefficients  $h(n)$ , given in the simulation section.
- Define target model: The desired smooth impulse-response profile is defined using the General Gauss1 model expressed as:

$$f_g(x) = a_1 \exp\left(-\left(\frac{x - b_1}{c_1}\right)^2\right) \quad (4)$$

where  $a_1$  is the magnitude,  $b_1$  is the center, and  $c_1$  is a parameter that controls the width of the Gaussian. These are the unknown parameters of the Gauss1 model to be estimated. The General Gauss1 model is adopted due to its inherent smoothness, symmetry, and parameter efficiency, enabling effective FIR impulse-response shaping with monotonic side lobe decay, improved stopband attenuation, and preserved linear-phase characteristics. Curve fitting: The curve fitting is applied to estimate the parameters of the General Gauss1 model. The Gaussian parameters,  $a_1$ ,  $b_1$ , and  $c_1$  are estimated by minimizing the sum of squared errors between the model and the given FIR coefficients. Accordingly, the expression of the objective function to be minimized is defined as follows:

$$Obj_f(a_1, b_1, c_1) = \sum_{n=0}^{N-1} [h(n) - f_g(n)]^2 \quad (5)$$

- Generate new FIR coefficients: The new FIR coefficients are computed using the fitted model based on the following expression:

$$h_{new}(n) = a_1 \exp\left(-\left(\frac{n - b_1}{c_1}\right)^2\right) \quad (6)$$

The flowchart of the proposed design approach is depicted in Figure 2.

### IV. SIMULATION RESULTS AND DISCUSSIONS

To validate the effectiveness of the proposed curve-fitting-based FIR filter design, simulations are carried out in the MATLAB environment. The performance of the developed FIR filter is compared with that of a conventionally designed FIR filter for two filter orders,  $N = 21$  and  $N = 9$ . The estimated parameters of the General Gauss1 model for both filter orders are listed in Table 1. The coefficient values of the conventional FIR filter and the proposed curve-fitting-based FIR filter are reported in Tables 2 and 3, respectively, for  $N = 21$  and  $N = 9$ . In addition, Figures 3 and 4 illustrate the corresponding plots of the impulse-response coefficients,  $h(n)$  and  $h_{new}(n)$ , and their frequency responses for the conventional and proposed design approaches at both filter orders. According to the results illustrated in Figures 3 and 4, the following observation can be made. For  $N = 21$ , the conventional FIR coefficients exhibit noticeable oscillations and alternating signs away from the center tap.

These abrupt variations generate pronounced side lobes in the impulse response, leading to ripples in the stopband and limited high-frequency attenuation. From the magnitude response shown in Figure 3(a), the stopband attenuation of the conventional design is approximately -45 dB to -50 dB at higher frequencies. In contrast, the proposed curve-fitting-based FIR coefficients form a smooth, bell-shaped envelope, strictly monotonic and centered around the main coefficient value. As seen in Figure 3(b), the impulse response decays gradually toward the edges without sign alternation, effectively suppressing side lobe oscillations.

This results in a smoother magnitude response with a significantly enhanced stopband attenuation of approximately -70 dB to -75 dB, representing an improvement of roughly 20–25 dB over the conventional design.

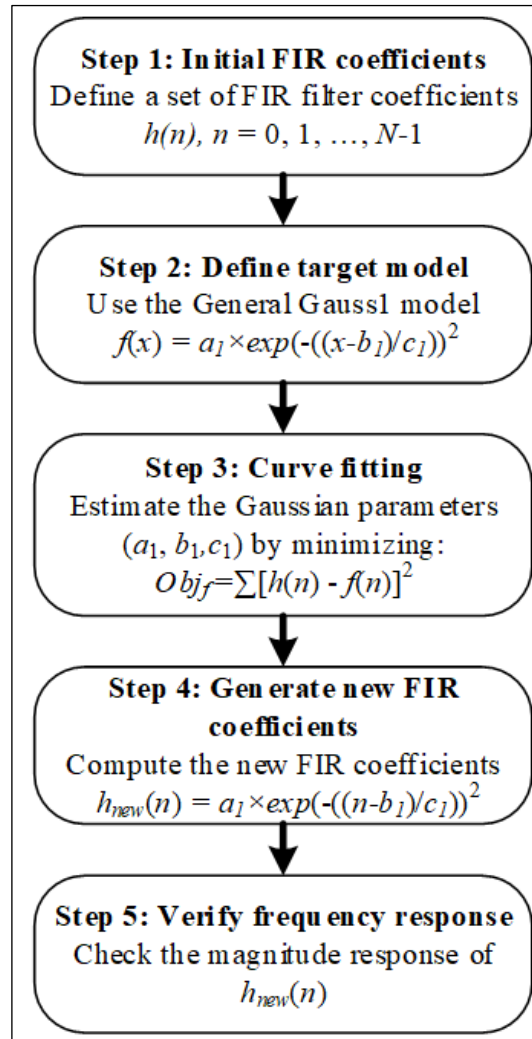


Figure 2: Flowchart of the proposed curve fitting-based FIR filter design procedure.

Source: Author, (2026).

For the low-order case,  $N = 9$ , the difference is even more significant. The conventional FIR filter shows relatively poor stopband rejection, with attenuation limited to about -30 dB to -35 dB, accompanied by strong oscillatory behavior in the impulse response as depicted in Figure 4(a). By contrast, the proposed curve-fitting approach produces a smooth, symmetric, Gaussian-like impulse response, with reduced edge coefficients and no abrupt variations, as shown in Figure 4(b). This controlled shaping translates into a magnitude response with stopband attenuation improved to approximately -55 dB to -60 dB, yielding a gain of roughly 20-25 dB, even under the severe constraint of low filter order. These numerical results demonstrate that the proposed General Gauss1-based curve-fitting approach consistently produces smoother and more regular FIR coefficients, which in turn enhance the stopband performance of the filter while preserving the same order. The improvement is particularly noticeable for low-order filters, where conventional designs are more sensitive to coefficient irregularities.

Table 1: Values of the General Gauss1 model estimated parameters for  $N = 21$  and  $N = 9$ .

| $N = 21$           |                |                   | $N = 9$            |                    |                    |
|--------------------|----------------|-------------------|--------------------|--------------------|--------------------|
| $a_1$              | $b_1$          | $c_1$             | $a_1$              | $b_1$              | $c_1$              |
| $0.3177 \pm 0,052$ | $10 \pm 0,280$ | $2.098 \pm 0,398$ | $0.3168 \pm 0,063$ | $0.3177 \pm 0,345$ | $0.3177 \pm 0,489$ |

Source: Author, (2026).

Table 2: Coefficients of the conventional and the designed FIR filter for  $N = 21$ .

| $n$ | Conventional FIR filter coefficients $h(n)$ | Designed FIR filter coefficients $h_{new}(n)$ |
|-----|---------------------------------------------|-----------------------------------------------|
| 0   | 0.0000000000000000                          | 0.000000000043541                             |
| 1   | 0.022891722130346                           | 0.000000003257592                             |
| 2   | 0.031781747161123                           | 0.000000154750541                             |

|    |                    |                   |
|----|--------------------|-------------------|
| 3  | 0.012308543211308  | 0.000004667718502 |
| 4  | -0.028311298354120 | 0.000089395187882 |
| 5  | -0.059555097489784 | 0.001087077803989 |
| 6  | -0.044829510979983 | 0.008393519769655 |
| 7  | 0.032016577306810  | 0.041149504435216 |
| 8  | 0.149776860419765  | 0.128092028531522 |
| 9  | 0.256840881845008  | 0.253172540638379 |
| 10 | 0.300000000000000  | 0.317722593312595 |
| 11 | 0.256840881845008  | 0.253172540658571 |
| 12 | 0.149776860419765  | 0.128092028551954 |
| 13 | 0.032016577306810  | 0.041149504445062 |
| 14 | -0.044829510979983 | 0.008393519772333 |
| 15 | -0.059555097489784 | 0.001087077804423 |
| 16 | -0.028311298354120 | 0.000089395187925 |
| 17 | 0.012308543211308  | 0.000004667718504 |
| 18 | 0.031781747161123  | 0.000000154750541 |
| 19 | 0.022891722130346  | 0.000000003257592 |
| 20 | 0.000000000000000  | 0.00000000043541  |

Source: Author, (2026).

Table 3: Coefficients of the conventional and the designed FIR filter for  $N = 9$ .

| $n$ | Conventional FIR filter coefficients $h(n)$ | Designed FIR filter coefficients $h_{new}(n)$ |
|-----|---------------------------------------------|-----------------------------------------------|
| 0   | -0.044829510979983                          | 0.008778702962381                             |
| 1   | 0.032016577306810                           | 0.042150255313100                             |
| 2   | 0.149776860419765                           | 0.129268575562083                             |
| 3   | 0.256840881845008                           | 0.253226186912343                             |
| 4   | 0.300000000000000                           | 0.316845224700316                             |
| 5   | 0.256840881845008                           | 0.253226186816267                             |
| 6   | 0.149776860419765                           | 0.129268575463992                             |
| 7   | 0.032016577306810                           | 0.042150255265124                             |
| 8   | -0.044829510979983                          | 0.008778702949059                             |

Source: Author, (2026).

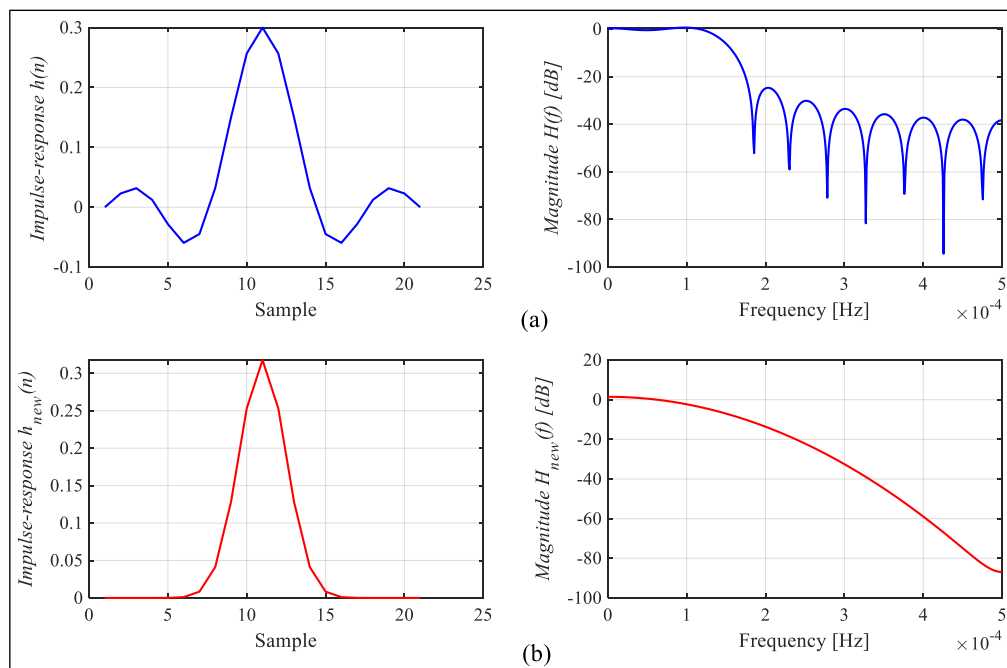


Figure 3: Impulse-response coefficients and their frequency responses for both design methods for  $N = 21$ .

Source: Author, (2026).

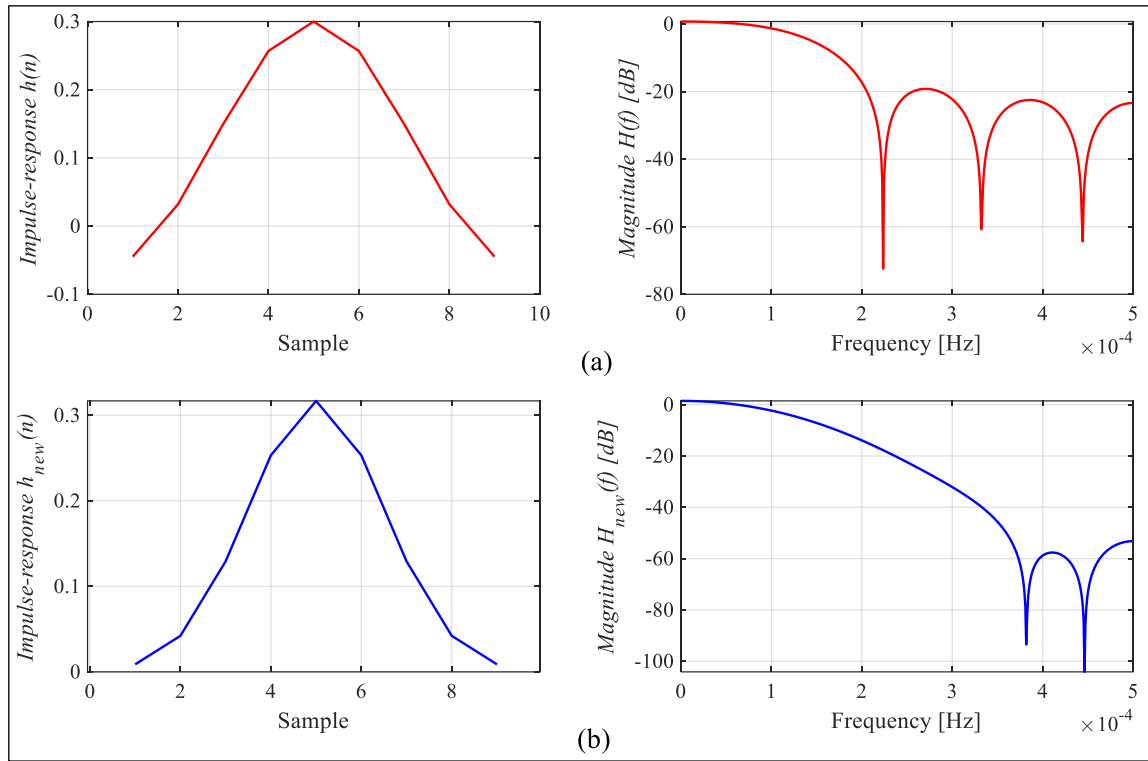


Figure 4: Impulse-response coefficients and their frequency responses for both design methods for  $N = 9$ .  
Source: Author, (2026).

## V. CONCLUSIONS

This paper presented a curve-fitting-based FIR filter design approach aimed at improving stopband attenuation under limited filter order constraints. By approximating the impulse-response coefficients using a smooth and symmetric General Gauss1 model, the proposed method enables controlled shaping of the FIR coefficients while preserving the inherent linear-phase property. Unlike conventional FIR designs, which often exhibit abrupt coefficient variations leading to side lobe oscillations and elevated stopband ripples, the proposed approach effectively suppresses these effects through smooth impulse-response modeling. Simulation results for low-order filters, with  $N = 21$  and  $N = 9$ , demonstrate a monotonic decay of the magnitude response and a steeper stopband attenuation slope.

In particular, the proposed design achieves an improvement in high-frequency stopband attenuation of approximately 20-25 dB compared to the conventional FIR filter. The findings confirm the effectiveness of the proposed framework for enhancing stopband performance in low-order FIR filter designs. Future work will focus on enhancing the parameter estimation stage by incorporating recent optimization algorithms, such as metaheuristic and hybrid optimization techniques, to further improve the accuracy and adaptability of the General Gauss1 model fitting.

## VI. AUTHOR'S CONTRIBUTION

**Conceptualization:** Raouf Amrane.

**Methodology:** Raouf Amrane.

**Investigation:** Raouf Amrane.

**Discussion of results:** Raouf Amrane.

**Writing – Original Draft:** Raouf Amrane.

**Writing – Review and Editing:** Raouf Amrane.

**Resources:** Raouf Amrane.

**Supervision:** Raouf Amrane.

**Approval of the final text:** Raouf Amrane.

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