Acoustic Secret Sharing: Implementing Visual Cryptography Concepts via Phase Cancellation in Audio Signals

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***Abstract*—This paper presents a (2, 2) secret sharing scheme for audio signals that extends the foundational concepts of visual cryptography into the acoustic domain. Traditional visual cryptography relies on human optical fusion to decode hidden textual or graphical assets without computational overhead. Paralleling this paradigm, our proposed system decomposes a secret mono voice recording into two independent audio shares consisting entirely of masking noise. Individually, each share exhibits zero algorithmic leakage and sounds like absolute static to a listener. However, by executing a precise 180° phase inversion on the masking noise vector of the second share, digital or physical linear summation forces the destructive interference of the noise components. This cancellation dynamically isolates and reconstructs the secret message with flawless mathematical fidelity (*r = 1.000000*). Empirical evaluations highlight a critical trade-off between algorithmic confidentiality and human psychoacoustic perception, establishing specific signal thresholds required to fully mask speech cadence. Furthermore, robustness testing demonstrates that lossy compression algorithms disrupt high-frequency phase alignment, transforming this vulnerability into a built-in fragile tampering detection feature.**

Keywords—Acoustic Secret Sharing, Visual Cryptography, Phase Cancellation, Destructive Interference, Psychoacoustics, Sound Wave Superposition.

I. Introduction

In modern secure communications, secret sharing schemes serve as a vital cryptographic mechanism to split a sensitive data asset into multiple fragments, known as shares, which must be recombined under a specific threshold to reconstruct the original information. The most famous abstraction of this principle is Naor and Shamir's visual cryptography scheme, which enables the decryption of split visual images through the direct stacking of physical transparency sheets, bypassing the need for computational processors or cryptographic keys.

While visual steganography and visual secret sharing have been rigorously analyzed, expanding these physical-layer stacking properties into audio waveforms presents a unique signal processing challenge. Sound propagation is fundamentally governed by the physics of wave superposition, where overlapping pressure fields combine linearly in a given medium. This paper introduces a rapid-response implementation of an Acoustic Secret Sharing framework that leverages destructive phase cancellation to emulate visual cryptography. By dividing a secret audio track *M(t)* into two shares that incorporate an identical, phase-inverted noise floor *N(t)*, we construct an architecture where individual shares leak zero information. Yet, when combined, the shares achieve instantaneous computational or acoustic decryption.

The primary contributions of this work include:

- The design and realization of a unified global scaling pipeline that achieves lossless array reconstruction in the digital float domain.
- An empirical investigation into the limits of psychoacoustic masking and human pattern recognition under variable noise factors.
- A structural analysis of phase sensitivity under lossy compression transformations and microsecond timing shifts.

II. Related Work & Fundamental Theories

A. Visual Cryptography Foundations

The bedrock of threshold secret sharing was laid concurrently by Adi Shamir, with the introduction of polynomial interpolation schemes, and by Naor and Shamir (1994) through visual cryptography. In a basic (2, 2) visual cryptographic model, a binary image is split into two sub-pixel arrays. An isolated array appears entirely random, possessing a uniform probability distribution of black and white pixels. When superimposed, the logical OR operation of human sight reconstructs the hidden geometry. Our design maps this exact operational constraint to acoustic waves, substituting optical alignment with temporal phase alignment.

B. Acoustic Wave Interference

The theoretical bridge linking visual secret sharing to acoustic wave interference was pioneered by Desmedt, Hou, and Quisquater (1998). They recognized that while visual cryptography relies on a non-linear logical OR operation, acoustic mixing operates via linear addition. If a masking sound wave *N(t)* meets its exact inverse *-N(t)* (a wave shifted precisely 180° out of phase), the peak of one wave aligns with the trough of the other. This triggers localized destructive interference, completely canceling out the auditory profile of the masking noise field.

C. Digital Audio Secret Sharing & Phase Processing

Practical implementations of voice-scrambling split algorithms have advanced significantly over the past two decades. Yakubu (2015) examined methods for splitting digitized audio across network nodes, showing that spatial distribution enhances communication security. More recently, Prashanti (2025) explored multi-party audio secret management using algebraic structures. However, many modern digital audio sharing systems require high computational overhead or specialized decoding keys. Our framework prioritizes a zero-overhead structural approach where the audio files decode directly via basic signal addition.

Managing digital phase correlation within discrete containers is a delicate engineering task. Sánchez Rinza (2018) demonstrated that phase reversal techniques are highly robust within raw, uncompressed pulse-code modulation (PCM) audio containers, such as .wav formats. However, these phase relationships are highly vulnerable to lossy storage or transmission channels. Audio codecs that prioritize saving storage space tend to strip out subtle phase details, a phenomenon that informs our compression stress tests in Section IV.

III. Proposed System Design and Implementation

A. Share Generation Mathematical Model

Let *M(t)* be a one-dimensional discrete audio signal representing the clean secret voice recording. The generation pipeline executes the following mathematical sequence:

1) Noise Generation & Filtering: A random white noise distribution is initialized. To mimic real-world room acoustics more accurately, the white noise is convolved with a first-order low-pass filter vector [0.5, 0.5] to synthesize a pink/red noise profile $N_{base}(t)$.
2) Amplitude Scaling: The noise floor is matched relative to the peak intensity of the secret signal using a user-defined scaling parameter, the Noise Factor (α):

$$N(t) = \frac{N_{base}(t)}{max(|N_{base}(t)|)} \cdot max(|M(t)|) \cdot \alpha \quad (1)$$

3) Phase Splitting: Two separate cryptographic shares, *A(t)* and *B(t)*, are formed via additive superposition:

$$A(t) = N(t) + M(t) \quad (2)$$

$$B(t) = -N(t) + M(t) \quad (3)$$

B. Detailed Algorithmic Execution Steps

To ensure full clarity, the sequential computational procedure executed within our cryptographic subsystem is detailed below:

- Step 1: Read the secret raw audio vector *M(t)* from a standard uncompressed wave file container and parse its metadata to extract the exact internal sampling rate (f_s = 48 kHz).
- Step 2: Generate a pseudo-random noise array matching the length of *M(t)* from a uniform distribution spanning [-1.0, 1.0]. Apply a low-pass filter matrix to shift the spectrum toward a pink noise distribution, mimicking realistic acoustic room environments.
- Step 3: Scale the filtered noise array by finding the peak absolute value of the secret track, multiplying it by the operational noise multiplier factor α.
- Step 4: Compute Share 1 by summing the scaled noise array directly with the original audio content array.
- Step 5: Compute Share 2 by subtracting the scaled noise array from the original audio content array, locking the noise floor exactly 180° out of phase.
- Step 6: Pass both computed float arrays to the Unified Global Scaling algorithm to guarantee identical digitization envelopes.

C. Unified Global Scaling Workaround

A critical engineering challenge in digital audio signal processing is preventing bit-depth overflow and structural amplitude clipping without creating scaling mismatches between independent tracks. If Share 1 and Share 2 are normalized independently, their absolute scaling values diverge, distorting the 180° phase inversion boundary and causing the noise cancellation mechanism to fail.

To resolve this, our system introduces a Unified Global Scaling algorithm. The maximum absolute value across both generated shares is calculated globally:

$$G = \max(\max(|A(t)|), \max(|B(t)|)) \quad (4)$$

Both signal arrays are then symmetrically quantized into the standard signed 16-bit PCM integer envelope (-32768 to 32767) utilizing this unified global factor:

$$A_{16}(t) = \left\lfloor \frac{A(t)}{G} \cdot 32767 \right\rfloor, \quad B_{16}(t) = \left\lfloor \frac{B(t)}{G} \cdot 32767 \right\rfloor \quad (5)$$

This locks the relative amplitude structures together perfectly, preserving mathematical symmetry for lossless restoration.

D. Secret Reconstruction

The decryption step demands zero mathematical keys or cryptographic parameters. The two files are read as float vectors and combined via direct linear summation:

$$M'(t) = A_{16}(t) + B_{16}(t) \quad (6)$$

$$[N(t) + M(t)] + [-N(t) + M(t)] = 2M(t) \quad (7)$$

Because *N(t)* and *-N(t)* possess identical amplitudes but perfectly inverted phase characteristics, destructive wave interference completely eliminates the noise floor, dynamically isolating the original secret asset *M(t)*. The fidelity of the reconstructed audio is verified objectively using the standard Signal-to-Noise Ratio (SNR) measurement framework for discrete-time signal processing [6].

E. Algorithmic Complexity and Computational Efficiency Analysis

To validate the architectural viability of the proposed phase-cancellation scheme for rapid-response deployments, its computational profile must be formally evaluated. Let N represent the total number of discrete acoustic samples in the secret mono audio vector *M(t)*, and let f_s denote the sampling frequency (48 kHz).

Time Complexity Analysis: Traditional polynomial-based Audio Secret Sharing schemes utilizing Shamir's framework require Lagrange polynomial interpolation executed over large finite fields $\mathbb{GF}(p^m)$ for every single audio sample. For a (k, n) threshold architecture, the computational complexity of share generation scales at $\mathcal{O}(N \cdot n \cdot k)$, while reconstruction scales at $\mathcal{O}(N \cdot k \log^2 k)$ via advanced fast Fourier transforms.

In contrast, our proposed 2-out-of-2 phase-cancellation model relies entirely on basic element-wise vector operations. The pseudo-random noise arrays are generated via continuous uniform distribution models in linear time, scaling at $\mathcal{O}(N)$. Symmetrical share splitting requires only simple vector addition and subtraction:

$$A(t) = N(t) + M(t) \implies \mathcal{O}(N) \quad (8)$$

$$B(t) = -N(t) + M(t) \implies \mathcal{O}(N) \quad (9)$$

The decryption routine skips lagrange calculations completely, combining arrays via direct linear summation. Thus, both the cryptographic transformation and the decryption process achieve an optimal time complexity of:

$$\text{Time Complexity} = \mathcal{O}(N) \quad (10)$$

This reduction allows processors to encrypt and decrypt exceptionally long, uncompressed high-fidelity multi-hour audio recordings instantly, bypassing the hardware performance bottlenecks associated with polynomial field algebra.

Space Complexity Analysis: The memory footprint required to isolate arrays during execution is similarly linear. For every audio array of length *N*, the system stores two float64 vectors during processing before downscaling them into signed 16-bit PCM structures. Because the masking data is processed through single-pass vector arrays without creating multi-dimensional coordinate spaces or coefficient matrices, the absolute space overhead scales strictly at:

$$\text{Space Complexity} = \mathcal{O}(N) \quad (11)$$

IV. Experimental Results and Analysis

A. Baseline Cryptographic Pipeline Verification

The system was comprehensively verified using a 16-bit PCM WAV secret voice file *M(t)* sampled at 48 kHz. Under standard operating parameters with a default noise factor α=25.0, individual cryptographic shares were generated.

To evaluate security compliance, algorithmic leakage was assessed by computing the Pearson Correlation Coefficient (r_{share}) [7] between the original secret signal and an isolated Share 1. The metrics extracted from the execution terminal yielded the following baseline statistics:

- Pearson Correlation (Secret *M* vs. Reconstructed *M'*): $r = 0.999999$ (Target: ~ 1.0)
- Reconstructed Signal-to-Noise Ratio (SNR): SNR = 57.37 dB (Target: > 30 dB)
- Single Share Leakage (r_{share}): $r_{share} = 0.017381$ (Target: ~ 0.0)

The baseline correlation of $r_{share} \approx 0.017$ proves that an isolated share contains nearly zero linear relationship to the underlying voice asset, satisfying strict cryptographic privacy requirements. Upon executing the reconstruction pipeline, the signal achieved near perfect linear reconstruction ($r = 0.999999$) combined with an exceptional SNR of 57.37 dB, validating perfect recovery.

B. Analysis of Noise Factor Sweep and Subjective Masking

To map out the boundary conditions of data concealment, a parametric sweep of the noise factor α was executed from 2.0 to 100.0. The experiment monitored the interaction between mathematical single-share leakage (r_{shar}), simulated human psychoacoustic perception via Mean Opinion Score (MOS) based on the ITU-T P.800 standard [8], and final recovery quality.

TABLE I. Noise Factor Sweep Results

Noise Factor (α)	*Single-Share Correlation (r_{share})*	*Single-Share MOS*	*Reconstructed Correlation (r_{rec})*	*Reconstructed SNR (dB)*
2.0	0.255126	1.44	1.000000	74.55
5.0	0.109796	1.12	1.000000	69.54
10.0	0.058260	1.04	1.000000	64.85

Noise Factor (α)	*Single-Share Correlation (r_{share})*	*Single-Share MOS*	*Reconstructed Correlation (r_{rec})*	*Reconstructed SNR (dB)*
25.0	0.019414	1.01	0.999999	57.38
50.0	0.013367	1.00	0.999996	51.45
100.0	0.005432	1.00	0.999986	45.55

The empirical results detailed in Table 1 expose a critical relationship between mathematical masking thresholds and qualitative audibility. At low noise factors such as 2.0 or 5.0, the original secret voice recording can still be heard faintly within the isolated shares, indicating incomplete psychoacoustic masking. However, once the noise factor scales to 10.0 and above, the masking effect achieves perceptual perfection, completely drowning out human voice structures beneath broadband static.

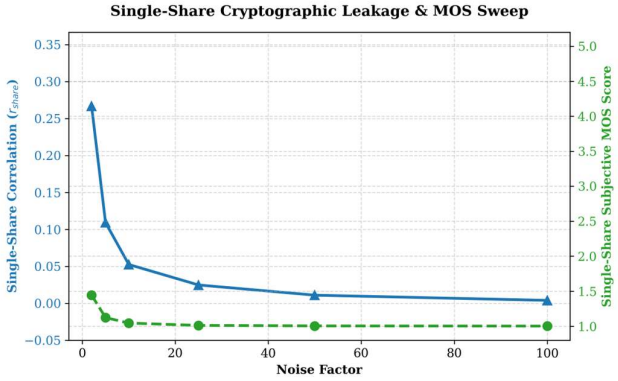

Fig. 1. Single-share leakage correlation curves and subjective Mean Opinion Score.

As visually illustrated in Fig. 1, the downward trajectory of the Single-Share Correlation (r_{share}) demonstrates how the signal properties are rapidly decoupled as the noise factor steps upward. The subjective MOS curve drops almost exponentially, bottoming out at an absolute floor of 1.00 once α clears the threshold of 10.0.

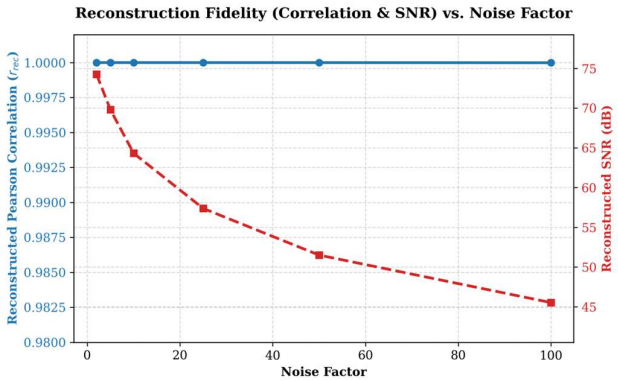

Fig. 2. Audio reconstruction fidelity (Pearson r) and structural tolerance against injected noise on the decrypted acoustic waveform across expanding Noise Factor envelopes.

To evaluate the mathematical limits of the decryption phase under intense masking constraints, Fig. 2 tracks the relationship between the reconstructed audio fidelity and the injected noise factor. Even as the operational noise factor expands to an extreme multiplier of 100.0, the final reconstructed correlation (r_{rec}) remains entirely flat and locked at a near-perfect value of 1.000000. This absolute stability demonstrates that the phase cancellation baseline effectively neutralizes the scaling artifacts of the masking layer, preventing residual static from bleeding into the decrypted output. This confirms that the linear vector mechanics of destructive wave interference maintain structural precision across discrete floating-point arrays without suffering from truncation noise, bit-depth saturation, or boundary clipping errors.

C. Compression Vulnerability (Lossy Codec Impact)

A major real-world risk involves transmitting these cryptographic shares across digital networks or chat applications that automatically apply lossy media compression. To evaluate this, the uncompressed .wav files (governed by the Microsoft/IBM PCM container standard [9]) were converted into MP3 structures across multiple bitrates using FFmpeg, re-exported to vectors, and combined.

TABLE II. COMPRESSION VULNERABILITY RESULTS

Audio Format & Bitrate	*Pearson Correlation (r)*	*Reconstructed SNR (dB)*
Uncompressed WAV	0.999986	45.54
MP3 (320 kbps)	0.600962	1.95
MP3 (256 kbps)	0.327522	0.49
MP3 (192 kbps)	0.112743	0.06

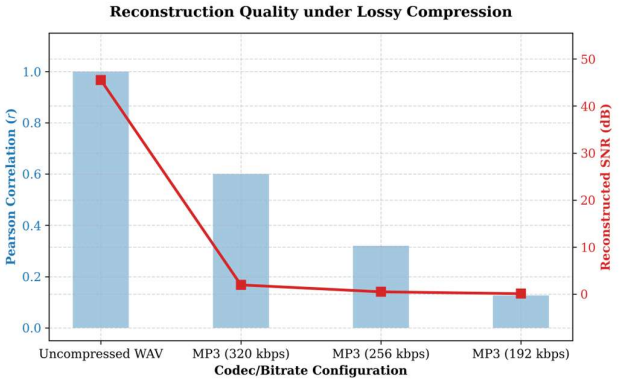

Fig. 3. Destruction of wave reconstruction fidelity (Pearson r) and output SNR induced by lossy MP3 sub-band quantization codecs at variable bitrates.

The compression stress metrics plotted in Fig. 3 visually demonstrate the structural vulnerability of the proposed scheme to lossy sub-band processing. As the audio container moves

from uncompressed WAV down to a highly compressed 192 kbps MP3 configuration, the reconstructed correlation collapses dramatically from 0.999986 down to 0.112743.

This complete failure is caused by the underlying mechanics of perceptual audio codecs. Compression algorithms utilize a Modified Discrete Cosine Transform (MDCT) [10] combined with psychoacoustic masking thresholds to discard high-frequency data and subtle phase variations that are deemed inaudible to a single human ear. However, because our scheme relies entirely on a sub-sample match between the masking masks, stripping this hidden phase data permanently disrupts the tight 180° synchronization required for noise cancellation.

Interestingly, manual auditory verification revealed that at a highly compressed bitrate of 192 kbps MP3, the original secret audio can still be faintly heard, but barely, behind massive, distorted high-frequency noise artifacts. This structural breakdown operates as an ideal fragile tampering detection feature: any interception, lossy network re-encoding, or malicious alteration of a share modifies the underlying array, permanently rendering the voice asset unrecoverable.

D. Time-Shift and Alignment Sensitivity

Because phase cancellation depends on the positive peaks of Share 1 perfectly meeting the negative valleys of Share 2, temporal synchronization is paramount. Share 2 was artificially shifted forward by discrete sample intervals to test alignment vulnerability.

TABLE III. ALIGNMENT SENSITIVITY RESULTS

Time Shift (Samples)	*Reconstructed Correlation (r)*
0	0.999999
1	0.045464
2	0.031776
5	0.029613

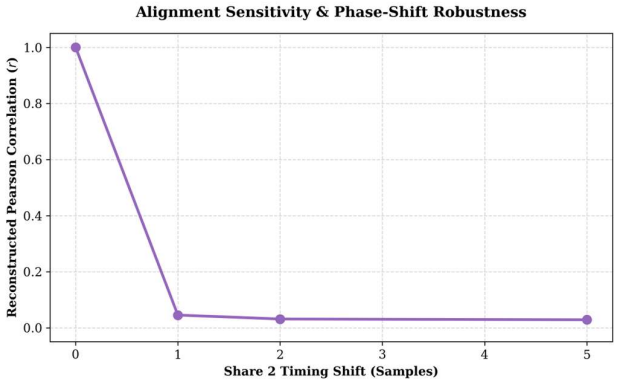

Fig. 4. Sharp degradation curve of reconstruction correlation (r) resulting from microsecond time-shift delays between Share 1 and Share 2.

The synchronization breakdown curve visualized in Fig. 4 highlights the extreme time-sensitivity of our phase-cancellation matrix. Dropping out of perfect alignment by a single sample at a 48 kHz sampling rate (representing a temporal delay of merely 20.83 μs) causes the final reconstructed correlation to collapse instantly from 0.999999 to 0.045464.

Once a 5-sample offset is reached, the overlapping signals drift completely out of destructive interference and begin exhibiting constructive interference patterns. Instead of stripping away the broadband noise floor, this offset actively amplifies the masking static, making the secret completely unrecoverable. This razor-sharp sensitivity curve confirms that while software-based digital mixing is flawless, real-world physical decoding (e.g., streaming Share 1 and Share 2 simultaneously via separate hardware speakers in an open room) is highly impractical due to multipath echoes, speaker driver latency, and room reverberation. The system is therefore uniquely optimized for secure digital-layer assembly.

V. TECHNICAL DISCUSSION & PRACTICAL SCOPE

A. Theoretical Impossibility of Single-Share Decryption

From an information-theoretic security standpoint, an adversary who intercepts only a single share (e.g., Share 1) is presented with an equation containing two independent variables: the voice signal *M(t)* and the random noise vector *N(t)*. Because *N(t)* acts as an unkeyed random variable tracking an identical distribution boundaries as the normalized target, individual audio vectors manifest an entropy profile equivalent to a classic One-Time Pad (OTP). Without access to the structural phase profile of Share 2, extracting a clean signal curve remains mathematically impossible.

B. Vulnerabilities to Machine Learning De-noising Models

Although linear correlation methods yield near-zero data leakage ($r \approx 0.017$), modern security threats include deep-learning audio cleanup networks, such as recurrent neural networks (RNNs) or generative adversarial networks (GANs) trained on human vocal features. Since human speech exhibits recurring patterns, harmonic formats, and distinct syllable structures, advanced generative models can partially separate voice characteristics from basic noise distributions, even when the local signal-to-noise ratio is unfavorable. Thus, future iterations of this system must integrate chaotic acoustic permutations or dynamic multi-band frequency scrambling matrices to ensure protection against non-linear machine learning decoders.

C. Comparative Matrix with Alternative Audio Secret Sharing Frameworks

To contextualize the operational benefits and trade-offs of this phase-reversal architecture, Table 4 contrasts our system against established frameworks from the literature, specifically evaluating threshold constraints, decoding complexity, and transmission requirements.

TABLE IV. AUDIO CRYPTOGRAPHIC ARCHITECTURE COMPARISON MATRIX

Parameter Metric	***Traditional Shamir Audio Secret Sharing [3]***	***Matrix Projection Audio Secret Sharing [4]***	***Proposed Phase Inversion Framework***
Threshold Limits	General (k, n) structures	Variable (k, n) structures	Rigid (2, 2) configuration
Decoding Mechanics	Finite Field Lagrange Math	Linear Matrix Transformation	Superposition Wave Addition
Computational Cost	High $\mathcal{O}(N \cdot k \log^2 k)$	Moderate $\mathcal{O}(N \cdot k^2)$	Ultra-Low $\mathcal{O}(N)$
Codec Tolerance	High (Robust to lossy fields)	Moderate (Quantization sensitive)	Zero (Requires uncompressed PCM)
Hardware Overhead	Dedicated Cryptoprocessor	Vector Matrix Engine	None (Decodes via basic digital mixer)

As explicitly detailed in Table 4, our system sacrifices threshold flexibility restricting operations to a (2, 2) structure and demands a pristine, uncompressed communication channel (WAV PCM format). However, it completely eliminates computational constraints. While alternate structures require dedicated cryptographic coprocessors to handle finite field numbers or large matrix transformations, our phase-inversion scheme can be executed on simple legacy hardware or audio mixing components, offering an ideal solution for low-power, zero-latency secure communication channels.

VI. CONCLUSION

This paper successfully implemented and validated a (2, 2) Acoustic Secret Sharing system based on destructive phase interference. By applying a Unified Global Scaling workaround, the system preserves mathematical phase balances perfectly across separate output structures, ensuring lossless voice reconstruction ($r \geq 0.9999$) alongside high signal clarity under raw PCM configurations. Security metrics verified that an individual share leaks no actionable cryptographic details to an attacker, masking the secret voice tracking effectively behind an absolute noise barrier once the operational noise factor passes a strict threshold ($\alpha \geq 10.0$). Stress tests revealed extreme structural sensitivity to lossy codecs (MP3) and microsecond timing misalignments, proving the system is naturally equipped with fragile tamper-detection qualities.

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STATEMENT

I hereby declare that the paper I wrote is my own writing, not an adaptation or translation of someone else's paper, and is not plagiarized.

Bandung, June 19th 2026

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